BIOLOGICAL CONTROL OF CEREAL APHIDS IN MICHIGAN WHEAT

By

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ABSTRACT

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Cereal aphids (Hemiptera Aphididae) are important pests of wheat and can cause yield loss through both direct feeding injury and indirectly by transmitting viruses. Previous work has demonstrated that natural enemies are effective in suppressing cereal aphids in wheat fields in Europe and North America; however, no studies have been done in Michigan. The objectives of this thesis research were to characterize the natural enemy community in wheat fields and evaluate the role of different natural enemy groups in regulating cereal aphid population growth. I investigated these objectives in four winter wheat fields on the Michigan State University campus farm in East Lansing, Michigan. I monitored and measured the impact of natural enemies by experimentally excluding or allowing their access to wheat plants infested with cereal aphids. I found that the natural enemy community in the wheat fields consisted mostly of foliar-foraging and ground-dwelling predators with relatively few parasitiods. In combination, these natural enemy groups were very effective at reducing cereal aphid population. I also investigate the role of each natural enemy feeding guild (foliar-foraging versus ground-dwelling predators) independently. The result illustrates that ground-dwelling predators were more effective at suppressing cereal aphid populations than foliar-foraging predators in wheat fields. Overall, my research demonstrates the importance of biological control in in wheat and suggests that effective conservation of natural enemy communities can protect wheat from direct damaged caused by cereal aphids.

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CHAPTER 1

LITERATURE REVIEW

Cereal aphids (Hemiptera Aphididae) are important pests of wheat (*Triticum aestivum* L.) and other small grains in many parts of the world (Vickerman and Wratten 1979, Alsuhaibani 1996, Brewer and Elliott 2004, Haley et al. 2004, Li et al. 2013), causing yield loss through both direct injury and indirect damage (van Emden and Harrington 2007). Many studies have shown the importance of natural enemies in inhibiting aphid populations (Edwards et al. 1979, Chambers and Adams 1986, Lang 2003, Brewer and Elliott 2004). Alternatively, natural enemies have also failed to control aphids in other situations (Holland et al. 1996). In some cases it was reported that the presence of parasitoids and predators increased virus spread, typically by increasing aphid movement among plants (Roitberg and Myers 1978, Smyrnioudis et al. 2001). This review examines the biology and impact of cereal aphids on crops, and the natural enemy communities associated with cereal aphids.

Cereal Aphids

The bird cherry oat aphid *Rhopalosiphum padi* (L.), English grain aphid *Sitobion avenae* (F.), greenbug *Schizaphis graminum* (Rondani), and the Russian wheat aphid *Diuraphis noxia* (Mordvilko) are the most economically important pests of cereals in the United States (Pike and Schaffner 1985, Kieckhefer and Kantack 1988, Kieckhefer and Gellner 1992, Pike et al. 1997, Brewer and Elliott 2004). Most of these species transmit barley yellow dwarf virus (BYDV) and cereal yellow dwarf viruses (CYDV) (Rochow 1960, Gray et al. 1998, Chapin et al. 2001, Hadi et al. 2011). Chapin et al. (2001) observed seasonal flight activity, abundance, and vector potential of cereal aphids in South Carolina. Four species attacked wheat in different seasons of

the year. *Schizaphis graminum* and rice root aphid, *Rhopalosiphum rufiabdominalis* (Sasaki) colonized wheat seedlings soon after crop emergence and apterous colonies peaked in December - January and decreased during the rest of the season. *Rhopalosiphum padi* was the second most abundant aphid species and caused more economic loss than *S. graminum* and *R. rufiabdominalis*. *Rhopalosiphum padi* populations peaked in February and March at 10 aphids per row meter. Both BYDV and yield loss were significantly associated with *R. padi* aphid peak density and aphid-day accumulations. These authors also showed that *R. padi* was primarily responsible for transmitting the predominant virus stereotype PAV. Infective alates of *R. padi* were collected from December until April. English grain aphid, *S. avenae* was the last and most abundant species to infect wheat during all years of the study. It can transmit late season viruses and also caused direct damage and yield loss, feeding on wheat heads and flag leaves

Bird cherry oat aphid Rhopalosiphum padi (L.)

Rhopalosiphum padi is dark olive green with a reddish-brown patch on the back. The antenna and cornicles are black. It is holocyclic in northern North America and anholocyclic in the mid-western and southeastern United States and is the most prominent vector of BYDV and CYDV (van Emden and Harrington 2007). It feeds on bird cherry *Prunus padus* (L.) in Europe and chokecherry *Prunus virginiana* (L.) in North America as its primary host, and usually infests wheat as its secondary host, in early spring (Dixon 1971). *Rhopalosiphum padi* feeds on plant phloem tissue from which it extracts plant sap (Riedell et al. 2003). The preferred feeding location of *R. padi* is at the base of the stem and the lower leaves of cereal seedlings (Chongrattanameteekul et al. 1991), and they frequently change position as the plants grow (Qureshi and Michaud 2005). In autumn, gynoparae and males return to bird cherry which provide the aphids with a rich source of food (Dixon 1971)

English grain aphid Sitobion avenae (F.)

Sitobion avenae adults are 2.5 mm long, light green to brown with black antennae, cornicles, and joints. They overwinter as eggs, late instar nymphs, or adults in many species of Poaceae (van Emden and Harrington 2007). The overwintering forms are all females, which in the spring give birth to live young. These progeny mature into wingless females which produce live offspring without mating. In early spring, the aphids feed on cereal grains. As these plants mature and become less succulent, winged aphids develop and migrate to wild or cultivated grasses, where they spend the summer. In the fall, after the winter cereal grain crops are planted, the aphids return to these crops or volunteer cereals. Males appear during the fall or early winter and mate with the females, which then lay eggs on the grains where they have been feeding. Each female lays only about eight eggs. As many as 17 generations occur each year. The preferred feeding location of *S. avenae* is the head (Chongrattanameteekul et al. 1991), with colonies feeding upon the leaves before collecting on the heads among the ripening kernels. When sufficiently large populations develop, their feeding shrivels the growing kernels. This aphid species is also a known vector of the barley yellow dwarf virus in the United States.

Impacts of aphids

Infestation of cereals by aphids can result in considerable losses of grain, both in quality and quantity (Dixon 1977). Cereal aphids cause direct damage through phloem feeding, and indirect damage via production of honeydew (Vereijken 1979) or transmission of BYDV and CYDV. The most significant damage occurs in the fall before wheat dormancy. Yield reduction during the fall by direct feeding of *R. padi* without transmitting yellow dwarf viruses in winter wheat can reach 20 to 70% (Cook and Veseth 199, Riedell et al. 1999).

Yield loss of wheat and rye caused by *R. padi, S. graminum* and *S. avenae* was studied by Kieckhefer and Kantack (1988) by infecting caged plots at three different plant stages. At harvest, higher yield loss was observed in plots where aphids fed on the seedling stage (2-3 leaves) in the fall; where an average of 25-30 aphids per plant resulted in a 50% reduction in wheat yield. Less yield loss occurred when aphids fed during the spring in the boot stage. No loss was observed when aphids fed on mature plants. The yield crop damage caused by *S. graminum* and *R. padi*, were more than the damage was caused by *S. avenae*.

Indirect damage by aphids can be due to their production of honeydew, which can cover a plant's epidermis reducing photosynthesis, promoting senescence, and contributing to the growth of saprophytic fungi which may also have a negative effect on photosynthesis and leaf duration (Vereijken 1979, Rabbinge et al. 1981). Vereijken (1979) found that in 3 field tests with *S. avenae*, about half the damage caused was attributable to fungal growth on the honeydew produced by the aphid. It has been shown that in laboratory studies honeydew can cause approximately 25% yield loss (Rabbinge et al. 1981)

Aphids as disease vectors

Many cereal aphids are also vectors of the yellow dwarf virus, family *Luteoviridae* (Ajayi and Dewar 1983, Fereres et al. 1988, Royer et al. 2005). In North America *R. padi, S. graminum, S. avenae*, corn leaf aphid *Rhopalosiphum maidis* (Fitch), and *R. rufiabdominale* have all been reported as vectors of yellow dwarf viruses (Irwin and Thresh 1988, Gray et al. 1998, Chapin et al. 2001). *Rhopalosiphum rufiabdominale, R. padi* and *S. graminum* and *S. avenae* were also found in wheat in Alabama, Florida and Missouri transmitting yellow dwarf viruses (Hadi et al. 2011, Hadi et al. 2012),

Yellow dwarf viruses

Yellow dwarf viruses cause serious disease of wheat worldwide (Plumb and Thresh 1983). Yellow dwarf pathogens include barley yellow dwarf virus (BYDV) and cereal yellow dwarf virus (CYDV) both of which belong to family Luteoviridae. There are serotypes of BYDV belonging to the genus Luteovirus, including PAV, RMV, and SGV (Gray et al. 1998). One species of cereal yellow dwarf virus, cereal yellow dwarf virus-RPV belongs to genus Polerovirus (Hadi et al. 2011). Symptoms of BYDV include leaf necrosis and discoloration, stunting, delay or lack of heading (Riedell et al. 1999). Yellow dwarf viruses cause damage to more than 150 species of grasses (Poaceae) including all small grains. In North America, yield loss due to the disease on grains can reach up to 60% -70% (Miller and Rasochova 1997, Riedell et al. 2003, Jimenez-Martinez and Bosque-Perez 2004). These viruses are obligately vectored by 25 aphid species (Miller and Rasochova 1997, Hadi et al. 2012). Unlike direct injury from aphid feeding where plants can recover after aphids are removed, cereal plants infected with BYDV do not recover from infection. Viral infection in wheat also increases host susceptibility to fungal pathogens, drought, and other environmental factors (Irwin and Thresh 1988, Riedell et al. 2007). Epidemics of virus in winter wheat have been observed mostly in the fall and are primarily due to *R. padi* activity in North America (Pike and Schaffner 1985, Pike et al. 1997).

Root characters, shoot characters and wheat yield show responses to infection of BYDV transmitted by *R. padi* at 2 to 3 leaf stage. Compared to controls, treatment of 2-3 leaf stage wheat with only *R. padi* had increased total root length of about 30%, while treatments with *R. padi* plus BYDV exhibited a 40% decrease in total root length. Plants infected with *R. padi* alone had fewer and shorter tillers, and lower shoot dry weight at anthesis compared to plants that were not infected with *R. padi*. Plants infected with BYDV and the combination of the *R. padi* plus

BYDV reached anthesis at later time than the treatments with *R. padi* and control treatment (Riedell et al. 2003).

Control of aphids

Chemical, cultural, and biological methods have been used to control aphids and the spread of viruses in cereals. Insecticides can be effective but are costly to purchase and apply. Also, repeated use of insecticides can result in development of insecticide resistance, cause negative impacts on beneficial insects, and increase aphid movement from plant to plant, resulting in increased virus spread (Irwin and Thresh 1990, Shufran et al. 1997). Host-plant resistance to aphids is promising but must constantly address the emergence of new aphid biotypes with the ability to survive on previously resistant plant lines (Roberts and Foster 1983, Formusoh et al. 1992). Smith et al. (2004) showed that the variety "Treasure" and five other new varieties from Iran and the former Soviet Union were resistant to *D. noxia.* Leaf pubescence of wheat also provides a possible mechanism of resistance to aphids (Roberts and Foster 1983). Biological control of cereal aphids by natural enemies (parasitoids and predators) can be an alternative control (Symondson et al. 2002, Brewer and Elliott 2004).

The role of natural enemies in aphid control

Globally, cereal aphids are attacked by variety of natural enemies (Puterka et al. 1993, Van Emden and Harrington 2007). Cereal crops in North America attract several groups of aphid natural enemies including ladybeetles (Coccinellidae), adult and larva lacewings (Chrysopidae), hoverflies larva(Syrphidae), parasitoid wasps (Hymenoptera, *Aphidiidae*), carabids (Carabidae), rove beetles (Staphylinidae), and spiders (Araneae) (Mohamed et al. 2000, Chapin et al. 2001, Brewer and Elliott 2004, Lee et al. 2005). Predators and parasitoids acting either independently

or together can reduce aphid population density (Kring et al. 1985, Losey and Denno 1999, Schmidt et al. 2004, Macfadyen et al. 2009), thereby reducing plant damage and increasing yield (Östman et al. 2003).

Classical biological control, the importation and release of novel natural enemies, was conducted against *D. noxia*, resulting in 29 species of exotic predators and parasitoids being released in the United States (Hopper et al. 1998, Mohamed et al. 2000). However, only four hymenopteran parasitoids were recovered (Prokrym et al. 1998). Mohamed et. al. (2000) conducted a survey to identify parasitoids and predators of *D. noxia* in organic wheat, barley and crested wheatgrass (*Agropyron cristatum* L.), and to determine the impact of weeds on aphids and their natural enemies. These authors also used cage exclusion methods to understand the impact of parasitoids and predators on *D. noxia*. Crested wheatgrass had fewer *D. noxia* and natural enemies than wheat and barley. During this study they observed 41 species of predators and parasitoids including: 15 carabids, 12 coccinellids, 6 spiders, 5 syrphids, 2 nabids, and 2 chrysopid species. The most abundant were coccinellids and nabids, with *Hippodamia convergens* and *Nabis alternatus* the most common species. In this experiment, only one species of parasitoid, *Diaeretiella rapae* (Hymenoptera: Braconidae) was found. In an exclusion cage study, aphid populations were 2.6 to 11.2 times higher in the caged, than in the open plots.

Excluding natural enemies from aphid colonies demonstrates how important natural enemies are in biological control. Schmidt et al. (2003) studied cereal aphid biological control in Europe by reducing populations of ground-dwelling predators (spider, carabids, and staphylinids beetles), flying predators and parasitoids, and combinations of both ground-dwelling and flying natural enemies. Compared with open fields where access of parasitoids and predators was not restricted, aphid populations were 18% higher with reduced densities of ground-dwelling

generalist predators, 70% higher in cages where flying parasitoids and predators were excluded, and 172% higher when both natural enemies were excluded. Similarly, work by Thies et al. (2011) in six European regions showed that aphid populations were 28% higher in plots excluding ground-dwelling predators, 97% higher in plots that excluded both flying natural enemies, and 199% higher when both enemy groups were excluded. These European results show that both communities of parasitoids and predators are important in controlling cereal aphids, but the effect of flying parasitoids and predators was generally stronger than grounddwelling predators, while the combination of the two showed the best result on pest suppression.

Coexistence of different aphid species may have a positive impact on biological control. For example, Formusoh and Wilde (1993) showed that *Coccinella septempunclata* (L.) and *Hippodamia convergens* (Guerin-Meneville) did not show a preference between *S. graminum* and *D. noxia*. The lack of preference implies the predator feeds on whichever prey species is in abundance and easily accessible. Therefore, in agroecosystems where both aphid species coexist, Coccinellidae will prey on more easily accessible *S. graminum*. The development of resistant wheat cultivars with minimum leaf curl could allow for the compatibility of biological control with host plant resistance. Bergeson and Messina (1998) studied direct and indirect impact of *R. padi* on increase of *D. noxia* populations. They found that the presence of the green lacewing *Chrysoperla plorabunda* significantly reduced *D. noxia* populations, and the rolled leaves that *D. noxia* cause did not prevent lacewing predation. However, *C. plorabunda* was less effective in the experiment where both aphids were present. This might be because *R. padi* is more accessible to predators than *D. noxia*.

Predators

Predators are frequently most effective in the early season when aphid populations are relatively low (Chiverton 1986, 1987, Lang 2003), but can also control population peaks, even in the presence of alternative prey (Winder 1990). For example von Berg et al. (2009) found that even with the presence of alternative prey (i.e. thrips, springtails, mites), flying and grounddwelling predators suppressed aphid populations below threshold levels, by switching from alternative prey to aphids.

Aphidophagus Coccinellidae are often the dominant natural enemy in cereal fields and other agroecosystems in North America (LaMana and Miller 1996, Obrycki and Kring 1998, Elliott and Kieckhefer 2000, Wright and DeVries 2000, Clement et al. 2004). Coccinellidae overwinter as adults (Colunga-Garcia and Gage 1998) and co-occur with *R. padi* and other cereal aphids in the spring (Phoofolo et al. 2007). Adult Coccinellids can consume up to 100 aphids per day (Xue et al. 2009, Hallett et al. 2013) and dramatically reduce aphid numbers in dense patches as well as when aphid populations are low in wheat fields (Elliott and Kieckhefer 2000). Many Coccinellids are effective biological control agents of cereal aphids (Rice and Wilde 1988). Phoofolo et al. (2007) showed that *Hippodamia convergens* preyed on *R. padi* and *S. graminum*. *H. convergens* and *Coccinella septempunctata* are primarily predaceous on aphids, while *Coleomegilla maculata* feeds on a variety of plant and other alternative prey in additional to aphids (Hodek and Honek 1996).

Ground-dwelling predators can also be effective in aphid suppression, and their impact is thought to be the greatest early in the growing season (Sunderland and Vickerman 1980, Dennis and Wratten 1991, Lang 2003). Among the ground-dwelling predators, Carabidae probably

contribute the most to aphid suppression in cereals. These polyphagous predators often colonize cereal fields from neighboring habitats (French and Elliott 1999), and are known to consume R. padi, S. avenae and other aphids species (Edwards et al. 1979, Chiverton 1986). The greatest impact on aphid populations occurs in early summer (May) when aphid populations are low and reproduction is slower than in summer. However, Carabidae can continue to impact aphid densities until aphid populations peak (Winder 1990, Winder et al. 1994). They can reduce aphid density by preying on aphids directly when the aphids drop from plant (Duffield et al. 1996, Symondson et al. 2002), or by climbing the plant. In a study examining the relative importance of ground-dwelling predators on aphid populations, Lang (2003) manipulated populations of ground beetles and spiders. Excluding ground beetle resulted in an increase in spiders that was not associated with a reduction in aphid density, and aphid populations were highest in the plots where Carabidae were removed. Although cereal aphids are considered low quality food for ground-dwelling predators (Toft 2005), several other studies suggest that ground beetles regularly consume cereal aphids. Sunderland and Vickerman (1980) dissected the gut of 12,000 individual ground-dwelling predators, collected from winter wheat and barley fields in Washington. They found that sixteen species of Carabidae, 3 species of Staphylinidae and 1 species of Dermaptera all had aphids in their diet.

Parasitoids

Feng et al. (1991) reported that the parasitoid *Aphidius ervi* attacked *S. avenae*, *Diaeretiella rapae*, and *Aphelinus varipes* attacked *D. noxia* and *R. padi*. Pike et al. (1997) documented species abundance, geographic distribution, and seasonal occurrence of the primary parasitoids of cereal aphids in eastern Washington. They found thirteen species of primary parasitoids including, *Aphelinus albipodus*, *Aphelinus asychis*, *Aphidius naphis*, *Aphidius ervi*,

Aphidius matricariae, *D. rapae*, *Ephedrus* sp, *Lysiphlebus testaceipe*, *Monoctonus washingtonensis*, *Praon unicum*, *Praon occidentale*, and *Praon yakimanum*. The dominant parasitoids were *D. rapae* on Russian wheat aphid, *L. testaceipes* on bird cherry-oat aphid, and *A. naphis*, *A. ervi*, and *D. rapae* on English grain aphid. *Lysiphlebus testaceipes* is also an important parasitoid of cereal aphids in the US Southern Plains (Jones et al. 2005, Jones et al 2007), where it is followed in importance by *D. rapae* (Giles et al. 2003).

Negative impact of natural enemies

Although the positive impact of natural enemies on control of cereal aphid can be great, some studies also report negative impacts of predators and parasitoids in wheat. For example, parasitoids and predators may increase the spread of viruses by increasing aphid movement and dispersal (Roitberg and Myers, 1978). Aphids have defensive strategies to avoid and escape from natural enemies by walking or drop off the plant or kicking predators when the predator comes close (Dixon, 1958). McConnell and Kring (1990) observed that the adults and nymphs of S. graminum were dislodged 4-5 times more often than they were consumed by parasitoids. In addition, parasitized aphids remain alive for a few days and if viruliferous, may transmit a virus to other plants. To study the impact of a predator, C. septempunctata, and a parasitoid, Aphidius *rhopalosiphi*, on the spread of BYDV by *R. padi*, Smyrnioudis (2001) conducted a laboratory experiment. Viruliferous R. padi were caged with the parasitoid or predator in wheat seedlings and virus infections were observed after two, seven and fourteen days. In plots without A. rhopalosiphi, BYDV infestation was greater at 7, 14 days versus plots where A. rhopalosiphi was present. In plots with the predator, aphids frequently moved between plants and more plants were infected with BYDV than in the control. After 14 days all plants were infected in plots with the predator.

Summary

Cereal aphids are one of the principal pests of the wheat throughout the world and can cause economic yield loss by feeding on the plant, producing honeydew or by transmitting yellow dwarf viruses (Karsten et al. 2009). Naturally occurring enemies that prey on the cereal aphids can reduce their populations, thereby increasing yield, and reducing the need for chemical control. The impact of the natural enemy groups on cereal aphid populations, in combination or alone, is well studied in Europe and parts of North America but to our knowledge biological control of cereal aphids has not been studied in Michigan wheat. The purposes of this thesis are: 1) quantify the natural enemy community in selected Michigan wheat fields, 2) examine the impact of natural enemy community on cereal aphid population growth, and 3) compare the relative contributions of different groups of natural enemies, specifically foliar-foraging versus ground-dwelling predators.

CHAPTER 2

BIOLOGICAL CONTROL OF CEREAL APHIDS ON WHEAT IN MICHIGAN Abstract

Natural enemies provide important ecosystem services by suppressing populations of insect pests in many agricultural crops. However, the role of natural enemies against cereal aphids in Michigan winter wheat (Triticum aestivum L.) is largely unknown. We characterized the natural enemy community in wheat fields and evaluated their role in controlling cereal aphid populations, using exclusion cage studies during the spring and summer of 2012 and 2013. The natural enemy community impacting populations of Rhopalosiphum padi (L.) and Sitobion avenae (F.) (Hemiptera: Aphididae) were monitored in 1) open plots presenting no barriers to natural enemies, 2) closed cages excluding all natural enemies, and 3) sham cages with holes to allow access by the natural enemy community. Our result showed that populations of R. padi were dramatically higher in natural enemy exclusion plots. The closed plots in our study had a maximum 57 times higher cumulative aphid-days than the open and sham plots. The maximum number of *R. padi* and *S. avenae* in the closed plots exceeded economic injury levels reaching 38 and 29 per tiller respectively. In contrast, the maximum numbers of cereal aphids in the open and sham plots were below economic injury levels and did not exceed 3 aphids per tiller. Since the numbers of cereal aphids in the sham cages were no different from the open cages, we concluded that any microclimatic effects caused by the cages were insignificant. Our results suggest that the existing natural enemy community is successfully in suppressing cereal aphid populations in Michigan winter wheat, and should be actively conserved.

Keywords: Biological control, natural enemy, cereal aphid, *Rhopalosiphum padi*, *Sitobion avenae*

Introduction

Common wheat, *Triticum aestivum* (L.) and related species are among the world's staple food crops. Worldwide, about 670 million tons of wheat are grown on 225 million ha of land annually (Singh et al. 2008). During the 2012 - 2013 growing season, the United States produced 62 million tons of wheat, mostly in the Great Plains and Northwest regions of the country (USDA-ERS, 2013). However, Michigan is also a major wheat growing state, producing approximately 1.5 million tons annually, ranking number 13th in production among the 46 wheat producing states (USDA National Agricultural Statistic Service, 2012).

Cereal aphids (Hemiptera: Aphididae) are the principal pests of wheat throughout the world. In North America, the aphid pest complex on wheat primarily consists of four aphid species, the bird cherry-oat aphid (*Rhopalosiphum padi* L.), English grain aphid (*Sitobion avenae* F.), greenbug (*Schizaphis graminum* Rondani), and Russian wheat aphid (*Diuraphis noxia* Mordvilko). These aphids cause economic damage by feeding directly on the plants and indirectly transmitting barley yellow dwarf viruses (BYDV) (Vickerman and Wratten 1979, Kieckhefer and Kantack 1988, Kieckhefer and Gellner 1992, Elliott et al. 1998, Chapin et al. 2001, van Emden and Harrington 2007). Additionally, greenbug and Russian wheat aphids inject a toxin into the leaves via their saliva, causing additional yield reductions (Duveiller et al. 2007). Previous work showed that a mean density of 25-30 aphids per stem can cause up to 50% reduction in some yield component (Kieckhefer and Kantack 1988). When aphids transmit plant viruses, damage can be even greater. For example, yield loss due to BYDV alone can reach up to 60% -70% (Cook and Veseth 1991).

Both chemical and biological methods have been used to manage aphids and reduce the spread of viruses in cereals. while effective in aphid control, intensive use of insecticides can

lead to increased production costs associated with insecticide purchase, handling, and application (Webster et al. 1995, Meehan et al. 2011), development of insecticide resistance, and increased aphid movement from plant to plant increasing virus spread (Teetes et al. 1975, Irwin and Thresh 1988, Shufran et al. 1996), and negative effects on human health and the environment (Flickinger et al. 1991). Insecticides can also reduce the abundance and diversity of predatory insects that regulate aphid populations (Brown et al. 1983, Basedow et al. 1985, Wiles and Jepson 1992, Banken and Stark 1998, Geiger et al. 2010). Fostering biological control organisms in an early season crop like winter wheat may have important implications for biocontrol in later season crops like corn and soybean, as mobile natural enemies may move to adjacent crops after early season crops are harvested (Sivakoff et al. 2012).

Biological control of pests by natural enemy communities is an important ecosystem service (Östman et al. 2001, Losey and Vaughan 2006, Swinton et al. 2006). Naturally occurring enemies that prey on aphids can prevent populations from multiplying beyond economic thresholds and prevent yield loss (Edwards et al.1979, Chiverton 1986, Larsson 2005, Bianchi et al., 2006, Karsten et al., 2009), thereby reducing the need for insecticide use. Reducing chemical inputs can in turn increase populations of beneficial insects. For example, in an organic wheat field, the abundance of natural enemies and aphid control were higher than in a conventional field (Krauss et al. 2011). Östman et al. (2001) showed that *R. padi* establishment was lower in organic compared to conventional fields which could be a result of higher numbers of natural enemies. Numerous studies have used exclusion cages to measure the effect of natural enemies on aphid populations. In one European study, cereal aphid populations were 172% higher on wheat plants when natural enemies were excluded (Schmidt et al. 2003). Another study conducted in wheat also showed that cereal aphid numbers were 12 times higher when predators

were excluded (Hopper et al. 1994).

The complex of aphid natural enemies in cereal crops has been described for Europe (Thies et al. 2011), Germany (Schmidt et al. 2003) and the United Kingdom (Chambers et al. 1986, Winder et al. 1994). In North America the natural enemy community of cereal aphids was reviewed (Brewer and Elliott 2004) and studied in South Dakota (Elliott et al. 1998), eastern Washington (Pike and Schaffner 1985, Clement et al. 2004), and Colorado (Mohamed et al. 2000, Lee et al. 2005) but, to our knowledge, has not been described in Michigan or the Midwest. To investigate the role of natural enemies in controlling cereal aphid populations in East Lansing, Michigan wheat fields, we conducted exclusion cage field studies in 2012 and 2013. The overall goal of this research was 1) to characterize the natural enemy community, and 2) determine its effect on aphid population growth in Michigan winter wheat fields.

Methods

Study sites and experimental design

Experiments were conducted in four different winter wheat fields in 2012 (2 fields) and 2013 (2 fields) on the Michigan State University campus, East Lansing, Michigan (**Figure 1**). The fields were planted in October of 2011 and 2012. Each field received herbicide, fungicide and fertilizers at rates determined by the farm manager (**Table 1**). No insecticides were applied in the fields in either year. In each field, a 30 x 20 m area was delineated at least 35 m from the field edge. Individual plots within this area were established 5 m equidistant from each other in a completely randomized design (**Figure 2**). Treatments included open plots, which provided unrestricted access of natural enemies to aphids, closed plots which excluded all natural enemies, and sham cages to control for cage effects. Open plots consisted of circular area of 0.36 m,



Figure 1. Winter wheat fields (shown in white) used as study sites in 2012 (field 1 and 2) and 2013 (field 3 and 4) Michigan State University campus, East Lansing, Michigan.



Figure 2. Example of plot layout (field 2) in completely randomized design using three treatments; open, closed and sham plots, conducted on the Michigan State University campus, East Lansing, Michigan. The study area was 30m x 20m, with 5 m between the plots, and 35 m from any of the field margins.

Studios sitos	Voor	Area / ha	Cultivar	Seeding	Fungicide mg / ha	Herbicide	Fertilizer	
Studies sites	Tear	Alea / Ila					rate/ ha	kg/ha
Field 1	2012	8.7	Unknown	10/5/2011	94.6	Affinity Broadspec*	46-0-0	73.9
Field 2	2012	18.5	Unknown	10/18/2011	94.6	Affinity Broadspec	46-0-0	181
Field 3	2013	12.1	Red Devil	10/4/2012	0	Affinity Broadspec	46-0-0	41.3
Field 4	2013	9.5	Ruby Red	10/17/2012	0	Affinity Broadspec	46-0-0	83.5

Table 1. Agronomic records from Michigan State University campus farm fields used for cereal aphid and natural enemy studies, East Lansing 2012 and 2013.

*DuPont TM Thifensulfuron-methyl – 25%, Tribenuron- methyl- 25%, other ingredients – 50%

without any barrier to natural enemies. Closed plots consisted of 1 m tall, 0.36 m diameter tomato support cages, covered with sewn sleeves of no-see-um mesh (approx. 625 holes per 6.45 cm, Skeeta, Bradenton, FL). The bottoms of the cages were buried 15 cm into the ground to prevent access by ground-dwelling predators. The top of the sleeves were tied with nylon cord to prevent flying predators from entering. The sham cages were identical to closed plots with the exception that the sleeves had multiple 10 cm slits on each side and at the bottom of the mesh allowing entry of predators and parasitoids, including foliar-foraging and ground-dwelling natural enemies (**Figure 3**). All treatments were replicated five times per field in a completely randomized design.



Figure 3. Photo illustrating natural enemy exclusion treatments used in our study A) closed plot caged to exclude all natural enemies, B) open plot allowing access to all natural enemies and C) sham plots, which are caged but, with holes on the ground and canopy levels to allow access by natural enemies.

Natural enemy community sampling

To characterize the overall natural enemy community in the wheat fields, we used a variety of sampling methods. To sample the ground-dwelling predator community, pitfall traps (n = 4, plastic Solo cups, 11 cm in diameter and 14 cm in depth) 1/3rd filled with 40 % propyleneglycol solution were established next to the plots and 4 m apart from one another. In addition, 23 x 28 cm yellow sticky card traps (n = 4, PHEROCON AM, Great Lakes IPM, Vestaburg, Michigan) were placed next to the pitfall traps to sample flying predators. The yellow sticky cards were hung on a plastic step-in fence posts (Zareba Systems, Lititz, PA), and positioned just above the plant canopy. Finally, on each sample date, natural enemies were counted by visual observation for a fixed time (five minutes) in each plot. Any natural enemies found in closed plots were manually removed during the sampling. All the predators were identified in the field or returned to the laboratory for identification. Araneae and Opiliones were identified to order while most other organisms were identified to family. Due to their potential importance in aphid control, Coccinellidae were identified to species. Coccinellidae that were difficult to identify in the fields or were missing identifying features on sticky cards were categorized as "other Coccinellidae". The overall average of each natural enemy taxa with standard error of the mean (SEM) was calculated by field and by year.

Aphid population growth

For the experiment, virus free *R. padi* were obtained from an MSU laboratory colony (C. Malmstrom lab). The aphid colonies were maintained on wheat and oat (*Avena sativa* L.) plants in a greenhouse under natural light conditions, supplemented by sodium plant growth lights operating at 16 L : 8 D, and maintained at 18° C to 26° C, and 65 - 70 % RH. Wheat and oat

plants were sown in 10 cm square pots. When the plants were about 15 cm tall, they were infested with mixed stages of *R. padi*. New plants were added to the colony as needed, and old plants were discarded.

On May 18, 2012 and May 14, 2013 cage treatments were established when wheat plants were at the six-seven Feekes growth stage (Miller 1999,Wise et al. 2011) in 2012, and at the six Feekes growth stage in 2013. Each plot was infested with 50 laboratory reared *R. padi* of mixed adult and nymphal stages. Prior to aphid infestation, other insects were removed from each plot by hand, and by vacuuming the plots using a modified leaf blower (Fiedler and Landis 2007). Aphid infected leaves with 50 *R. padi* from the greenhouse plants were cut off and placed between the leaves of the middle wheat plant of each plot. In 2012, the initial establishment of *R.padi* in the plots was very low and all plots were reinfested with 50 additional aphids on May 23. After infestation aphid abundance was assessed once per week for three consecutive weeks by counting all aphids on all plants within the plots. Alate and apterous aphids were recorded separately. In both years, naturally occurring *S. avenae* were also observed and were counted separately. To control for the effect of sampling, all the plots, even if they did not have any aphids, were manipulated as if counts were being taken to ensure all plants and aphids received the same amount of disturbance.

Statistical analyses

Statistical analyses tested the hypothesis that the natural enemy community suppresses aphid population growth. To provide a meaningful comparison of experiment aphid pressure, and to meet assumptions of homogeneity and variance, cumulative aphid-days were used instead of raw aphid counts. Cumulative aphid-days was calculated by the following equation

$$CAD = \sum_{i=1}^{d} \frac{(A_i + A_{i+1})(D_i - D_{i+1})}{2}$$

Where d is total days sampled, A_i is the population of aphids on day i, D_i date of sample i. Plots where aphids failed to establish from the beginning were excluded from statistical analyses. ANOVA procedures (R version 3.0.2, R Core Team 2013) were used to analyze cumulative aphid-days (for each species, sites and years), with the aphids per tiller on the treatments (open, closed, sham) and field as factors. If significant differences occurred, means were compared by Tukey's Honestly Significant Difference (HSD) test ($\alpha = 0.05$).

Results

Natural enemy community

Using all three sampling methods, we collected a total of 4,065 natural enemies representing 13 taxa. Overall, seven taxa of ground-dwelling natural enemies were captured in pitfall traps over both years. In 2012, the most common family in field 1 were Formicidae followed by Araneae, Carabidae and Opiliones (**Table 2**). In contrast, in field 2 the most common natural enemies were Araneae followed by Carabidae. In 2013, in field 3 and field 4 Carabidae were the most common taxa followed by Araneae and Staphylinidae.

Yellow sticky cards captured six families of flying predators. In 2012, in field 1 the most common family was Dolichopodidae followed by Chrysopidae and Syrphidae while in field 2 the most common family was Syrphidae followed by Chrysopidae and Dolichopodidae and *Harmonia axyridis*. In 2013, Syrphidae were the most common natural enemies in both fields followed by Nabidae in field 3, Cantharidae and the coccinellid *Coleomegilla maculata* in field 4.

Collection methods	201	2	2013	
Pitfall trap	Field 1	Field 2	Field 3	Field 4
Coccinellidae	0.2 ± 0.1	0.7 ± 0.2	0.1 ± 0.1	1.2 ± 0.5
Carabidae	9.1 ± 1.7	4.6 ± 1.2	14.9 ± 3.5	12.8 ± 2.1
Formicidae	30.7 ± 10.2	2.6 ± 0.8	2.9 ± 1.2	7.6 ± 1.9
Araneae	12.8 ± 1.7	17.5 ± 1.8	10.8 ± 2.0	7.5 ± 1.5
Opiliones	7.1 ± 1.4	1.4 ± 0.3	0.1 ± 0.1	0.3 ± 0.2
Elateridae	0.4 ± 0.2	0	0.1 ± 0.1	0.2 ± 0.1
Staphylinidae	NA	NA	7.6 ± 2.4	4.9 ± 1.3
Yellow sticky card				
C. maculata	0.2 ± 0.1	0.4 ± 0.1	0.4 ± 0.2	1.2 ± 0.3
H. convergens	0.6 ± 0.2	0.6 ± 0.3	0	0
C. septempunctata	0.3 ± 0.1	0.3 ± 0.2	0	0.1 ± 0.1
H. axyridis	0.4 ± 0.2	2.0 ± 0.4	0	0
Other Coccinellidae	0.2 ± 0.1	0.4 ± 0.2	0.2 ± 0.1	0.2 ± 0.2
Dolichopodidae	2.9 ± 1.1	3.1 ± 0.7	0	0
Chrysopidae	2.4 ± 0.8	5.1 ± 1.0	0.8 ± 0.3	0.3 ± 0.2
Syrphidae	1.7 ± 0.5	10.1 ± 1.6	4.8 ± 1.4	4.0 ± 1.0
Nabidae	0	0	1.2 ± 0.8	0.3 ± 0.2
Cantharidae	0.1 ± 0.0	0.3 ± 0.2	0.8 ± 0.3	1.4 ± 0.6
Visual observation				
C. maculata	0	0	0.3 ± 0.1	0.5 ± 0.1
C. septempunctata	0.3 ± 0.1	0.1 ± 0.0	0.1 ± 0.1	0.3 ± 0.1
C. septempunctata larvae	0.2 ± 0.1	0.1 ± 0.0	0	0
H. axyridis	0.2 ± 0.1	0.1 ± 0.0	0.2 ± 0.1	0.2 ± 0.1
H. axyridis larvae	0.1 ± 0.0	0	0.03 ± 0.03	0.1 ± 0.0
Other Coccinellidae larvae	0.2 ± 0.1	0.3 ± 0.1	0	0
Chrysopidae larvae	0.1 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0
Syrphidae	0.3 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.3 ± 0.1
Carabidae	0	0.1 ± 0.0	0.2 ± 0.1	0
Araneae	0.1 ± 0.1	0.6 ± 0.2	0.1 ± 0.0	0
Anthocoridae	0.1 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.0

Table 2. Mean numbers (\pm SEM) of natural enemies captured in pitfall traps, yellow sticky cards and visually observed in four wheat fields in 2012 and 2013, Michigan State University campus farm East Lansing, Michigan.

During the visual sampling, six natural enemy families were observed. In 2012, *C. septempunctata* and Syrphidae were the most commonly observed in field 1. In contrast, Araneae were the most commonly observed taxa in field 2, followed by Coccinellidae larvae and Syrphidae adult. In 2013, the most common taxa were adult *C. maculata* in both fields, following by adult *Harmonia axyridis*, Syrphidae, Carabidae and Anthocoridae in field 3, and adult *C. septempunctata, H. axyridis* and Syrphidae in field 4.

Aphid population growth

Exclusion of natural enemies resulted in dramatically increased *R. padi* and *S. avenae* populations in both years (**Figure 4**). Cumulative aphid-days for *R. padi* varied significantly between years ($F_{1, 52}$ = 26.9, p = <0.001), sites ($F_{1, 52}$ = 6.3, p = 0.01) and treatments ($F_{2, 52}$ = 10.9, p = < 0.001). In 2012, *R. padi* numbers were lower than in 2013. Despite differences in years and sites, the treatment patterns were the same. Closed plots always had higher cumulative *R. padi* days per tiller than open and sham, with open and sham cages not significantly different from each other. Cumulative *S. avenae* days per tiller also varied significantly between treatments ($F_{1, 52}$ =3.9, p = 0.03), while year and sites were not significant. The closed plots for *S. avenae* contained significantly higher cumulative aphid number per tiller than sham and open plots, with sham cages not significantly different from open plots.

Discussion

The natural enemy community effectively controlled aphid population densities in wheat in two sites in both years. Similar to studies in other North American wheat growing regions (Mohamed et al. 2000, Brewer and Elliott 2004, Clement et al. 2004, Elliott et al. 2006) we found Coccinellidae adults and larvae, Chrysopidae adult and larvae, Syrphidae adults, and



Figure 4. Mean cumulative aphid numbers (\pm SEM) per tiller of; a) *Rhopalosiphum padi* in 2012, b) *R. padi* in 2013, c) *Sitobion avenae* in 2012, d) *S. avenae* in 2013, among treatment in closed, exclusion of all natural enemy, open exposed to all natural enemies, and sham to control for cage effect. ANOVA was used to test statistical differences. Different letters above the treatments indicate statistically significant differences among aphids per tillers at $\alpha = 0.05$.

numerous ground-dwelling predators Carabidae, Staphylinidae, Araneae and Opiliones were the most frequently collected natural enemies in our wheat fields. In other studies, the convergent lady beetle, *H. convergens*, and the common damsel bug Nabidae were the most common predators observed (Rice and Wilde 1988, Elliott et al. 1998, Mohamed et al. 2000), but in our research *H. convergens* was observed only in 2012, and Nabidae were only observed in 2013. Also, unlike other studies, we did not observe Syrphidae larvae or parasitoid wasps. This may be due to the relatively low aphid population at the field level or the early season timing of our study. In contrast, we observed relatively high numbers of Opiliones, Elateridae, Cantharidae, and Anthocoridae. These communities of ground-dwelling and foliar-foraging natural enemies, acting either independently or together, can reduce aphid population density (Symondson et al. 2002, Schmidt et al. 2003, Schmidt et al. 2004, Macfadyen et al. 2009, Thies et al. 2011). Numerous studies show that adult Coccinellidae can suppress cereal aphid populations (Rice and Wilde 1988, Elliott and Kieckhefer 1990, Messina and Hanks 1998) Also, results have shown that certain Carabidae consume R. padi and S. avenae (Edwards et al. 1979, Griffiths et al. 1985, Chiverton 1986) and can reduce aphid density (Symondson et al. 2002) by climbing the plant (Vickerman and Wratten 1979) or by preying on aphids when they drop from plants (Duffield et al. 1996). Previous authors showed that certain predator taxa interact synergistically to consume more aphids and reduce aphid populations in combination (Soluk 1993). For example, coccinellid foraging reduces aphid populations directly by predation, but also indirectly by dislodging aphids from the vegetation onto the ground where they can be consumed by Carabidae (Losey and Denno 1999).

Aphid populations per tiller for both species varied across sites and years, and were significantly higher in closed versus open or sham plots. In no case were aphid numbers in sham

cages statistically different from the open cages, suggesting that cages effects were minimal, a finding that conforms earlier work in soybean (Costamagna et al. 2008, Gardiner et al. 2009). In contrast, the closed plots in our study had up to 57 times higher cumulative aphid-days than the open plots. Exclusion studies looking at aphid numbers per cage found similar results. An exclusion cage study in Colorado reported that cereal aphid numbers were between 2.6 and 11.2 times higher in caged wheat plots compared to open plots (Mohamed et al. 2000). Other studies reported cereal aphid numbers three to six times higher when predators were excluded (Chambers et al. 1983, Holland and Thomas 1997).

Natural enemies are important for Michigan wheat production because they can keep aphid populations below damaging levels. The average numbers of *S. avenae* we found in the closed plots reached 42 aphids per tiller, while in the open plots numbers of *S. avenae* never exceeded 1 per tiller. The average numbers of *R. padi* in our study reached 62 aphids per tiller in the closed plots The open plot had an average of 7 aphids of *R. padi* per tiller, which is much less than the economic thresholds. The economic threshold in Michigan for both species is 12-15 aphids per tiller (C. Difanzo). Although we did not take yield measurements, based on these thresholds it appears that aphid numbers in our closed plots were high enough to cause yield damage.

Under the conditions we studied natural enemies regularly provided sufficient aphid suppuration, to keep cereal aphids population below economically damaging levels. In contrast, the use of preventive insecticides may be harmful to existing and effective natural enemy communities (Wiles and Jepson 1992, Banken and Stark 1998), and result in pest resurgence (Dutcher 2007). Some Michigan farmers have been adopting preventive spray to counter occasional pest including the True Armyworm (*Pseudaletia unipuncta* Haworth) (Ben Werling
personal communication) In contrast, our result suggests insecticide sprays should only be used when natural enemies cannot control the aphid population and the aphid is above the economic threshold. Relying on natural biological control provided by aphid predators and only using chemical control when necessary will help insure more economical and sustainable insect pest management in Michigan wheat.

CHAPTER 3

RELATIVE ROLE OF GROUND-DWELLING AND FOLIAR-FORAGING PREDATORS IN CONTROLLING CEREAL APHIDS IN, MICHIGAN WHEAT

Abstract

Diverse communities of natural enemies are important biological control agents of cereal aphids. Depending on their foraging strategies, aphid natural enemies can be categorized as foliar-foraging predators and parasitoids or ground-dwelling predators, and both guilds have been shown to contribute to suppressing cereal aphid population growth. We investigated the effect of each natural enemy guild independently and together on field populations of Rhopalosiphum padi (L.) and Sitobion avenae (F.) (Hemiptera: Aphidae) in two Michigan State University campus wheat (Triticum aestivum L.) fields. We experimentally manipulated natural enemies with cages and barriers to exclude 1) foliar-foraging predators and parasitoids, 2) ground-dwelling predators, 3) and all natural enemies, and compared aphid populations per tiller in these treatments to open plots as a control. Populations of R. padi were dramatically and significantly higher in all natural enemy exclusion plots. Additionally, R. padi densities were significantly higher in plots where ground-dwelling predators were excluded compared to plots where foliar-foraging predators were excluded. No statistically significant differences were observed in numbers of S. avenae between treatments. Our results suggest that, ground-dwelling predators play a larger role in cereal aphid suppression than foliar-foraging natural enemies, and in combination, predators can almost completely halt aphid population growth. We conclude that existing natural enemy communities can be highly effective in biological control of aphids under the conditions we studied.

Keywords: Cereal aphids, natural enemies, foliar-foraging predators, ground-dwelling predators.

Introduction

Cereal aphids (Hemiptera: Aphididae) are serious pests of grain crops worldwide (Alsuhaibani 1996, Mohamed et al. 2000). However, naturally occurring predators and parasitoids can frequently reduce aphid population growth and subsequent yield losses (Helenius 1990, Dennis and Wratten 1991, Östman et al. 2001, Lang 2003, Östman et al. 2003, Schmidt et al. 2003, Bianchi et al. 2006), reducing the need for chemical control (Krauss et al. 2011). Cereal aphids are attacked by a wide variety of natural enemies with different foraging strategies (Chambers et al. 1986). Foliar-foraging natural enemies include Coccinellidae (Coleoptera), Chrysopidae (Neuroptera), Syrphidae (Diptera), and parasitoid wasps (Hymenoptera). These taxa typically forage in the upper vegetation of cereal plants, often fly between plants while foraging, and predominantly feed on aphids (Chambers et al. 1983). Ground-dwelling generalist predators include Carabidae (Coleoptera), Staphylinidae (Coleoptera), and Araneae. These enemies live and forage near the ground and may include diverse prey in their diets, including aphids (Symondson et al. 2002). Ground-dwelling predators primarily prey on aphids occurring on the lower portion of the plant, or that have fallen from the plant due to disturbance. Both groups of natural enemies, acting independently or together, can reduce aphid population density (Symondson et al. 2002, Schmidt et al. 2004), in turn reducing plant damage and increasing yield (Östman et al. 2003).

Some studies show that foliar-foraging and ground-dwelling predators can interact synergistically, suppressing aphid populations to greater extent than when they act independently (Schmidt et al. 2003, Straub et al. 2008). For example, Losey and Denno (1999) found that in alfalfa in the absence of foliar-foraging predators, ground-dwelling predators had a very small effect on aphid populations. However, when foliar-foraging Coccinellidae predators were added

to the system, the effect of both predator groups on aphid suppression was higher than the sum of each community. The reason for this synergetic effect was that Coccinellidae foraging caused aphids to drop from the vegetation onto the ground, where they were consumed by Carabidae (Losey and Denno 1999).

Various have examined the role of natural enemies in suppressing cereal aphids. Thies et al. (2011) manipulated the natural enemy community in cages in cereal fields in five European regions and demonstrated that, compared to the open field, aphid populations were 28% higher with reduced densities of ground-dwelling predators, 97% higher with reduced densities of flying parasitoids and predators, and 199% higher with the removal of both enemy groups. Similar observations were made by Schmidt et al. (2003) in cereal fields in Germany where aphid populations were 18% higher with reduced densities of ground-dwelling predators, 70% higher with reduced densities of flying parasitoids and predators, and 172% higher with reduced densities of both natural enemies groups. These studies show that although both foliar and ground-dwelling natural enemies is often stronger, and the greatest pest suppression occurs when these two communities act in combination.

Foliar-foraging predators, especially Coccinellidae, are often the dominant natural enemy of aphids in cereal fields and many agroecosystems in North America (LaMana and Miller 1996, Obrycki and Kring 1998, Elliott and Kieckhefer 2000, Wright and DeVries 2000, Clement et al. 2004). Most species of Coccinellidae overwinter as adults (Colunga-Garcia and Gage 1998) and simultaneously occur with the bird cherry oat aphid, *Rhopalosiphum padi* (L.), and other cereal aphids in the spring (Phoofolo et al. 2007). Adult Coccinellids are capable of consuming up to100 aphids per day (Xue et al. 2009, Hallett et al. 2013) and dramatically reduce aphid

numbers in wheat fields (Elliott and Kieckhefer 2000).

The impact of the ground-dwelling predator guild is thought to be the greatest early in the growing season (Sunderland and Vickerman 1980, Dennis and Wratten 1991, Lang 2003), although they continue to feed on aphids up until aphid populations peak in cereals in early summer (Winder 1990, Winder et al. 1994). Among the ground-dwelling predators, Carabidae probably contribute the most to aphid suppression in cereal crops. These polyphagous predators often colonize cereal fields from neighboring habitats (French and Elliott 1999), and are known to consume *R. padi*, English grain aphids, *Sitobion avenae* (F.), and other aphids species (Edwards et al. 1979, Chiverton 1986). They can reduce aphid density by preying on aphids directly when the aphids drop from plant (Duffield et al. 1996, Symondson et al. 2002), or by climbing the plant. In a study examining the relative importance of ground-dwelling predators on aphid populations, Lang (2003) manipulated populations of ground beetles and spiders and found that aphid population was highest in the plots where Carabidae were removed implying a substantial predation impact of ground beetles.

The American Midwest is a major wheat producing area; however, studies have not been performed in wheat in this region to understand the effect of natural enemies on cereal aphid suppression. The purpose of this study was to determine the effect of ground-dwelling and foliarforaging predator guilds on cereal aphid suppression in Michigan. We used predator exclusion barriers to exclude different groups of natural enemies from populations of two species of aphid occurring in wheat fields on Michigan State University campus, East Lansing Michigan.

Our hypotheses for the study were 1) the natural enemy community as whole would significantly suppress aphid populations, and 2) foliar-foraging predators are more effective in

suppression of cereal aphid density than ground-dwelling predators.

Methods

Study sites

The experiments were conducted in 2013 in two winter wheat fields (*Triticum aestivum* L.) on the Michigan State University campus farm, East Lansing, Michigan. The wheat varieties were Red Devil and Ruby Red and were planted in the fall of 2012. Each field received herbicide, fungicide and fertilizers at rates determined by the university farm Manager (**Table 1** chapter 2). No insecticides were applied in either field.

Plot establishment

On May 14, we selected a 30 x 20 m area at least 30-35 m from a field edge. Within this area, individual 1 x 1 m plots were established 5 m equidistant from each other. The plots were assigned to 4 different treatments in a completely randomized design. Treatments included: exclusion of foliar-foraging predators and parasitoids (-F), exclusion of ground-dwelling predators (-G), exclusion of both foliar and ground-dwelling natural enemies (-F-G), and fully open plots (O), which were exposed to all natural enemies. Each of the four cage treatments consisted of a 1 m³ PVC frame, erected around the plots, with the legs buried in the soil. In the plots excluding ground-dwelling predators (-G), and in the plots excluding all natural enemies (F-G), a 30 cm tall corrugated plastic barrier was erected around the PVC frame. The bottom 10 cm of this barrier was buried in the soil so that 20 cm was left above ground to restrict access by ground-dwelling predators (**Figure 5 A**, **B**). To exclude all natural enemies (-F-G) and foliar-foraging predators and parasitoids (-F), the top and all sides of the PVC frame were covered with no-see-um mesh (approx. 625 holes per 6.45 cm, Skeeta, Bradenton, FL), to prevent flying

predators from entering the cage. To exclude all natural enemies (-F-G), the bottoms of the mesh were buried 5 cm into the ground while in –F plots, the bottoms of the mesh were raised 2 cm above the ground to allow access by ground-dwelling predators (**Figure 5 C**). Finally, open plots (O) consisted of 1 x 1 m area demarcated with flags, without any barrier to natural enemies (**Figure 5 D**). All treatments were replicated five times in each field



Figure 5. Photo illustrating the natural enemy exclusion experiment in Michigan State University campus wheat fields. Each plot was assigned a cage treatment to exclude different groups of natural enemies from aphid populations. Treatments included exclusion of A) foliarforaging predators and parasitoids (-F), B) ground-dwelling predators (-G), C) and all natural enemies (-F -G), and D) open plot (O), which allowed access to all natural enemies and served as a control.

Predator sampling

Natural enemies were sampled weekly from May 21 until June 5. To sample the grounddwelling predator community, pitfall traps (plastic Solo cups, 11 cm diameter and 14 cm depth) 1/3rd filled with 40 % propylene glycol solution were established inside of each plot and 5 m apart from one another. Twenty pitfall traps were placed at each study site. To capture foliar predators, 23 x 28 cm yellow sticky card traps (PHEROCON AM, Great Lakes IPM, Vestaburg, Michigan) were placed in the center of the sampling plots. The yellow sticky cards were hung on a 1 m plastic step-in fence post (Zareba Systems, Lititz, PA) above the plant canopy and were moved up as the plant canopy grew. Also, on each sample date, natural enemies were counted by visual observation of each plot for five minutes. The visually observed natural enemies were identified in the field and the natural enemies on the traps returned to the laboratory for identification. Araneae and Opiliones were identified to order while all other organisms were identified to family, except Coccinellidae which were identified to species. Coccinellidae that were difficult to identify under field conditions were categorized as "other Coccinellidae".

Aphid population growth

Virus free *R. padi* were obtained from a laboratory colony (C. Malmstrom, MSU). The aphid colonies were maintained on wheat and oat (*Avena sativa* L.) plants in a greenhouse under natural light conditions, supplemented by sodium plant growth lights operating at 16 L : 8 D, and maintained at 18° C to 26° C, and 65-70 % RH. Wheat and oat plants were sown in 10 cm square pots. When the plants were about 15 cm tall, they were infested with mixed stages of *R. padi*. New plants were added to the colony as needed, and old plants were discarded

On May 14, 2013 at the Feekes stage five all plots were infested with 100 laboratory

reared *R. padi* of mixed adult and nymphal stages. Before the aphid infestation, natural enemies were removed from each plot by hand or vacuuming the plots using a modified leaf blower (Fiedler and Landis 2007). The aphids were transferred to the treatment plants by cutting leaves infested with aphids from the cultured greenhouse plants and placing them between the leaves of the middle wheat plant of the plot. Aphid abundance was assessed once per week after infestation, by counting all aphids on all plants within the plots. Both alate and apterous aphids were recorded. On the first sampling date, naturally occurring *S. avenae* were also observed, so from that date on, counts of *S. avenae* were also recorded. To control for the sampling effect, all the plots, even if they did not have any aphids, were manipulated as if counts were being taken to ensure all plants and insects (aphid sand natural enemies) received the same amount of disturbance.

Statistical analyses

Statistical analyses were done to test the hypothesis that foliar-foraging predators are more effective on suppressing cereal aphid population then ground-dwelling predators, and that in combination both natural enemy guilds suppress aphid population growth to greater degree than, when they act independently. ANOVA procedures (R version 3.0.2, R Core Team 2013) were used to analyze the aphid population growth per tiller in 4 treatments (-F, -G, -F –G, O plots). An ANOVA of aphid observations by cage treatment specifying repeated-measures by plot was nested within site, as this model structure produced residuals that conformed to the assumptions of ANOVA most closely. We used pairwise t-tests that had been Holm-adjusted for multiple comparisons to compare treatments.

Results

Predator sampling

Overall, using all three methods of sampling we captured a total of 4,567 individual natural enemies. In the pitfall traps, seven taxa of natural enemies were captured. No enclosure method completely prevented the occurrence of natural enemies (**Table 3**). In the –F-G plots, the most frequently captured taxa were Staphylinidae followed by Carabidae, Aranea and Formicidae. In contrast, in –G, -F, and O plots, the Carabidae were the most common taxon, followed by Araneae, and Staphylinidae. Overall, the numbers of ground-dwelling predators captured in the –F-G and -G plots were less than they were on the –F and O plots.

On yellow sticky cards, we captured five families of flying predators. In -F -G plots, a single Coccinellidae was captured. In the -G plots Syrphidae were the most common family captured, followed by Cantharidae. In –F plots, the Coccinellid *Coleomegilla maculata*, followed by Syrphidae were the most common taxa captured, and in O plots, Syrphidae followed by *C*. *maculata* and Cantharidae were most frequently captured.

In visual observations, we occasionally observed adult *C. maculata*, *C. septempunctata*, Syrphidae, Formicidae, Araneae and Opiliones in the -F -G plots. In -G plots *C. maculata* followed by Syrphidae, were most commonly observed. In the –F plots, *C. maculata* followed by Araneae and Carabidae were most commonly observed. In the O plots, the natural enemy commonly was dominated by *C. maculata* followed by Syrphidae and Carabidae.

For Carabidae and Coccinellidae, often the most important predators of cereal aphids, the exclusion techniques sufficiently reduced their numbers to allow us to examine their effect on aphid population growth (**Figures 6** and **7**).

Collection methods	Plots			
	-F-G	-G	-F	0
Pitfall traps				
Coccinellidae	0.1 ± 0.0	0.5 ± 0.2	0.5 ± 0.3	0.9 ± 0.3
Carabidae	3.5 ± 0.6	4.2 ± 0.9	15.4 ± 2.0	12.9 ± 1.1
Formicidae	1.3 ± 0.4	1.9 ± 0.5	3.0 ± 0.7	1.2 ± 0.3
Araneae	2.0 ± 0.5	3.8 ± 0.5	10.4 ± 1.0	11.1 ± 1.4
Opiliones	0.1 ± 0.0	0.1 ± 0.1	0.4 ± 0.2	0.1 ± 0.1
Elateridae	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.0 ± 0.0
Staphylinidae	3.7 ± 0.9	3.8 ± 0.7	8.0 ± 1.8	6.5 ± 1.2
Yellow sticky card				
C. maculata	0.0 ± 0.0	0.5 ± 0.1	0.4 ± 0.1	0.7 ± 0.2
H. convergens	0.0 ± 0.0	0.03 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
C. septempunctata	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.03 ± 0.03
Other Coccinellidae	0.03 ± 0.03	0.2 ± 0.1	0.03 ± 0.03	0.4 ± 0.1
Chrysopidae	0.0 ± 0.0	0.6 ± 0.3	0.03 ± 0.03	0.6 ± 0.2
Syrphidae	0.0 ± 0.0	2.5 ± 0.5	0.2 ± 0.1	2.6 ± 0.5
Nabidae	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.3 ± 0.2
Cantharidae	0.0 ± 0.0	1.0 ± 0.2	0.03 ± 0.03	0.7 ± 0.3
Visual observations				
C. maculata	0.7 ± 0.2	1.8 ± 0.4	0.8 ± 0.3	1.6 ± 0.4
C. septempunctata	0.1 ± 0.1	0.1 ± 0.1	0.03 ± 0.03	0.2 ± 0.1
<i>C. septempunctata</i> larvae	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.3 0 0.1
H. axyridis	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Other Coccinellidae larvae	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.2 ± 0.1
Crabidae	0.0 ± 0.0	0.1 ± 0.0	0.5 ± 0.2	0.4 ± 0.2
Syrphidae	0.1 ± 0.0	1.9 ± 0.4	0.2 ± 0.1	0.8 ± 0.2
Formicidae	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
Araneae	0.2 ± 0.1	0.4 ± 0.2	0.6 ± 0.3	0.2 ± 0.1
Opiliones	0.1 ± 0.1	0.03 ± 0.0	0.1 ± 0.0	0.03 ± 0.03
Cantharidae	0.0 ± 0.0	0.03 ± 0.0	0.0 ± 0.0	0.03 ± 0.03
Chrysopidae	0.0 ± 0.0	0.03 ± 0.0	0.0 ± 0.0	0.03 ± 0.03
Nabidae	0.0 ± 0.0	0.0 ± 0.0	0.03 ± 0.03	0.0 ± 0.0

Table 3. Mean number (\pm SEM) of most abundant natural enemies captured in pitfall traps, yellow sticky cards and by visual observation in wheat study sites in Michigan State University campus, East Lansing, Michigan, 2013.



Figure 6. Abundance of Carabidae captured in pitfall traps in –G (excluding ground-dwelling predators),-F-G (excluding all natural enemies), -F (excluding foliar-foraging predators) and O plots (exposed to all natural enemies) in 2013.



Figure 7. Abundance of Coccinellidae captured in sticky cards in traps in –G (excluding ground-dwelling predators),-F-G (excluding all natural enemies), -F (excluding foliar-foraging predators) and O plots (exposed to all natural enemies) in 2013.

Aphid population growth

Treatments manipulating natural enemies had different effects on population growth of *R*. *padi* and *S. avenae. R. padi* populations varied significantly among treatments ($F_{3, 113} = 11.2$, p = < 0.001), and there was no significant site effect. In -F-G plots, *R. padi* increased from 100 aphids / m² to a mean of 3750 / m² (> 5 aphids / tiller) over the three week interval (**Figure 8**). Aphid increase was significantly lower when foliar-foraging predators had access to plots (-G plots). Aphid population increases were even lower when ground-dwelling predators alone (-F plots) had access to plots. Finally, in plots where all natural enemies had access (O plots), aphid populations were lower than all other 3 treatments and did not increase during the 3 week period (mean= $28.3 / m^2$ or < 0.10 aphids / tiller) indicating that the natural enemy community as a whole was very effective in preventing *R. padi* increases.

S. avenae population were dramatically lower than *R. padi.* Although ANOVA suggested that populations varied significantly between treatments ($F_{3, 113}=3.7$, p = 0.05), Posthoc pairwise comparisons did not find any statistically significant differences, although the general pattern of population growth by treatments was largely similar to that of *R. padi* (**Figure 9**).

Discussion

From our previous study (Chapter 2) we know that existing natural enemy communities in wheat are effective at suppressing cereal aphid populations below economic thresholds. The main objective of this study was to determine the relative contribution of natural enemy feeding guilds (foliar-foraging versus ground-dwelling predators) to cereal aphid population suppression. Similar to other studies in North America (Elliott and Kieckhefer 1990, Elliott et al. 1991, Mohamed et al. 2000, Brewer and Elliott 2004) the most common taxa of foliar-foraging



Figure 8. Mean number (\pm SEM) of *R. padi* among treatments; -F-G (excluding all natural enemies), -G (excluding ground-dwelling predators), -F (excluding foliar-foraging predators) and O (open plot, exposed to all natural enemies) in 2013. ANOVA with repeated measures was used. For treatment comparisons pairwise t-tests that have been Holm-adjusted were used. Different letters indicate statistically significant differences within treatments at $\alpha = 0.05$ during a sampling period.



Figure 9. Mean number (\pm SEM) of *S. avenae* among treatments; -F-G (excluding all natural enemies),-G (excluding ground-dwelling predators), -F (excluding foliar-foraging predators) and O (open plot, exposed to all natural enemies) in 2013. ANOVA with repeated measures was used. For treatment comparisons pairwise t-tests that have been Holm-adjusted were used. Different letters indicate statistically significant differences within treatments at $\alpha = 0.05$ during a sampling period.

predators that we found were adult Syrphidae, adult and larval Coccinellidae, adult Chrysopidae, Cantharidae and Nabidae, and the most common ground-dwelling predators were Carabidae, Staphylinidae, Araneae and Opiliones. Dissimilar to other North American studies, we observed very low numbers of parasitoid wasps. The overall abundance of ground-dwelling predators, especially Carabidae, in our study were higher than the density of foliar-foraging predators.

Similar to other studies (Chambers et al. 1986, Brewer and Elliott 2004), our results showed both foliar-foraging and ground-dwelling predators in combination were effective at suppressing aphid populations. In fact, when both predator groups were present (in the open plots), aphid population growth was even less than what we would have expected by combining the results from the top closed and bottom closed cages. This significantly lower aphid population growth provided by the combination of foliar-foraging and ground-dwelling predators suggests a synergy between the different natural enemy feeding groups. Losey and Denno (1999) showed the synergystic interaction of ground-dwelling and foliar-foraging predators on pea aphid in alfalfa. The aphids, in response to foraging Coccinelidae, dropped from the alfalfa canopy to the ground where they were consumed by ground-dwelling predators. Our results confirm that in combination these two foraging groups better suppress aphid populations than when acting alone.

In our study, ground-dwelling predators alone were more effective than foliar-foraging predators. These results are in contrast to previous European work (Schmidt et al. 2003, Thies et al. 2011) where foliar-foraging predators and parasitoids were more effective. Schmidt et al. (2003) conducted an experiment in the early season (May) in Germany and found that parasitoid wasps provided more effective aphid control than ground-dwelling predators. Thies et al. (2011) conducted a similar experiment in five European regions and their results suggested that

parasitoids and foliar-foraging predators were more important in controlling cereal aphids than ground-dwelling predators, but the relative importance of parasitoids and foliar-foraging predators greatly differed among European regions.

The increased efficacy of ground-dwelling predators that we observed in the present study might be due the early season importance of ground-dwelling predators. Many studies (Chiverton 1986, Kromp 1999, Lang 2003) suggesting that the effects of ground-dwelling predators on suppressing aphids are strongest in early May, when aphid densities in cereals are low and reproduction is slower than in summer. In contrast, flying predators like Coccinellidae which primarily feed on aphids (Elliott et al. 1998) usually become more important once aphid population densities become higher (Evans and Youssef 1992). Our study in wheat fields also was conducted in the early season, starting in the middle of May and continuing until the 6th of June. Finally, aphids are most easily accessed by ground-dwelling predators when they are dislodged to the ground by predators, wind or rainfall (Winder 1990).

In conclusion, the role of ground-dwelling predators in controlling cereal aphids should be reconsidered. They appeared to be more important in suppressing aphid population than foliar-foraging predators. Future studies need to determine the factors, such as landscape characteristics, management practices, and climate that make ground-dwelling predators more effective and abundant in Michigan wheat fields.

This study highlights the importance of conservation biocontrol to enhance resident natural enemy populations. Natural enemy populations can be fostered by providing favorable micro-habitats for them (Thomas et al. 1991). Collins et al. (2002) showed that the presence of beetle banks (grassy ridges) in the middle of wheat fields increased the number of Carabidae,

which in turn decreased cereal aphid populations. Dong et al. (2012) showed that the presence of a ryegrass-margin on the edge of wheat fields enhanced the population density of Coccinellidae. Providing habitat for these important predators can enhance biological control services against aphids and other pests.

CHAPTER 4

CONCLUSIONS AND FUTURE DIRECTIONS

Biological control of cereal aphids on wheat in Michigan

Cereal aphids (Hemiptera: Aphidae) are serious pests of grain crops worldwide (Alsuhaibani 1996, Mohamed et al. 2000). Previous research has demonstrated that natural enemies that prey on aphids are important in inhibiting aphid population growth and reducing subsequent yield losses (Helenius 1990, Dennis and Wratten 1991, Östman et al. 2001, Lang 2003, Östman et al. 2003, Schmidt et al. 2003, Bianchi et al. 2006), which in turn reduces the need for chemical control (Krauss et al. 2011). In North America, the natural enemy community in wheat (*Triticum aestivum* L.) studied in the Southern and Western great Plants (Pike and Schaffner 1985, Mohamed et al. 2000, Clement et al. 2004, Brewer and Elliott 2004Lee et al. 2005) but, to our knowledge, has not been described in Michigan or the Midwest. The objectives of this thesis research were to characterize the natural enemy community in Michigan wheat fields and evaluate the role of different natural enemy groups together and independently on cereal aphid population growth. We investigated these objectives in 4 winter wheat fields in the Michigan State University campus in East Lansing, Michigan.

Overall, we found that the natural enemy community at our study sites, effectively controlled aphid population densities in wheat. The community that consisted of foliar-foraging predators including Coccinellidae species Chrysopidae, Syrphidae, Nabidae Cantharidae and Anthocoridae, as well as numerous ground-dwelling predators Carabidae, Staphylinidae, Araneae and Opiliones. In contrast to other regions, parasitoid wasps were rarely observed in our study locations.

The effect of natural enemy community on aphid population densities was studied using artificially infested *Rhopalosiphum padi* (L.) and natural occurring *Sitobion avenae* (L.). Our work illustrated that populations for both species across sites and years were significantly higher in caged plots where natural enemies were reduced compared to sham and open plots and that were partly or totally exposed to natural enemies. Aphid numbers in sham cages were statistically not different from the open plots, suggesting that cage effects were minimal. The maximum number of cereal aphids in caged plots with reduced natural enemies was over the economic threshold, but in plots where natural enemies were not reduced, the maximum number of aphids was much less than the economic thresholds level. This result indicates that natural enemies can contribute to control cereal aphids in the wheat fields

Relative role of ground-dwelling and foliar-foraging predators in controlling cereal aphids

In addition to evaluating the overall impact of all natural enemies together on aphid population growth, this study also illustrated the relative role of each natural enemy feeding guild, foliar-foraging versus ground-dwelling predators independently. The results confirmed that, these guilds better suppressed aphid population growth in combination than when they acted alone, and resulted in negative aphid population growth over 3 weeks suggesting a synergy between foliar-foraging and ground-dwelling predators.

The abundance of ground-dwelling predators, especially Carabidae, was higher than the density of foliar-foraging predators. Although many others studies (Schmidt et al. 2003, Thies et al. 2011) showed that foliar-foraging predators were more important in decreasing aphid populations, our result showed the opposite. Our work illustrated that ground-dwelling predators alone suppressed aphid population growth more than foliar-foraging predators alone. Therefore, the role of ground-dwelling predators in controlling cereal aphids should be reconsidered. They

appeared to be more important in suppressing aphid population than foliar-foraging predators in wheat fields under Michigan State University campus, East Lansing, Michigan growing conditions. Future studies need to determine the factors, such as landscape characteristics, management practices, and climate that make ground-dwelling predators more effective and abundant in Michigan wheat fields.

Natural enemies are important for Michigan wheat production because they can keep aphid populations below damaging levels. From our study it is clear that natural enemies can contribute to cereal aphid control and insecticides are not uniformly needed. Prescriptive insecticide use may be harmful to existing and effective natural enemy communities (Wiles and Jepson 1992) and may result in pest resurgence (Dutcher 2007). Our result suggests insecticide sprays should only be used when natural enemies cannot control the aphid population and aphid numbers are above the economic threshold. Relying on natural biological control provided by aphid predators and only using chemical control when necessary will help insure more economical and sustainable insect pest management in Michigan wheat. APPENDIX

APPENDIX

Identifying natural enemies consume bird cherry oat aphids under laboratory conditions

The bird cherry oat aphid (*Rhopalosiphum padi* L.) can cause direct and indirect damage to wheat (*Triticum aestivum* L.) and other small grains by feeding on leaves and as a vector of barley yellow dwarf virus (BYDV) (Vickerman and Wratten 1979).While many predaceous and omnivorous arthropods can be found in Michigan wheat fields, less is known about which species may be the most important predators. To help determine which of the predators found in field samples many be important in aphid suppression, we conducted a laboratory assay to determine which potential predators in wheat consumed the greatest number of aphids. Results of this preliminary study were used to help interpret and direct subsequent field studies.

Methods

Adult Carabidae and Coccinellidae beetles were collected from wheat fields on the campus of Michigan State University, East Lansing, Michigan during May 2012 and tested as potential natural enemies of wheat aphids. We used dry (without any killing solution) 11 plastic Solo cups; 11 cm diameter and 14 cm depth pitfall traps to collect carabid beetles, and swept vegetation to collect coccinellids. Pitfall traps were set out at approximately 5 PM and natural enemies collected the following morning at approximately 8 AM. Potential predators were individual held at $21-25^{\circ}$ C in a growth chamber and provided with water from a moistened dental wick until used in feeding trials that day. *Rhopalosiphum padi* were obtained from a laboratory colony reared on potted wheat maintained at $21-25^{\circ}$ C, L: 18 / D: 6 in a growth chamber. For each feeding trial, two uninfested wheat leaves were cut in half and the four pieces placed in 100 mm x 15mm Petri dishes lined with filter paper size 8.5 cm to which 2.5 ml water

was added to maintain constant humidity. To avoid damaging aphid mouth parts, aphids were collected from infested plants by gently tapping leaves over a paper sheet to allow them to remove stylets and drop naturally, or by gently pushing the aphid from behind with the brush tip until it began to move. A mix of adult and nymphs (approximately 50:50) were then transferred to a leaf in each Petri dish using a moisten paint brush. Aphids were held in a growth chamber at $21-25^{0}$ C, L: 18 / D: 6 and 50 - 60% relative humidity and allowed to settle and begin feeding for 30 minutes prior to introduction of a potential predator.

At the beginning of each trial a single natural enemy was placed in each Petri dish (n = 10 replicates per predator) and returned to the growth chamber. After 3, 6 and 21h, dishes were observed to determine the number of remaining aphids. Aphids that died but were not consumed were not counted as predated.

Results

Two species of Coccinellidae beetles; *Coccinella septempunctata*, and *Harmonia axyridis* and four species of Carabidae; *Poecilus chalcites*, *Scarites subterraneus*, *Anisodactylus rusticus*, and *Anisodactylus santaecrusis*, were collected in sufficient numbers to conduct feeding trials. Both species of Coccinellidae were effective on consuming *R. Padi* (Figure 10), while the two Carabidae species *S. subterraneus* and *A. rusticus* were more effective than *Poecilus chalcites and A. santaecrusis* (Figure 11).



Figure 10. Mean number of *R. padi* (\pm SEM) alive, missing and dead in the petri dishes containing Coccinellidae at 3, 6 and 21 hours



Figure 11. Mean number of *R. padi* (± SEM) alive, missing and dead on the petri dish with Carabidae at 3, 6 and 21 hours

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