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INCREASING BIOLOGICAL CONTROL OF ONION MAGGOT, DELIA ANTIQUA (MEIGEN), WITH INTEGRATIVE MANAGEMENT CONTROL METHODS AND APPROACHES

By

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ABSTRACT

INCREASING BIOLOGICAL CONTROL OF ONION MAGGOT (DELIA ANTIQUA (MEIGEN)) WITH INTEGRATIVE MANAGEMENT CONTROL METHODS AND APPROACHES

By

Brian P. McCornack

Onion maggot, *Delia antiqua* (Meigen), is the most economically important pest in Michigan onions, *Allium cepa* L. In years of severe outbreak it can cause a 40-80% reduction in yield. Management options for this pest includes a heavy reliance on a broad spectrum insecticide, chlorpyrifos, for effective control. The goal of this research is to determine the potential for integrating the insect growth regulator cyromazine with modified cultural practices to conserve biological control agents and enhance the Integrated Crop Management program for onions in Michigan. My objectives were to: 1) examine carabid beetle predation of onions maggot larvae and pupae using greenhouse and laboratory studies, 2) determine the effects of refuge habitats on carabid communities in Michigan onions, and 3) evaluate the combination of cyromazine and refuge strips in onions as a new tool for management of onion maggot. In greenhouse and laboratory studies, several carabid beetle species consumed onion maggot pupae and larvae in no-choice bioassays. Significant differences in the number of pupae recovered depending on pupae depth and the predator species tested was observed. Larvae consumption/disappearance ranged from 47-57% in the greenhouse study, however, there were no significant differences observed. The presence of a refuge strip significantly increased the number of beetles captured in the adjacent onion crop habitat. Differences at the species level was also observed. Integrating multiple aspects of onion maggot control (i.e. biological, cultural, and chemical) will provide a more efficient and sustainable approach to managing onion maggot populations in Michigan onions.

"To forget how to dig the earth and
tend soil is to forget ourselves."

-Gandhi

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CHAPTER 1:

INTRODUCTION

ONION PRODUCTION

Onions, *Allium cepa* L., is a biennial usually planted as seeds by commercial growers (Jones and Mann 1963). Onions are thought to be among the first plants to be cultivated by early humans. Garlic, *Allium sativum* L., is a closely related species and was heavily used in ancient times for its pungent flavor and medicinal properties. There are many onion cultivars in production today varies in characteristics such as day-length requirement, skin color (white, brown, yellow, red, or purple), size (3-15 cm diameter), shape (globe-shaped, flattened or spindle-shaped), and pungency and sweetness. The variety and the chemical characteristics of the soil where they are grown mainly determine the expression of pungency and sweetness.

Typical onion production in Michigan takes place on high organic (muck) soils that contain sufficient nutrients for bulb production. Planting in Michigan begins in mid to late April and ends in early May. Harvest usually begins in early September and ends in mid to late October. Most production of onions in the northeastern United States occurs in New York and Michigan, and in the United States, approximately 70,000 ha of onions are harvested each year (NASS 2000). In 1999, Michigan growers harvested 1619 ha of dry bulb onions with a production value of $10.8 million (NASS 2000).

ONION PESTS

There are major and minor insect pests that affect onions. Major pests include the onion thrips, *Thrips tabaci* L. and onion maggot, *Delia antiqua* (Meigen). Onion thrips feed on newly emerged leaves by damaging leaf cells with their rasping mouthparts and feeding on the sap released at the point of injury. If thrips populations become high enough, girdling occurs and severe leaf damage causes the leaf to die. Heavy infestation of onion thrips can kill seedlings early in the growing season and can reduce yields and bulb quality (Hoffman et al. 1996). Few control methods are available for control of onion thrips. Physical factors such as heavy rains can wash out thrips populations in neck of the onion plant. Growers rely heavily on chemical control strategies for management of this pest. Other minor pests include Western flower thrips (*Frankliniella occidentalis* (Pergande)), cutworms, aster leafhopper (*Macrosteles quadrilineatus* Forbes), mites and several species of aphids (Hoffman et el. 1996).

The second major pest of onions and perhaps the most important is the onion maggot. It is the most serious and economically significant pest of onions in Michigan and much of the northeastern U.S. and Canada (McEwen et al. 1981, Ellis and Eckenrode 1979, Wells and Guyer 1966). Onion maggot is a specialist herbivore on onions (Ellis and Eckenrode 1979b) and a few other minor *Allium* species. Michigan has three distinct onion maggot generations each season, with the initial spring emergence of adults occurring in late April or early May (Eckenrode et al. 1975, Loosjes 1976). First generation larvae are usually considered to have the most impact economically, because the onion plant is in its most vulnerable stage (Miller and Cowles 1990). Small onion

seedlings cannot withstand heavy feeding by onion maggot due to extensive vascular tissue damage. A single maggot can destroy as many as 12-15 seedlings before pupating (Loosjes 1976); onion maggot has the potential of causing a 40-80% reduction in yield without proper chemical or cultural control strategies (Zandstra et al. 1996).

ONION MAGGOT

Distribution. Because the onion maggot is such a major pest in commercial onions, its geographic distribution has been reviewed extensively. Onion maggot is mainly limited to the northern latitudes (35-60° N) in the temperate zone of the Holarctic region (Finch 1989, Hill 1987). The onion maggot was originally a palaearctic species but was introduced into eastern North America during the early 1800's in cargos of onions. From its original point of introduction it spread to the western region of the United States and Canada (Loosjes 1976). A general compilation of information was supplied by Scott (1969) after the original description of onion maggot in the late 1820s. Loosjes (1976) also went on to describe the geographical distribution of the onion maggot by mapping general occurrence and local observations cited in annual reviews and bulletins.

Life history. The onion maggot has six distinct stages in its life-cycle: egg, 3 larval instars, pupa, and adult. Onion maggots overwinter as pupae. Initial spring adult emergence occurs approximately after an accumulation of 200 degree-days above a base temperature of 4.4°C (Eckenrode et al. 1975). A temperature-dependent preoviposition period of 103 degree-days, base 4.4°C, is required. Gravid females deposit their eggs at bases of onion stems or leaf axils of onion plants. Newly deposited eggs require 50

degree-days, base 3.88°C, before eclosion (Carruthers 1979). Newly hatched larvae feed on the roots and the developing onion bulb. As feeding progresses, secondary invasion of soft-rot organisms occurs and this plus direct damage of plant tissue quickly produces physical evidence of plant stress (Doane 1953).

Onion maggot has three distinct larval stages. First, second and third larval instars complete development in 37, 89, and 161 degree days (base 4.4°C), respectively (Carruthers 1979). Following the completion of the third instar, the larva exits the onion plant and burrows into the soil. Pupal depths range from 4 to 15 cm below the surface of the soil (Carruthers 1979, Rygg 1960, Loosjes 1976). Whitfield et al. (1986) reported survival of overwintering pupae was not dependent on pupal depth or habitat, and suggested moisture and temperature were the critical factors.

Male onion flies often emerge a few days earlier than the females (Rygg 1960), and this emergence is reported to coincide with the flowering of dandelions in early spring (Baker 1925). This may give males a competitive edge in discovering newly emerged unmated females. Male insects often develop more rapidly or at lower developmental thresholds to accommodate for this early emergence (Price 1997). After a 3-4 d post-eclosion period (McDonald and Borden 1995), copulation occurs and the life-cycle continues.

Univoltine and multivoltine insect populations are highly dependent on many biotic and abiotic factors, but the major abiotic stimuli determining the number of onion maggot generations per year is temperature. Onion maggot is typically a multivoltine species averaging 3-4 generations per year depending on seasonal temperature ranges

(Loosjes 1976). Southwestern France has as many as 5 generations per year (Loosjes 1976). In places with low seasonal degree-day accumulations such as northern Norway, onion fly populations are univoltine (Rygg 1960). The final generation in multivoltine populations are incomplete and pupae from these generations go into a facultative diapause (Loosjes 1976).

Diapause induction seems to be strongly age dependent in the onion maggot and the third instars of the late season generation usually undergo diapause. Short day length in combination with low temperatures during the third instar induces diapause (Drummond 1982). There is a low percentage of diapause at longer day lengths, if the temperature is <18°C, and a high percentage diapause at shorter day lengths even if the temperature is high (Loosjes 1976). The correct balance of temperature and daylength is needed to stimulate or inhibit onion maggot diapause.

Photoperiod also influences flight activity. When the photoperiod is longer than 8 h, diurnal adult onion maggot exhibit a major peak of activity in the evening (Watari and Arai 1997). Finch et al. (1986) showed that adult onion flies spend most of the day resting in shaded habitats provided by surrounding foliage and avoid the onion crop. The late afternoon/evening peak in flight activity is mainly females searching for suitable ovipositional sites (Havukkala and Miller 1987). Results from a study by Watari and Arai (1997) shows most of the egg deposition occurs after 10-12 h of light and suggests that this major peak in activity is controlled by a circadian pacemaker. They defended their hypothesis by shifting the growth chamber photoperiod and found egg-laying coincided with the photoperiod of the chamber.

A post-eclosion interval of several days is often required by many Diptera before mating. There are considerable biotic and abiotic factors that determine this post-eclosion interval and the interactions are complex in nature. Usually, this time delay for both sexes is dependent on meeting physiological criteria for processes such as oogensis and accessory gland maturation (Chen 1984). Having female spermatozoa present in the female reproductive tract often will inhibit sexual receptivity for both sexes (Adams and Hintz, 1969). The time of occurrence is usually correlated with distinct stages in the morphological development of the ovaries (McDonald and Borden 1995). The post-eclosion interval lasts for 1-2 wks and as the adults age, mating begins (Loosjes 1976). This usually occurs after dispersal to suitable host plants and ovariole maturation (Judd and Borden 1988). Research by McDonald and Borden (1995) does not support the hypothesis that mating occurs only in the presence of mature ovarioles. However, they showed a strong age to sexual receptivity correlation. Age of the female onion maggot adult had a strong effect on its probability of being fertilized (McDonald and Borden 1995), and no adults of either sex mated before 3 d of age.

Mating. Mate location and acceptance is an important aspect to the mating biology of many insect species. The ability of one species to recognize a conspecific and the sex of a conspecific is important in producing future generations. A well-studied phenomenon in onion maggot is their courtship behavior. McDonald and Borden (1996) categorized seven courtship behaviors expressed by onion maggot adults: inspection from the substrate, aerial inspection, contact from the substrate, contact from the air, genital alignment, copulation, and male-male interaction. The sequence of events that make up

this unique mating behavior relies primarily on indiscriminate visual recognition of potential mates. This is then followed by a detection of semiochemicals that inform the receiver of species-specific and sex-specific information. Elements such as genital alignment and attempted copulation illustrates this ability by males to discriminate between sexes, sexually immature and mature females, and between other species (McDonald and Borden 1996).

When a male creates a species-specific profile by detecting unique cuticular hydrocarbons, this activity might also function as a reproductive isolation mechanism (Blomquist et al. 1987). The specificity of this so-called cuticular hydrocarbon "blueprint" increases qualitatively and quantitatively in conjunction with female age (Blomquist et al. 1987). This could ultimately reduce the time spent searching or copulating with unsuitable mates and increase the amount of time spent searching for more suitable female onion maggot adults.

The amount of time spent copulating may also have an affect on the reproductive success of onion maggot. Insemination may ultimately be effected by the male's ability to grasp and remain *in copulo.* This could impart some competitive advantage to the most-fit males. On the other hand, females may also benefit from shorter copulation events by being able to mate with several males. It is unclear, however, which sex ends a copulation event, thus making it difficult to assess which sex is receiving the competitive advantage. Regardless, McDonald and Borden (1996) showed copulation duration in onion maggot to be brief and highly variable.

Female reproductive behavior is affected by extracts from mature male reproductive tracts. Spencer et al. (1995) illustrated this in the lab. Purely virgin females receiving a fraction of an equivalent male extract remained "unmated in the presence of males and began laying unfertilized eggs at a normally mated rate." When such extracts are transferred to the female after copulation, these sex peptides are believed to act as mate-guarding substances (Miller et al. 1994). Male extracts appear to be a potent behavioral modifier and may have permanent effects on the behavior of sexually mature females (Spencer et al. 1995). This sexual adaptation seems to be an advantage for the male onion fly in helping reduce sperm competition with other males when fertilizing eggs.

Host plants. Perhaps the most important biotic factor influencing onion maggot distribution and population dynamics is its host plant. Onion maggot attacks only *Allium* species and the onion is the preferred host (Ellis et al. 1979). Other species attacked by onion maggot include *Allium ascolonicum* L. (shallot), *Allium sativum* L. (garlic), and *Allium schoenoprasum* L. (chives) (Ellis and Eckenrode 1979b). The presence of onion maggot is in direct correlation with areas of high onion production and there is no important wild host for the onion maggot in Michigan or for other onion maggot populations across the United States. This is perhaps the most important factor limiting onion maggot distribution.

The temporal occurrence of host plants in a particular habitat also influences onion maggot populations. A well-accepted method of protecting crops against *Delia* species is to vary planting times. This helps to reduce migrant flies from entering the field

or to reduce crop susceptibility to female onion flies during peak egg-laying (Coaker 1987). Onion seedlings that sprout early are at a greater disadvantage, which could select for late-germinating *Allium* plant species. Late planting is a management option, although it may cause lower yields due to possible host dry conditions during germination and less time to reach maturity.

Allium species including *A. cepa* contain unusually high amounts of organic sulfur. This sulfur takes the form of alkylcesteine sulfoxides and gamma-glutamyl peptides (Miller and Harris 1985). Chemicals such as n-propyl disulfide and n-propyl mercaptan are effective attraction and oviposition stimulates for adult onion maggots (Matsumoto 1970) and these chemicals are unique to *Allium* plant species.

Host selection and host quality. Insects use many physical and chemical cues to select the best suitable host for oviposition and food allocation. Because chemical cues are important for plant-herbivore interactions, adult onion maggots use these cues to detect the most suitable hosts. Selecting a suitable host for oviposition often involves the use of behavioral sequences triggered by a particular stimulus (Shorey 1977). Chemical stimuli, such as the n-propyl disulfide compound found in *Allium* species, can often trigger female ovipositional behavior repertoires. For example, a typical ovipositional sequence or repertoire includes running up and down leaf surfaces, sitting, grooming, extension of the proboscis so the labellum contacted leaf and soil surfaces, movements of the tip of the abdomen over surfaces (surface probing), subsurface probing of soil crevices with the ovipositor, and finally oviposition (Harris and Miller 1991).

Long-range host orientation is also dependent on chemical cues. However, interpreting the influence of host odors on long-range host location in the field can be complicated. Local weather variations (Vernon et al. 1981), compositional changes in odors over time (Miller et al. 1984), host and non-host olfactory interference (Vernon and Borden 1983), and variability in onion maggot populations (Martinson et al. 1989) can all influence the success of onion maggot in finding a suitable host. In the field, females searching for ovipositional sites are strongly attracted to decomposing onions (Dindonis and Miller 1980).

Tactile stimuli also play a role in finding suitable host plants. When a young onion seedling is blown by the wind, the stem of the small plant creates a space between the soil and the base of the stem. The length and depth of this space is an important ovipositional stimulus for females. Mowry et al. (1989) found that onion maggot females oviposite most eggs in holes >4 mm deep and 0.6 mm diam. Not only was length and depth important, but the preferences in substrate quality was also stressed. Penetrability of the substrate rather than particle size was the dominant factor when selecting ovipositional substrates (Mowry et al. 1989). Soil type can potentially influence the distribution of this economically important pest species.

Other host cues used by the onion maggot in locating a suitable host plant are visual. Leaf shape, color, hue, and brightness influence the attractiveness of a host plant. Onion maggot adults favor long leaf blade models that are similar in structure to their natural host (Degen and Stadler 1996). Color hue or saturation determines attractiveness

to onion maggot adults in the field and the magnitude of a response is determined by the attractive key wavelength intensity (Vernon and Bartel 1985).

Host age can also determine its attractiveness. Optimal visual, olfactory, gustatory, and tactile stimuli that solicit strong ovipositional responses resemble those from a small onion plant at the 3-4 leaf stage (Mowry et al. 1989). All stimuli are equally important in generating a positive ovipositional response, and work by Harris and Miller (1991) supports the hypothesis that temporal summation of inputs from multiple sensory organs can trigger egg-laying.

Because onion maggot relies heavily on the success of its host, host quality becomes an important biotic factor affecting onion maggot fitness. There are many components that are associated with host quality and the most important is nutrition. Blaine and McEwen (1984) showed low concentrations of chlorine to be essential for pupation. Proteins and sucrose are essential for longevity in onion maggot males and flies of any species lacking protein in their diets reduce their overall success (McDonald and Borden 1996b). Females especially depend on proteinaceous and carbohydrate nutrients for normal ovarian development, with the preferred carbohydrate source being sucrose (Blaine and McEwen 1984).

The adult is not the only life-stage that relies on proper nutrition. Larvae are also dependent on host plants providing proper nutrients at effective levels. Proteins, lipids and nucleic acids in cells can be affected negatively by activated forms of oxygen (Harris 1992), and this oxidative stress occurs in all organisms. However, most organisms exhibit adaptive defense mechanisms for these oxidative stresses, usually in the form of

superoxide dismutase (Fridovich 1983). Superoxide dismutase activity is strongly affected by diet. When larvae are fed a strict synthetic diet void of copper or zinc, they exhibit lower superoxide dismutase activity (Matsuo et al. 1997). This micronutrient dependency becomes essential for successful larval development and selects for larvae that are able to obtain these essential nutrients.

The onion maggot is morphologically adapted for microbe grazing (Marshall and Eymann 1981), and this probable microbial dependence is even recognized in nature. In the field, females searching for ovipositional sites are strongly attracted to decomposing onions (Dindonis and Miller 1980). Onion maggot larvae can fully develop on alternate substrate (i.e. substrate comprised only of microbes), but this event is usually rare (Eymann and Friend 1983). Though this phenomena is not selected for in nature, it cannot be discounted (Schneider et al. 1983). Doane (1953) reported onion maggot larval damage was commonly accompanied by soft-rotting bacteria such as *Erwinia carotovora* (Jones), and thought this relationship to be mutualistic.

Bacteria or possibly their products play major developmental roles in onion maggot survival (Marshall and Eymann 1981). Friend et al. (1959) showed that the presence of microorganisms on artificial medium can accelerate larval growth and onion maggots seem to require some nutrients not present on sterilized onion tissue. Sterile onions reduce maggot development considerably and larvae may even die when reared on sterile onions (Marshall and Eymann 1981).

CONTROL STRATEGIES

Currently, there are few effective pest management tactics for controlling onion maggot. Cultural and physical controls include crop rotation, removal of overwintering sites, delayed planting, minimization of mechanical damage, and planting windbreaks (Hoffmann et al. 1996, Martinson et al. 1988, Finch and Eckenrode 1985). Hoffman et al. (2001) effectively used nonwoven fibers as a physical barrier to prevent onion maggot adults from ovipositing eggs at the base of onion seedlings resulting in reduced numbers of larvae on onions. Other possible strategies include the use of olfactory repellents such as phenolics and monoterpenoids and pungent spices (Cowles and Miller 1992, Cowles et al. 1989).

Chemical control is the most commonly used method for onion maggot suppression and is the most effective. Commercial growers in regions of high onion maggot damage use a soil insecticide at planting (Harris et al. 1982). Of twelve insecticides registered since 1955 for control of onion maggot, only one, chlorpyrifos (Lorsbanâ, Dow AgroSciences LLC, Indianapolis IN) is currently labeled for use, and resistance to it is increasing (Grafius and Pett 1991). In 1998, chlorpyrifos was applied to 930 ha in Michigan (47% of the acreage used for dry bulb onion production) at a rate of 2.32 kg/ha with a total of 2160 kg of chlorpyrifos on onions in Michigan (MASS 1998). Resistance occurs with the continual usage of a select group of soil insecticides (Eckenrode and Nyrop 1995) over an extended period of time. To avoid resistance, frequent shifts to new materials is important. However, concerns raised by the Food Quality Protection Act of 1996 strictly limits registration of new soil insecticides

(Walters and Eckenrode 1996), and this creates a problem for a management system that heavily relies on chemical management strategies. Also, the very small market potential for onions makes insecticide registration unprofitable for chemical manufacturers. This has forced the onion industry to look for new alternatives in managing onion maggot.

Chemical control methods. Despite its economic importance, management options for this herbivorous insect are limited and heavy reliance on a single broad spectrum chemical generates a cause for concern. Because of the Food Quality Protection Act of 1996, this insecticide and its usage are at risk. Chlorpyrifos has been withdrawn from use in all indoor and outdoor urban markets. But even if use on onions is not restricted, development of resistance by onion maggot to chlorpyrifos is a concern (Harris and Svec 1976, Walters and Eckenrode 1996). New chemical alternatives to onion maggot control must be developed to maintain onions as a viable crop for Michigan vegetable farmers. Some of these management options include development of new chemicals for managing pest populations.

A chemical that is currently in the process of replacing chlorpyrifos is an insect growth regulator, cyromazine (Trigardâ, Ciba Plant Protection, Greensborro NC). Cyromazine has had Section18 emergency registration status for treatment of onion seed to be used in Michigan since 1996 (Hayden and Grafius 1990). It is an insect growth regulator that disrupts the molting process of some Diptera larvae (El-Oshar et al. 1985). Its low toxicity to beneficials and its effectiveness at low levels makes it a viable candidate for controlling onion maggot (Robbins et al. 1991, Davis and Grafius 1997, McCornack et al. 2001). Cyromazine's narrow range of activity (El-Oshar et al. 1985)

also makes it more compatible with biological control strategies. Grafius et al. (1997) showed predatory carabid beetle counts to be higher in cyromazine treated sections of the field than in areas treated with chlorpyrifos. Its specific range of activity helps to conserve beneficial soil arthropods and potential biological control agents within onion agroecosystems (Ebert 1999).

Biological control. Non-chemical strategies also need to be considered when designing a pest management strategy. Natural enemies and biological control agents are key components in managing pest populations. Tomlin et al. (1985) built miniature mass rearing beds containing onion maggot to attract local parasites and predators. They found 20 carabid species, 42 staphylinids, and 17 other predators (total 79) associated with the onion maggot in or near the rearing beds and they found 7 species of parasitoids (Tomlin et al. 1985). In the field, carabids prey on a variety of insect pests including: aphids (Hance 1990), codling moth, *Cydia pomonella* (L.) (Hagley and Allen 1988), onion maggot (Grafius and Warner 1989), black cutworm, *Agrotis ipsilon* (Hfn.) (Lund and Turpin 1977), European corn borer, *Ostrinia nubilalis* (Hübner) (Brust et al. 1986), armyworm, *Spodoptera exigua* (Hübner) (Clark et al. 1994), and wheat midge, *Sitodiplosis mosellana* (Gehin) (Floate et al. 1990). However, the economic impact of carabids on onion maggot populations is poorly understood. Grafius and Warner (1989) showed that *Bembidion quadrimaculatum* L. consumes onion maggot eggs in field arenas artificially infested with eggs. Ebert (1999) showed the importance of carabids in reducing onion maggot numbers late in the season, thus reducing the amount of ovipositioning by females in the spring. Data on the number of prey consumed by a

population of carabids in field conditions is needed to evaluate the impact of beneficial arthropods, and dispersal rates can give an indication on the effectiveness of a predator migrating to an area of outbreak (Best et al. 1981).

Other biological control agents include the parasitoids *Aleochara bilineata* (Gyllenhal) (Staphylinidae) and *Aphaereta pallipes* (Say) (Braconidae), the predatory flies *Coenosia tigrina* and *Scatophaga stercoraria* and a fungus *Entomopthora muscae* (Groden 1982, Ritcey 1991, Watson et al. 1995, Failes et al. 1992, Majchrowicz et al. 1990, Hagar 1978). However, the costs involved in mass rearing these agents and the need for innundative releases make them very costly to farmers and economically unfeasable for use in commercial onion production systems.

CARABIDS

Carabidae are found throughout the world and are the third-most diverse family of insects with over 30,000 described species (Larochelle and Lariviere 2001, Lorenz 1998, Ball 1979). Carabid beetles inhabit a wide range of environments including terrestrial and arboreal habitats. They often show strong habitat-specificity and because of this, they are excellent bioindicators of habitat quality or changes in quality due to disturbances in the environment (Kavanaugh 1992). Ground beetles are usually classified as either spring or autumn breeders; spring breeders overwinter as adults and mate in the spring while autumn breeders overwinter as larvae with the adults mating in the fall. Carabids mainly prefer moist, well-irrigated field conditions and seek shelter from the harsh winter conditions by burrowing below the soil surface and by hiding under crop residues or

surface trash (Kirk 1976). The seasonal abundance of ground beetles depends on nutrition, moisture, temperature, and beetle age.

Carabids are generalist predators in many agricultural landscapes. They feed on a variety of insect pests including onion maggot (Grafius and Warner 1989, Ebert 1999). However, little is known about their overall impact on onion maggot populations in onion cropping systems. In other systems, the exclusion of generalist predators such as carabids results in greater armyworm damage to the corn plants (Clark et al. 1994). Laub and Luna (1992) suggested that the presence of several carabid species in high numbers was followed by a decrease in abundance of armyworm. Augmenting carabid beetle populations in a field is likely to increase predation pressure on targeted pest species (Chiverton 1986, Menalled et al. 1999).

Predator density is not the only factor influencing rates of predation. Predator activity and searching behavior can also affect predation rates (Barney and Pass 1986). Rather than make generalizations about carabids at the family level, Barney and Pass (1986) suggested that foraging and feeding strategies should be examined at the species level. Factors that can influence these subtle differences in behavioral responses within the Carabidae families include morphological and physiological adaptations, predator density, and resource distribution (Bell 1990, Evans 1990). Habitat structure and complexity and community diversity might also contribute to the effectiveness of carabids as a management tactic. Clark et al. (1994) found community structure of generalist predators to be important in altering pest populations in agroecosystems.

CONSERVATION BIOLOGICAL CONTROL

The goal of any biological control program is to suppress and stabilize the target pest population below an economic threshold with the use of natural enemies (i.e. parasitoids, predators, pathogens, antagonists, or competitor populations) (van Driesche and Bellows 1996). Protection of predator and parasitoid populations is crucial for both native and exotic natural enemies and is key to the success of a conservation program. Successful programs are able to shift the predator-prey or parasitoid-host ratio to favor natural enemies (Johnson et al. 1986). There are three main approaches to biological control: introduction, augmentation, and conservation of natural enemies. Conservation biological control is the only method that seeks to indirectly alter existing natural enemy populations through manipulation of their environment. Conservation strategies seek to reduce the negative environmental influences while increasing positive influences. Tactics used in conservation biological control include: modification of pesticide applications (i.e. lower rates and frequency and use of insecticides with narrow host-range specificity); changes to the crop and non-crop habitats (i.e. intercropping, cover crops, preservation of field margins/borders, and creation of refuge habitats); and changes to cultural practices (i.e. use of no-till, reduced tillage, and crop rotation) (Landis et al. 2000).

One way conservation biological control practices increase natural enemy populations is by providing alternate foods sources for natural enemies when pest populations are low and not able to support the biological control community. For example, when coccinellids are provided field borders with alternate food sources or food

supplements when aphid numbers are declining in the crop habitat, these alternative food resources support growing coccinellid populations (Obrycki and Kring 1998). Adult syrphids need nectar and pollen sources for egg production (Schneider 1969). In sugarcane fields floral nectar sources are routinely unavailable for adult parasitoid wasps, so cane growers have attempted to remedy this by providing suitable shelter and plants in the fields for parasitoids (Jepson 1954). Wild carrot nectar provides food for an introduced parasitoid of the Japanese beetle, *Popilla japonica* (Newman) (Johnson et al. 1986). Enhancing natural enemy survival, longevity, and fecundity through conservation practices will ultimately influence their efficiency at controlling the target pest species (Gross 1987).

Another way conservation practices increase natural enemy populations is through the use of refuge habitats. These habitats may provide alternative food sources as described above and also provide sites for overwintering and a place for refuge from pesticides and from disturbances caused by farming practices (Desender 1982). Intensification of farming has reduced hedge size and number of grassy field borders, which are natural reservoirs for many polyphagous predators such as carabid beetles (Esau and Peters 1975). By introducing refuge habitats as successional strips, a diverse natural enemy fauna can be created (Thomas et al. 1991).

Carabids are generalist predators in many agricultural landscapes. They feed on a variety of insect pests including onion maggot (Grafius and Warner 1989, CHAPTER 2). Augmenting beetle populations in a field is likely to increase predation pressure on targeted pest species (Chiverton 1986, Menalled et al. 1999). In corn, the exclusion of

generalist predators such as carabids resulted in increased armyworm damage (Clark et al. 1994). However, little is known about their overall impact on onion maggot populations.

Carabids are very sensitive to disturbances in the environment and are easily affected by cultivation practices (Kromp 1999). In turfgrass, insecticide applications affect surface-foraging arthropods such as carabids through multiple routes of exposure: topical, residual, and dietary exposure (Kunkel et al. 2001). Refuge strips can increase the numbers and activity of carabids and other biological control agents in corn and soybeans (Carmona 1998, Menalled and Landis 1997, Lee et al. 2001). Grassy refuge habitats can also help replenish communities reduced by heavy insecticide use (Lee et al. 2001) and provide overwintering sites (Thomas 1990). In addition, they can provide alternate food resources for predators when pest populations in the field are low (Hawthorne and Hassall 1995).

Luff (1982) investigated the impact of stable environments on carabid beetle densities and found little fluctuation in carabid abundance from year to year, thus acting as a constant mortality factor in suppressing some pest species. Application of soil insecticide treatments and tillage practices lower the density of all predators in an agroecosystem by an order of magnitude (Brust et al. 1985). Refuge habitats that remain undisturbed are needed to maintain beetle populations. Strip vegetation can offer abundant food sources and suitable overwintering sites (Thomas 1990), promoting the survival of the natural enemy (Den Boer 1981). Field borders, grassy strips, or hedgerows can then become important shelters for these predators at certain times of the year (Best

et al. 1981). Jones (1979) found that several species would migrate to and from field borders into a crop area during the season and after harvest. Overall, ecologists recognize the need to study individual movements quantitatively, to better understand the spatial dynamics of any given population (Bell 1991).

Determining habitat suitability for natural enemies is a large concern. Aspects that affect habitat suitability include: single large or several small refuge areas, corridors (how habitats are connected), and refuge shape (circular versus long and narrow areas designated for preservation of the desired species) (Simberloff 1988). Even though determination of suitability is the first step in species conservation, many studies fail to thoroughly examine the habitat needs of specific natural enemies (Simberloff 1988). The success of any conservation biological control program relies on defining the biology and habitat needs of the control agent, but the research required for accurate data describing these aspects is costly, intensive, and time consuming (Zimmerman and Bierregaard 1986).

By understanding how a species uses a refuge habitat, we can find better ways of creating habitat structures that can be use in effective pest management strategies. One strategy in manipulating population densities of natural enemies, such as carabids, is to modify the habitat to favor recruitment (Gross 1987). Also, crop rotation can play a more important part in managing an agroecosystem than tillage practices when building a suitable habitat for promoting establishment of carabid communities (Weiss et al. 1990). Carcamo and Spence (1994) investigated the effects of crop types on carabid density and suggested that altering crop canopies changed the microclimate. This diversification in

the agroecosystem doesn't always promote higher rates of colonization. Instead, Letourneau (1990) suggested architectural complexity may influence or attract beetle migration into a specific community. Beetle abundance and species richness were higher in organic farms than chemically managed farms (Carcamo et al. 1995).

Though conservation biological control practices increase natural enemy populations, the amount of control they provide is not well understood and is somewhat limited. Systems where disturbances to the landscape occur regularly (i.e. cultivation of an annual crop) have less of a chance for success due to the discontinuous interactions between the pest and biological control agents (Gubbins and Gilligan 1997). Also, conservation is not a quick remedy or replacement for chemical control strategies. Conservation tactics are sometimes limited to cropping systems that have a high tolerance for direct damage and often restricted to pest species that cause indirect damage to the crop. For example, some crops have a no-tolerance level for pest infestation such as some small fruits. Onions also have a low tolerance for onion maggot damage since any damage to small plants causes stand loss and later damage will cause quality problems and loss at harvest. These systems often require high inputs of pesticides that can negatively affect the natural enemy community.

Natural enemy biology and the densities required for effective pest control are unknown for many biological control agents. How a species interacts, behaves, and uses a refuge habitat, its prey, or the landscape is not well understood in many cropping systems. The life history of the natural enemy needs to be well defined so that the timing

of supplemental sprays, pesticide applications, and planting of flowering nectar species can be effective at suppressing the pest population.

Conservation and augmentation of onion maggot natural enemies requires an integrative approach to onion maggot control. The incorporation of narrow spectrum insecticides (Grafius et al. 1997) can help conserve existing predator populations. Preservation of refuge habitats such as field margins and hedgerows (Menalled and Landis 1997) could potentially augment carabid communities in onion fields, thus increasing the importance of biological control. Integrating multiple aspects of onion maggot control will provide a more efficient and sustainable approach to managing onion maggot populations in Michigan onions.

Pest management costs also need to be considered when evaluating the role of conservation in biological control programs. Modification of pesticide schedules can reduce the amount of sprays by encouraging farmers to apply pesticides only when pest populations exceed specified levels (Hoy 1988). This can benefit natural enemy populations and could significantly decrease pesticide costs by using fewer sprays but still provide some level of control.

A major concern about the use of conservation tactics is the limited acceptance by the farming community. Reconstructing the landscape and incorporation of natural enemy refugia often requires land to be put out of production (Thomas et al. 1991). If the crop happens to be of great cash value, this could cause financial stresses to the farming operation. Herbicide programs may also need to be modified to protect the refuge strips.

Measures that illustrate the effectiveness of a given natural enemy are needed to justifty the area needed for reduction of pest populations in the field.

Even though refuges may provide excellent sources of food and shelter, they may also act as sinks for plant pathogens and pest insects. For example, incorporating grassy refuge strips into onion agroecosystems increases carabid abundance, however, there is a possibility for the harboring of onion maggot adults (Finch et al. 1986), which could affect onion maggot damage in the field. Both positive and negative effects relating to the control of a particular pest species need to be critically assessed before carrying out a management regime.

Natural enemy conservation coincides with the ideals defined by integrated pest management (IPM) approaches in agricultural systems. A true integrative approach to the management of a pest includes the use of a broad spectrum of chemical, cultural, and biological control practices to reduce a pest population below economically damaging levels. IPM also reduces the risk the insect resistance by spraying/applying control measures when the target pest population reaches an economic threshold. The objectives of any IPM program is to provide many control methods in designing a sustainable agroecosystem. However, chemical control is the most utilized tactic in managing pest outbreaks in most agroecosystems, especially in onion production. There are many reasons for its desirability: low cost, high efficiency, availability, a long history of success and low labor inputs are only a few examples.

Heavy reliance on insecticides such as chlorpyrifos in onions can select for resistant individuals within a population and the probability for failure increases. Adding

another chemical component like cyromazine would aid in reducing the chance for onion maggot resistance. Conservation biological control incorporates multiple chemical strategies and cultural practices, and it enhances the reliance on the biological control communities within existing agroecosystems.

If pesticides continue to be a major part of the system, understanding their impact on biological control agents is important. A key component to a sustainable management system is the added pest control received from biological control agents or natural enemies and other cultural practices and increased stability of the agroecosystem. By focusing on the overall impact of a particular management tactic or system, we can achieve a better evaluation of its effectiveness and efficacy.

Conservation and augmentation of onion maggot natural enemies requires an integrative approach to onion maggot control. The incorporation of narrow spectrum insecticides (Grafius et al. 1997) and preservation of refuge habitats such as field margins and hedgerows (Menalled and Landis 1997) can augment carabid communities. Integrating multiple aspects of onion maggot control will provide a more efficient and sustainable approach to managing onion maggot populations in Michigan onions.

The objectives of this study were to 1) measure the impacts of several carabid species on onion maggot larvae and pupae; 2) determine the effects of refuge habitats on carabid communities in Michigan onions; and 3) evaluate the combination of cyromazine and grassy refuge strips as a new tool for management of onion maggot.

CHAPTER 2:

CARABIDAE PREDATION ON ONION MAGGOT, *DELIA ANTIQUA* (DIPTERA: ANTHOMYIIDAE), LARVAE AND PUPAE IN THE GREENHOUSE AND LABORATORY

ABSTRACT

Carabids are generalist predators in many agricultural landscapes and are capable of feeding on a variety of insect species and weed seeds. Many carabids feed on both plant and animal material and use a wide host range, thus being able to feed on live prey, carrion, and plant material. Research studies have focused on evaluating effectiveness of adult carabids as predators of significant agricultural pests including onion maggot (Ebert 1999, Grafius and Warner 1989). In field observations, high activity-densities for *P. chalcites*, *P. lucublandis*, and *P. melanarius* appear to coincide temporally with onion maggot oviposition and larval development. Carabid beetle predation of onion maggot larvae and pupae were examined using greenhouse and laboratory studies. In this study, *Chlaenius sericeus* (Forster), *Poecilus lucublandis* (Say), *Pterostichus melanarius* (Illiger), and *Poecilus chalcites* (Say) consumed more onion maggot larvae per day than *Harpalus affinis* (Schrank) or *Harpalus pennsylvanicus* (DeGeer). *Scarites quadriceps* Chandoir consumed the most pupae per day and was the largest carabid species assessed. In a laboratory study, more pupae were consumed at 0 cm and 1 cm depths than at 4 cm or 8 cm depths.

KEY WORDS *Delia antiqua*, ground beetle, natural enemies, generalist predators, biological control agents

Carabidae are found throughout the world and are the third-most diverse family of insects in North America with over 30,000 described species (Kavanaugh 1992, Borror et al. 1981, Ball 1979). Carabid beetles inhabit a wide range of environments including terrestrial and arboreal habitats. They often show strong habitat-specificity and, because of this, they are excellent bioindicators of habitat quality or changes in quality due to disturbances in the environment (Kavanaugh 1992). Ground beetles are usually classified as either spring or autumn breeders; spring breeders overwinter as adults and mate in the spring while autumn breeders overwinter as larvae with the adults mating in the fall months of the growing season (Lindroth 1969). Carabids mainly prefer moist, well-irrigated field conditions and seek shelter from the harsh winter conditions by burrowing below the soil surface or by hiding under crop residues or surface trash (Kirk 1976). The seasonal abundance of ground beetles often depends on nutrition, moisture, temperature, and beetle age.

Carabids are generalist predators in many agricultural landscapes and are capable of feeding on a variety of insect species and weed seeds. Many carabids feed on both plant and animal material and use a wide host range, thus being able to feed on live prey, carrion, and plant material. Adults and larvae are mostly carnivorous, however, a few carabid species are known to damage crops. Some carabid species are known to feed on seeds of oats, barley, wheat, corn and even parsley (Thiele 1977). However, the damage is insignificant.

Research on predation by carabids has focused on evaluating effectiveness of carabid adults as predators of agricultural pests. Some carabid species are capable of consuming high numbers of aphids (Hance 1990), codling moth, *Cydia pomonella* (L.) (Hagley and Allen 1988), black cutworm, *Agrotis ipsilon* (Hfn.) (Lund and Turpin 1977), European corn borer, *Ostrinia nubilalis* (Hübner), (Brust et al. 1986), armyworm larvae, *Spodoptera exigua* (Hübner) (Clark et al. 1994), diamondback moth larvae *Plutella*

xylostella (L.) (Suenaga and Hamamura 1998), and different life stages of carrot weevil, *Listronotus texanus* (Stockton) (Baines et al. 1990).

Ebert (1999) examined the impact of increased carabid beetle populations on onion maggot egg densities with field studies. She concluded that predation was higher in plots containing greater numbers of carabid beetles. However, the experimental design did not allow for possible inferences pertaining to onion maggot egg survival. Grafius and Warner (1989) demonstrated that arenas containing greater numbers of *Bembidion quadrimaculatum* L. was correlated with less damage and fewer onion maggot eggs, thus showing the ground beetles potential as biological control agents of onion maggot in Michigan onion fields.

In field observations, high activity-densities for *P. chalcites*, *P. lucublandis*, and *P. melanarius* appear to coincide temporally with onion maggot oviposition and larval development (Figure 3). Carabid activity starts to increase early in the season with the presence of spring breeders (i.e. carabids that overwinter as adults and lay eggs). As this occurs, onion maggot adults emerge from overwintering puparia. These begin to oviposite shortly after their emergence and peak oviposition occurs between late May to late June. This first generation of onion maggots has the greatest damage potential because onion seedlings are in their most vulnerable stage. As onion maggot larvae are developing, carabid populations are at their highest. This same trend is also seen during the second onion maggot generation (mid to late July) and the occurrence of fall breeding carabids (i.e. carabids that overwinter as eggs and are now emerging in mid-summer as adults). But carabid impacts on onion maggot populations in commercial farming operations are not well understood. Future research on carabid predation and the use of refuge strips to increase populations in commercial fields will indicate whether carabids and refuge strips can significantly contribute to onion maggot population management.

The objective of this study was to examine carabid beetle predation of onion maggot larvae and pupae in greenhouse and laboratory studies.

MATERIALS AND METHODS

Adult carabids trapped from commercial onion fields in Clinton County MI between May and July 2001 were used for the studies. Carabids were kept at 21°C in plastic boxes supplied with a diet of dry dog food and water for a week prior to the experiments. An onion maggot colony was started from field-collected larvae during the summer of 2000 and was maintained by the J.R. Miller lab, Michigan State University, East Lansing MI. Onion maggot larvae and pupae were collected from the colony and used for the experiments.

No-choice predator bioassays.

Larval predation by carabids. To determine the daily predation rates of commonly collected beetles found in commercial onion fields, I used a predator arena of ten second-instar onion maggots placed in petri dishes (150 mm diam.) along with a moist cellulose sponge (5 x 10 x 10 mm). There were seven treatments: six carabid species (*Chlaenius sericeus, Harpalus affinis, Harpalus pennsylvanicus, Poecilus lucublandis, Pterostichus melanarius,* and *Poecilus chalcites*) and one group without predators to account for larval mortality and escape during the experiment. One beetle or no beetle (control) was put into each arena. The arenas were kept in a growth chamber at 21°C, photoperiod of 16:8 (light:dark). Daily for 6 d the number of onion maggot larvae consumed or attacked in each arena was recorded and all larvae were removed and replaced with new larvae from the lab colony. Data were analyzed with one-way ANOVA (PROC GLM, SAS Institute, version 8.1) blocked by day. Means were separated with Fisher's protected LSD test (a=0.05).

Pupal predation by carabids. To determine predation rates on pupae, onion maggot pupae were placed into petri dishes as described above. There were five carabid species tested (*H. affinis, H. pennsylvanicus, P. lucublandis, P. melanarius, P. chalcites* and *Scarites quadriceps*). One beetle was put in each arena. The arenas were arranged in a randomized complete block design and kept in a growth chamber at 21°C, photoperiod

of 16:8 (light:dark) and were blocked by day. The number of pupae eaten or partially eaten in each arena was recorded daily for 5 d. Eaten or partially eaten pupae were removed and replaced with new pupae from the lab colony. Data were analyzed as before.

Greenhouse and laboratory experiments.

Larval predation by carabids in onion pots. A greenhouse study was conducted to test the effects of carabid beetles on onion maggot larval numbers in a controlled environment. Eight fungicide treated onion seeds (BejoÒ Seeds, Inc.) were planted in square plastic pots (10 x 10 x 20 cm) at a depth of 3 cm in sifted organic muck soil from the Michigan State University Muck Soils Research Farm, Clinton County MI. The arenas were placed in the greenhouse in early May of 2001 and the pots were watered and weeded when needed. When the onion plants reached the 3-leaf stage, they were thinned to 4 onion plants per pot.

In August 2001, ten second instar onion maggots were placed in each arena and were allowed to acclimate to the greenhouse and arena conditions for 2 d. The four treatments tested included three carabid species (*P. chalcites*, *P. lucublandis*, and *P. melanarius*) and a control group without carabids to account for natural larval death, larval escape, and/or handling loss. After the 2 d acclimation period one beetle or no-beetle (control) was placed in each experimental arena and all arenas were arranged in a completely randomized design in a greenhouse with temperatures ranging from 21-27°C and a photoperiod of 16:8 (light:dark). The larvae were exposed to predators for 1 wk. Then the soil was searched and the number of larvae remaining in each arena was recorded and analyzed with one-way ANOVA (PROC GLM, SAS Institute, Version 8.1). Fisher's protected LSD test was used to separate mean differences between treatments (a=0.05). Data from arenas containing dead or missing predators were not used in the analysis.

Predation influenced by depth and carabid species. A lab study was conducted to measure the ability of carabid species captured in commercial onion fields to consume onion maggot pupae at different soil depths. This experiment tested consumption rates of buried pupae (0 cm, 1 cm, 4 cm, or 8 cm) by two common predator species (*P. lucublandis* or *P. melanarius*) found in onion agroecosystems.

The arena consisted of two 1 liter plastic cups (11.5 cm diameter, 14 cm height), one inverted on top of the other (Figure 1). Next, two 8 x 8 cm sections from the top cup were removed and replaced with a mesh screen (screen size = 1 x 1 mm). This allowed for air ventilation and light penetration into the arenas. Ten pupae were placed at the specified depths (0 cm, 1 cm, 4 cm, or 8 cm) and covered with muck soil, collected and sifted to remove all other potential food or predators from the Michigan State University Muck Soils Research Farm, Clinton County MI. A 2 dram vial filled with water and plugged with a moist cotton ball was used to maintain the humidity levels within the arena; it also provided a source of water for the predators. After the onion maggot pupae were placed in the arenas, a single beetle was added to each arena. Top and bottom halves of the arenas were secured together with tape. Predator arenas were placed on a bench at room temperature (approximately 21°C) with a photoperiod of 16:8 (light:dark).

The pupae were exposed to the predators for 1 wk and the numbers of onion maggot pupae remaining in each arena were recorded. Because depth is a continuous variable, a regression analysis was used (PROC REG and PROC UNIVARIATE, SAS Institute, Version 8.1) ($a=0.05$). Shapiro-Wilks tests for normality were used and data were transformed with $\log(x+1)$ to normalize the data before regression analysis. Arenas containing dead or missing predators were not used in the analysis. A parallel test group using no predatory beetles was used as a control to measure efficiency in pupae recovery techniques and all pupae were recovered. The control group was not used in the analysis.

RESULTS AND DISCUSSION

No-choice predator bioassays.

Larval predation by carabids. *C. sericeus*, *P. lucublandis*, *P. melanarius*, and *P. chalcites* consumed significantly more larvae per day than *H. affinis* or *H. pennsylvanicus* ($p<0.05$) (Table 1). *H. affinis* and *H. pennsylvanicus* are mainly phytophagous (Hagley et al. 1982, Kirk 1973), explaining the lower consumption rates for these two species. The mean number of onion maggot larvae consumed by *H. affinis* and *H. pennsylvanicus* was not different from numbers dead or missing in the control ($p>0.05$). These consumption rates represent what is occurring in a no-choice laboratory test with no limits to access to the larvae by the carabids.

Finch (1996) suggests that predator size plays a crucial role when it comes to cabbage root fly, *Delia radicum* L., egg predation. The relationship between prey and mandible size is key to the efficiency of carabids to consume cabbage root fly eggs. Total lengths of *C. sericeus*, *P. chalcites, P. lucublandis*, and *P. melanarius* range from 10. 1 to 13.5 mm, 10.5 to 13.0 mm, 9.0 to 14.0 mm, and 12.0 to 18.0 mm, respectively (Lindroth 1969). Finch (1996) found that the predator size had an influence on predator consumption of root fly eggs; the largest and smallest beetles consumed fewer eggs than medium sized beetles. The results from that study suggest that the ideal cabbage root fly egg predator ranges from 2.7-10 mm in length (Finch 1996).

This might also be the case when discussing onion maggot larvae predation by the species tested. Future bioassays that could address this question of size might be relevant to the incorporation of refuge strips in onion cropping systems. Since larger beetles have a tendency to consume more larvae (i.e. *P. lucublandis* and *P. melanarius*), the importance of these and other similar sized beetles as generalist predators in onion

agroecosystems needs to be evaluated. The relationship between predator and prey is essential to understanding the success of the intended biological control agent.

Pupal predation by carabids. *P. chalcites*, *P. lucublandis*, *P. melanarius*, and *S. quadriceps* consumed significantly more pupae per day than *H. affinis* and *H. pennsylvanicus* ($p<0.05$) (Table 2) . Predation was observed in *H. affinis* and *H. pennsylvanicus*, but variability was high and their mean pupae consumption rates were not significantly different from zero. The species that consumed the most pupae per day was also the largest carabid species assessed, *S. quadriceps* (16.0 to 20.0 mm). Again, this suggests that predator size might have an influence in the choices pertaining to prey size and consumption rates.

Greenhouse and laboratory experiments.

Larval predation by carabids in onion pots. A large number of onion maggot larvae were lost or disappeared in the absence of predators. Larvae consumption/disappearance ranged from 47-57%, however, there were no significant differences observed ($p>0.05$) ($F3,102=1.77$, $P=0.16$). These carabids apparently were not able to find and consume larvae buried in the soil or hidden within the onion plant tissue. Other possible reasons for the lack of differences include experimental design, the difficulty in retrieving larvae from the onion plants, natural larval death, and the probability of larvae escaping from the arena. Plant size could have also contributed to the low level of predation observed. Second instars were used and were placed in the pots when the onions were at the 3-4 leaf stage. Individual onion plants were large enough to support the growth of a developing larva. Since the larvae had all the resources needed to complete their development, their need to search for a new host plant was minimized and little plant-to-plant movement probably occurred. Therefore the probability of larvae moving onto the soil surface and potential predation by generalist predators such as carabids was low. Future behavioral studies would be needed to support this hypothesis.

Research on predation on onion maggot eggs and other closely related species has been well documented (Grafius and Warner 1989, Ebert 1999, Finch 1996). Finch and Elliott (1993) showed carabids to be effective predators of cabbage root maggot when the eggs were on the soil surface; none of the beetles they tested were able to find the eggs buried below the soil surface. However, little research has been done on the effectiveness of carabids on predation on onion maggot larval stages. Brust (1991) developed a method for observing below-ground arthropod predators and concluded that carabid larvae were significant predators of first, second, and third instars of southern corn rootworm, *Diabrotica undecimpunctata howardi* Barber. Brust (1991) was able to show a strong correlation between the number of southern corn rootworm larvae that disappeared and the number of predators observed.

Evaluating the impact of variables such as plant size, life stage of the prey items (egg vs. larvae vs. pupae), soil moisture, host quality, soil type, and duration of the study will be necessary to determine the role of these generalist predators in reducing onion maggot populations in the field.

Carabid predation influenced by depth and species. There was a significant relationship between pupae depth and rate of predation by both predators *P. lucublandis* ($F_{1,22} = 20.28$, $P=0.001$) and *P. melanarius* ($F_{1,22} =25.27$, $P<0.0001$). A parallel series was run without predators and all pupae were recovered. The zero consumption observed in the control group was expected and it validated the techniques used to recover the pupae. As pupal depth increased, the predation rates of onion maggot pupae for both species tested (*P. lucublandis* and *P. melanarius*) was significantly lower; the most pupae were consumed at 0 cm ($p<0.05$) (Figure 2). Variation in pupae consumption rates explained by the regression model was low for each species tested; r2 values for *P. melanarius* and *P. lucublandis* were 0.45 and 0.43 respectively. No pupae were consumed at the 4 cm and 8 cm depths, but high numbers of pupae were consumed at the soil surface. There was definitely a strong correlation between depth and the number of

pupae consumed, but 40-45% of the variation in consumption rates could be explained by my model.

The observed predation/depth relationship for these carabid species could be explained by their prey-searching behavior. Carabids are generalist predators and they use a variety of mechanisms for prey allocation: random search, sight, and chemical cues (Lovei and Sunderland 1996). They spend most of their time on the soil surface, and they most commonly search for prey using a random walk or search. As cues become stronger, they increase their turning angles, thus increasing the probability for finding the prey item. As the strength of the signal decreases, they resume a random, but a more straight walk. Since the pupae at 0 cm were exposed and the beetles were confined to small arenas, the probability of a beetle coming into contact with the pupae increased and number of onion maggot pupae consumed was high. As the depth of the buried pupae increases, the probability of a beetle finding pupae decreased.

Some carabid species such as *P. melanarius* have burrowing behaviors that could bring them into contact with pupae located below the soil surface (Wallin 1988). Burrowing was observed at 1 cm in this study, but few buried pupae were consumed by *P. melanarius*. This suggests that locating pupae by burrowing was a rare occurrence and it was not a common behavior used by *P. melanarius* for resource allocation. In the field, onion maggot rarely pupate at the soil surface; factors such as moisture and temperature affect onion maggot pupation depths.

The results from this experiment suggest that the probability of a carabid consuming onion maggot pupae decreases as the depth of the pupae increases. When examining the life history of the onion maggot, female onion maggot adults lay their eggs at the base of onion seedlings early in the season. As the egg hatches, maggots make their way into the root zone of the onion plant and eventually into the stem of the onion. As they grow and develop through 3 larval instars, they eventually pupate 5-8 cm below the soil surface. From my experiment I observed no predation of onion maggot pupae at this

depth. This does not, however, rule out the importance of carabids at reducing the number of pupae in the field because carabid larvae spend a majority of their developmental time in close contact with the soil (Lindroth 1969). Although little is known about carabid larvae prey preference and feeding behaviors. Future predation studies should address the role of immature carabids in the predator-prey complex in any biological control program using carabids for control of important soil arthropods.

Generalization about carabids and their potential ability to reduce pest populations in the field should be made with caution. Predator activity and searching behavior can also affect predation rates in the field (Barney and Pass 1986). Rather than make generalizations about carabids at the family level, Barney and Pass (1986) suggested that foraging and feeding strategies should be evaluated at the species level.

Factors that can influence these subtle differences in behavioral responses within the Carabidae family includes morphological and physiological adaptations, predator density, and resource distribution (Bell 1990; Evans 1990). Clark et al. (1994) found the community structure of generalist predators to be an important factor in altering pest populations in agroecosystems. Future field studies that tried to understand community diversity might contribute to the effectiveness of carabids as a management tactic.

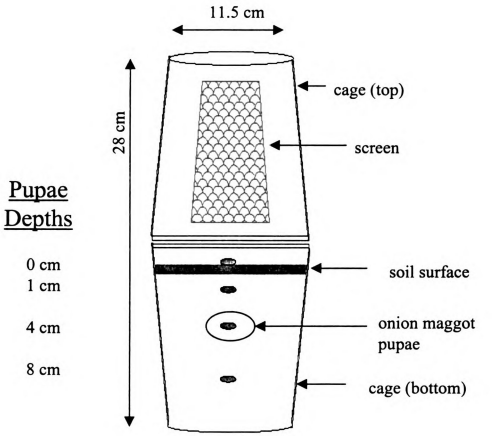


Figure 1. Arena design for pupal predation by carabids, *Pterostichus melanarius* and *Poecilus lucublandis*. One 1 liter plastic cup (11.5 cm diameter, 14 cm height) was inverted on top of another 1 liter plastic cup. The top cup had 2 sections (8 x 8 cm) removed and replaced with screen mesh (mesh size = 1 x 1 mm).

Table 1. Mean number of onion maggot larvae consumed per day by various carabid species captured in commercial onion fields.

Species	n	Larvae/day[1]	±	SE	
Chlaenius sericeus	20	5.1	±	0.41	a
Harpalus affinis	12	1.2	±	0.53	b
Harpalus pennsylvanicus	16	0.5	±	0.46	b
Poecilus lucublandis	20	3.6	±	0.46	a
Pterostichus melanarius	16	4.6	±	0.46	a
Poecilus chalcites	16	3.5	±	0.41	a
Control (No-predator)	16	0.1 [2]	±	0.46	b

[1] Means within a column followed by different letters are significantly different ($P<0.05$, Fisher's protected LSD test).

[2] Arenas that contained no-predators (control) were used to account for larval death and larval escape during the experiment.

Table 2. Mean number of onion maggot pupae consumed per day by various carabid species captured in commercial onion fields.

Species	n	Pupae/day[1]	±	SE	
Harpalus affinis	36	0.4	±	0.38	d
Harpalus pennsylvanicus	6	1.2	±	0.95	cd
Poecilus chalcites	24	2.3	±	0.47	c
Poecilus lucablandis	90	4.0	±	0.24	b
Pterostichus melanarius	18	4.9	±	0.54	b
Scarites quadriceps	6	8.2	±	0.94	a

[1] Means within a column followed by different letters are significantly different ($P<0.05$, Fisher's protected LSD test).

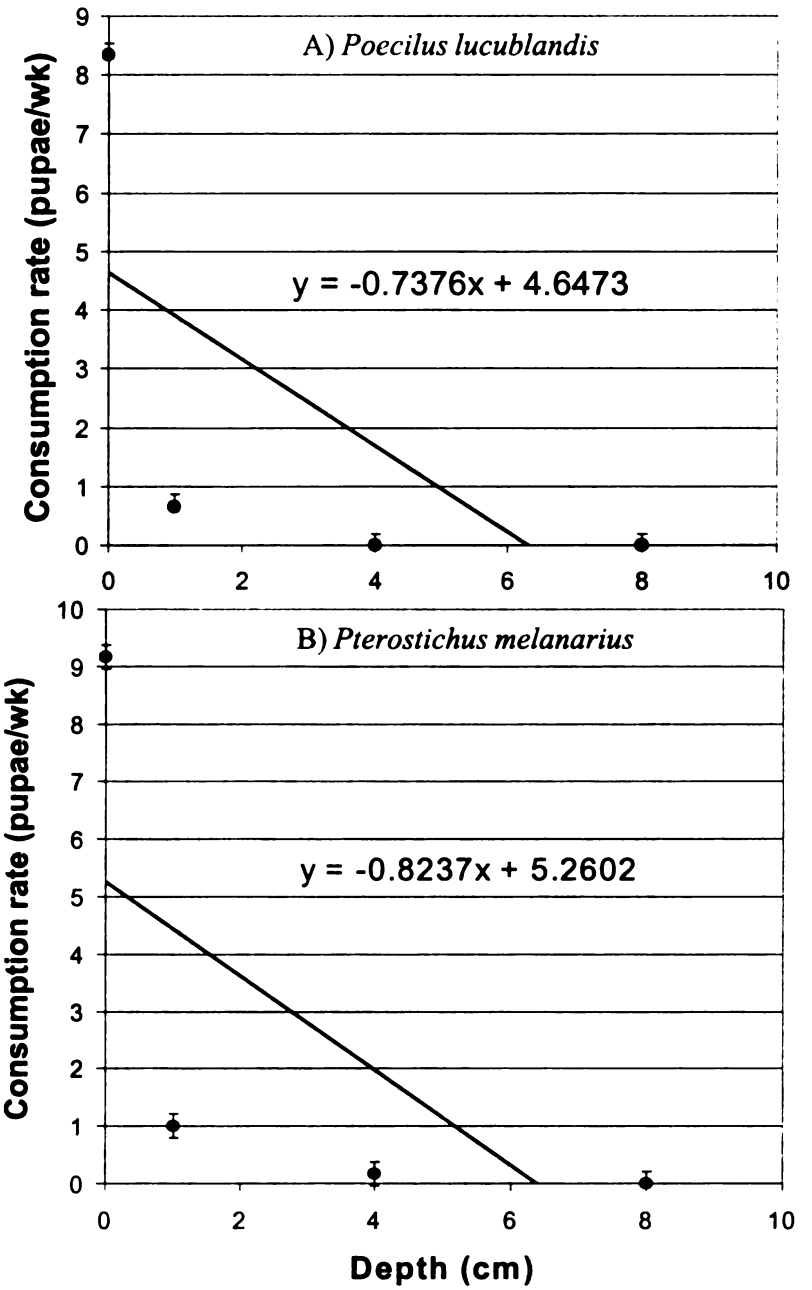


Figure 2. Correlation between mean number of onion maggot pupae consumed by A) *Poecilus lucublandis* and B) *Pterostichus melanarius* at varying depths (0 cm, 1 cm, 4 cm, or 8 cm).

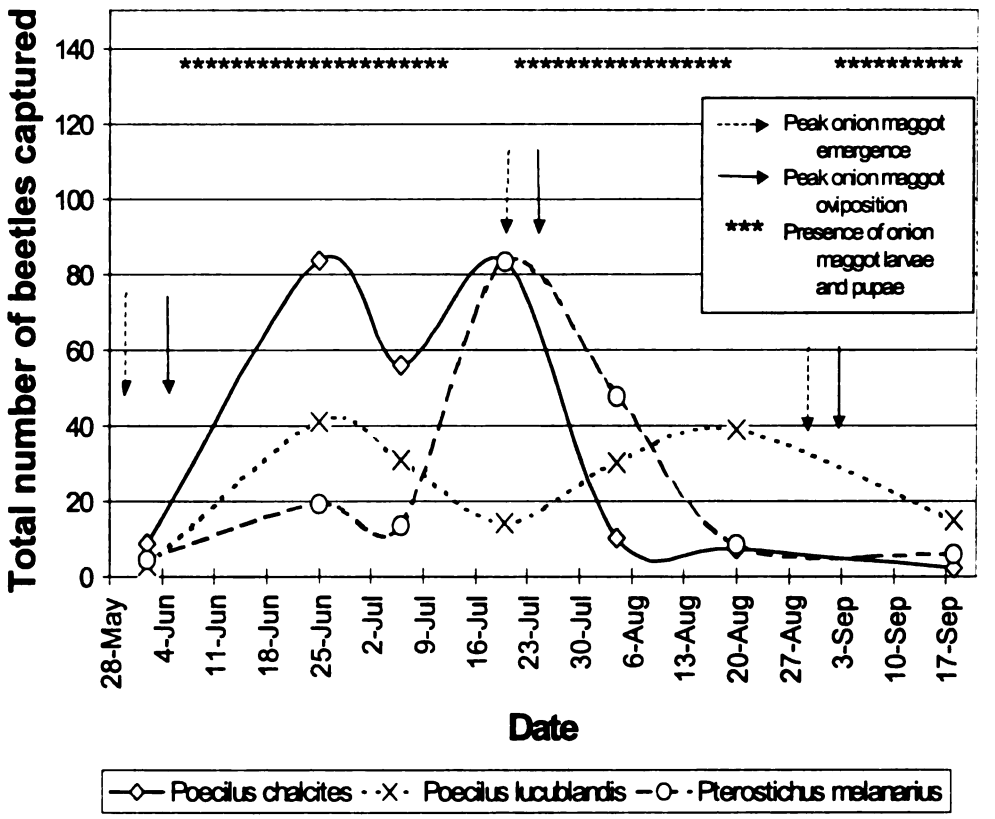


Figure 3. Carabid beetle activity-density for the species *Poecilus chalcites*, *Poecilus lucublandis*, and *Pterostichus melanarius* at the Michigan State University Muck Soils Research Farm, Clinton County MI in 2000.

CHAPTER 3:

GRASSY REFUGE STRIPS AND A NARROW SPECTRUM INSECTICIDE (CYROMAZINE) CONSERVE GROUND BEETLE (COLEOPTERA: CARABIDAE) POPULATIONS IN MICHIGAN ONIONS

ABSTRACT

Onion maggot, *Delia antiqua* (Meigen), is the most economically important insect pest in Michigan onions (*Allium cepa* L.). In years of severe outbreak it can cause a 40-80% reduction in yield. Effective management of this pest relies on the use of chlorpyrifos, a broad-spectrum insecticide, for control. Michigan onion growers need additional control methods for managing onion maggot. My objectives were to 1) determine the effects of refuge habitats on carabid communities in Michigan onions, and 2) evaluate the combination of cyromazine and refuge strips in onions as a new tool for management of onion maggot. We looked at the effect of newly established grassy refuges on carabid beetle populations in a Michigan onion field. The carabid activity-density within 3.6 m wide grassy refuge strips during 2000 was not significantly different from the activity-density within similar onion control strips. *Pterostichus melanarius* (Illiger) was the only species more abundant in the newly established refuges than in the onion habitats. However, the presence of a grassy refuge increased carabid populations in the adjacent crop habitat, including entomophagous predators such as *Poecilus chalcites* (Say) and *Bembidion quadrimaculatum* L. In 2001, significantly more *Elanphropus anceps* (LeC.) were captured in untreated or crop areas treated with cyromazine than crop

areas treated with chlorpyrifos; *E. anceps* was the only species directly affected by the insecticide treatments. Conservation practices including the use of narrow-spectrum insecticides and refuge strip habitats will help to define the role of generalist predators in the control of onion maggot.

KEY WORDS *Delia antiqua*, onion maggot, ground beetles, refuge habitats, conservation biological control, carabids, generalist predators

The onion maggot, *Delia antiqua* (Meigen), is the most serious and economically important insect pest of onions (*Allium cepa* L.) in Michigan and much of the northeastern United States and Canada (McEwen et al. 1981, Ellis and Eckenrode 1979, Wells and Guyer 1966). Onion maggot is a specialist herbivore on onions (Ellis and Eckenrode 1979b) and a few other minor *Allium* species. In Michigan the onion maggot has three distinct generations each year, with the initial spring emergence of adults occurring in late April or early May (Zandstra et al. 1996, Eckenrode et al. 1975, Loosjes 1976). First generation larvae have the most impact economically, because the onion plant is in its most vulnerable stage and a single maggot can destroy up to 12-15 seedlings before pupating (Miller and Cowles 1990, Loosjes 1976). Onion maggot has the potential of causing a 40-80% reduction in yield without proper chemical or cultural control strategies (Zandstra et al. 1996).

Despite its economic importance, management options for this pest are limited. Heavy reliance on a single broad-spectrum insecticide by growers generates a cause for concern. Chlorpyrifos (Lorsbanâ, Dow AgroSciences LLC, Indianapolis IN) is the only chemical currently registered for control of onion maggot in Michigan onions. Because of

the Food Quality Protection Act of 1996, chlorpyrifos has been withdrawn from use in all urban markets and from minor uses in other crops. Even if use on onions is not restricted, development of resistance by onion maggot to chlorpyrifos is a concern (Harris and Svec 1976). Cyromazine (Trigardâ, Ciba Plant Protection, Greensborro NC) has had emergency registration (Section 18) status as a seed treatment for control of onion maggot since 1996. It is an insect growth regulator that disrupts the molting process of some Diptera larvae (El-Oshar et al. 1985). This specific range of activity helps to conserve beneficial soil arthropods within onion agroecosystems (Ebert 1999). New alternatives for onion maggot control must be developed to maintain onions as a viable crop for Michigan vegetable farmers.

Carabids are generalist predators in many agricultural landscapes. They feed on a variety of insect pests including onion maggot (Grafius and Warner 1989, CHAPTER 2). Augmenting carabid beetle populations in a field is likely to increase predation pressure on targeted pest species (Chiverton 1986, Menalled et al. 1999). In corn, the exclusion of generalist predators like carabids results in increased armyworm damage (Clark et al. 1994). However, little is known about their overall impact on onion maggot populations.

Carabids are very sensitive to disturbances in the environment and are easily affected by cultivation practices (Kromp 1999). Refuge strips can increase the numbers and activity of carabids and other biological control agents in corn and soybeans (Carmona 1998, Menalled and Landis 1997, Lee et al. 2001). Grassy refuge habitats can also help replenish communities reduced by heavy insecticide use (Lee et al. 2001) and provide overwintering sites (Thomas 1990). In addition, they can provide alternate food

resources for predators when pest populations in the field are low (Hawthorne and Hassall 1995).

Conservation and augmentation of onion maggot natural enemies requires an integrative approach to onion maggot control. The incorporation of narrow spectrum insecticides can help conserve existing predator populations (Grafius et al. 1997). Preservation of refuge habitats like field margins and hedgerows (Menalled and Landis 1997) could also potentially augment carabid communities in onion fields, thus increasing the importance of biological control. Integrating multiple aspects of onion maggot control will provide a more efficient and sustainable approach to managing onion maggot populations in Michigan onions.

My objectives were to 1) determine the effects of refuge habitats on carabid communities in Michigan onions, and 2) evaluate the combination of cyromazine and refuge strips in onions as a new tool for management of onion maggot.

MATERIALS AND METHODS

1999 field study.

Predator enclosures were established in an onion field located at the MSU Muck Crops Research Farm, Clinton County MI in August 1999. This was a one-factor treatment design with three treatments: full-enclosure plot, partial-enclosure plot, and a grassy border. Plots were arranged along the edge of an established grassy border. Plots (10 x 10 m) were surrounded by a 20 cm high plastic barrier that was secured 20 cm deep into the ground to reduce carabid migration between plots (Lee et al. 2001). The plastic barrier was secured into the soil using wooden stakes. Full enclosure plots were surrounded by plastic barrier on all sides to prevent carabid movement into or out of the

plots (Figure 4). On the partial-enclosure plots, the side closest to the grassy border remained open to encourage carabid migration into the plot from the grassy border. The grassy border plots were adjacent to the full enclosure plots and were used to monitor the carabid populations; no physical barrier was constructed.

Pitfall traps were used to monitor carabid activity-density. Traps (4/plot) were located in the second and forth rows of each onion plot (2 m from the barrier wall and 6 m between each trap) and in similar locations in the grassy border plots (Figure 4). Traps were checked 4-5 times/wk between 1 Aug and 8 Sept 1999 and carabids in the traps were identified to species and released on site.

Trap catches were totaled over the entire trapping period. The data was analyzed with one-way ANOVA (PROC GLM, general linear model, SAS Institute 8.1) (P=0.05). Activity-densities for each carabid species that accounted for >5% of the total trap catch were analyzed. All data were normalized with a log(x+1) transformation before analysis.

Established grassy refuges within an onion field.

Field experiments were conducted at the Michigan State University Muck Soils Research Farm, Clinton County MI in 2000 and 2001. The overall field dimension was 30 m long by 183 m wide. The south side of the field was adjacent to a well-established grassy border, and the north edge was adjacent to a tree line running east and west. I created raised beds (30 m x 1.7 m x 0.3 m high) with a standard commercial onion bedder. A 3.6 m wide grassy refuge treatment consisted of a mixture of three cover crop species: orchard grass (*Dactylus glomerata* L.), white clover (*Trifolium repens* L.), and red clover (*Trifolium pratense* L.); I rounded and hand-raked the raised beds assigned to the grassy refuge strip treatment. The orchard grass, white clover, and red clover were

sown with a hand-spreader at the recommended seed application rates of 5-7 kg/ha, 1-2 kg/ha, and 2-7 kg/ha, respectively. Onion control strips were planted to onions and were not treated with an insecticide; the control strip mimicked normal onion field conditions and canopy cover. We measured the impact of newly seeded refuge strips on carabid beetle populations in 2000 and the effects of established refuges, insecticides, and interactions between refuges and insecticides in 2001. The same field and refuge strips were used in both years, arranged in a randomized complete block design.

Newly established grassy refuges. A one factor experiment with two treatments was planted in early May 2000 and was blocked by location. There were 4 blocks with 2 plots per block. Each plot contained ten beds; four onion beds on either side of a two-bed (3.6 m wide) treatment strip (Figure 5). Treatments consisted of refuge strips or onion control strips as described above. Crop areas on both sides of the treatment strips (four-bed crop areas) were planted to onions. Herbicides, fungicides, fertilizer, and irrigation were applied throughout the growing season according to standard commercial practices; no insecticide was used in this experiment.

Carabid activity-density was measured with dry pitfall traps for 4 consecutive days every other week from 9 May – 18 September 2000. There were 36 traps/plot (24 traps in the adjacent crop areas and 12 traps in each treatment strip); traps were evenly spaced throughout the refuge and crop areas (Figure 5). Traps were checked daily and the carabids were identified to species and released; traps were covered with plastic lids when not in use. I took specimens to the lab when specimens could not be identified in the field. Catches within the crop areas, within the treatment strips, and within the entire plot (traps located within the crop area plus traps in treatment strips) were analyzed with

one-way ANOVAs with subsamples (PROC GLM, SAS Institute version 8.1) (P=0.05). Activity-densities for carabid species that accounted for >5% of the total trap catch were analyzed. All data were normalized with a log(x+1) transformation before analysis.

Insecticide and refuge habitat effects on predator populations. In 2001, I evaluated the impacts of a combination of insecticide application and refuge habitat on carabid populations using predator inclusion/exclusion plots. I used a split-plot design with the whole-plots arranged in a randomized complete block design. The whole-plot factor was the same treatment strips as in 2000 (3.6 m wide grassy refuge strip or two-bed onion control strip), and the sub-plot factor was an insecticide treatment (chlorpyrifos, cyromazine, or untreated) applied to onions in the three-bed crop areas adjacent to the 3.6 m wide refuge treatment strips (Figure 6). Each whole-plot (30.5 x 17 m) was sectioned off lengthwise into three sub-plots (10 x 17 m) and I randomly assigned sub-plot treatments within each whole-plot (Figure 6). To prevent predator movement between sub-plots, all sub-plots were completely and individually enclosed with a 20 cm high plastic barrier secured 20 cm into the soil and supported by corner and side-wall stakes (Lee et al. 2001).

Ground-dwelling predators were monitored in the insecticide treated or untreated crop area and within treatment strip habitats using dry pitfall traps (11.5 cm diam., 15 cm ht.). Each sub-plot contained 12 traps (8 traps in the crop area and 4 in the treatment strip) arranged as in the previous experiment. A total of 288 pitfall traps were arranged and monitored as in 2000.

Catch for each trap was totaled over the whole season and catch/trap were analyzed with a split-plot ANOVA (P=0.05) (PROC GLM, SAS Institute, Version 8.1).

Catches within the crop areas, within the treatment strips, and within the entire plot (traps within the crop area plus the traps in treatment strips) were analyzed. Activity-densities from individual carabid species that accounted for >5% of the total trap catch were also analyzed. All data were normalized with a log(x+1) transformation.

Species richness within the entire plot, within the crop area, and within the treatment strips was analyzed. Shannon Weaver's index (H') was used to assess species diversity. Species diversity (H') is a measure of uncertainty for species within the community (Hayek and Buzas 1997). When more species are present and the individuals are more evenly spread divided across these species, the value for H' will be higher than for fewer species or a more uneven distribution (Hayek and Buzas 1997). Shannon Weaver's indices (H') and the total number of species captured within the refuge or control strips, within the crop areas, or within in the entire plot were used to access refuge, insecticide, and refuge*insecticide effects on species diversity and species richness. Treatment effects on onion harvest weights and numbers within the crop areas were also determined.

RESULTS AND DISCUSSION

1999 field study.

Significantly more carabids were captured in the grassy border plots than in the full-enclosure or partial-enclosure plots ($p<0.05$). However, the total number of carabids captured in plots that had sides open to the grassy field border were not significantly different from plots that were fully enclosed ($p>0.05$) (Table 3) (Figure 7). At the species level, there were significant differences within the five carabid species tested ($p<0.05$)

(Figure 8). *Pterostichus melanarius* (Illiger), *Poecilus chalcites* (Say), and *Harpalus pennsylvanicus* (DeGeer) were more abundant in the grassy field border ($p<0.05$) (Figure 8). There were no significant differences in the mean activity-densities between full-enclosure and partial-enclosure plots for *Bembidion quadrimaculatum* L., *P. melanarius*, *P. chalcites*, *H. pennsylvanicus*, and *Amara aenea* (DeG.) ($p>0.05$) (Figure 8). The mean number of carabids captured per plot was the highest in the grassy border plots compared to onion plots for all the species tested except *B. quadrimaculatum* (Figure 8). Larger beetles such as *P. melanarius*, *P. chalcites*, and *H. pennsylvanicus* are better dispersers and would be expected to be common in the partial-enclosure plots, especially since they were collected in the nearby grassy border. Conversely, the opposite was observed in the much smaller species *B. quadrimaculatum*. In this species significantly more beetles were captured in the full-enclosure and partial-enclosure plots than in the grassy border ($p<0.05$ (Figure 8). A longer sampling period and more replicates from grassy field borders from multiple fields would help to clarify the role of grassy borders in contributing to in-field carabid communities.

Established grassy refuges within the field.

Newly established grassy refuges. A total of 6,194 carabids representing 25 species was captured during the 2000 trapping period (Table 4). The total catch of all carabids per trap within the treatment strips was not significantly affected by the presence of refuge vegetation ($p>0.05$) (Table 7) (Figure 9). *Anisodactylus sanctaecrusis* (F.), *P. melanarius*, *A. aenea*, *Stenolophus comma* (F.), *P. chalcites*, *B. quadrimaculatum*, *Elaphropus anceps* (LeC.), *Stenolophus ochrapezus* (Say), and *Poecilus lucublandis* (Say) each accounted for >5% of the total catch. However, *P. melanarius* was the only

species with a significantly greater activity-density per plot and per trap in the refuge strips than in the onion control strips ($p<0.05$) (Table 8) (Figure 10B). The total numbers of *E. anceps* captured was significantly higher in the onion control strip habitat than in the refuge strips ($p<0.05$) (Figure 10B). Carmona and Landis (1999) also found *P. melanarius* to have a greater activity-density in newly established refuge strips than in the crop area (corn). This very large and mobile species can disperse 2-90 m/day (Wallin and Eckbom 1988). Because of its great dispersal rate and freedom of movement for beetles between treatment and crop in this experimental design, the greater *P. melanarius* numbers in the refuge strip appears to be due to a preference for this habitat.

The combined per trap catch for all carabids within the crop areas adjacent to refuge habitats was higher, however, it was not significant ($p>0.05$) (Table 6) (Figure 9). Trap catches for the common carabid species captured within the adjacent crop area were significantly affected by the presence of a refuge strip ($p<0.05$) (Table 8). Activity-density for *P. chalcites* was significantly higher in crop areas adjacent to refuges than in the crop areas adjacent to control strips ($p<0.05$) (Figure 10A).

The combined activity-density of all carabids captured per trap within the entire plot (carabids captured in the treatment strips plus those captured within the crop areas) was not significantly affected by the presence of the refuge vegetation ($p>0.05$) (Table 5) (Figure 9). The trap catch for *E. anceps* was significantly lower in the control treated plots than in the refuge treated plots ($p<0.05$) (Figure 10C). *P. melanarius* and *S. ochropezus* were higher in the refuge treated systems, however, it was not significant ($p>.05$) (Figure 10C).

When looking at the seasonal carabid activity within the adjacent crop areas and within the entire plot, there are no significant differences between the refuge strips or the onion control strips ($p>0.05$) (Figure 11A,C). However, this was not the case for trap catches within the refuge strips or control strips. Significantly more beetles were captured in the refuge strips around 1 June 2000 than in the onion control strips (Figure 11B). Because the refuges were established in the spring of 2000, it is hard to interpret the differences in activity-densities observed early in the season.

Pitfall trap data needs to be interpreted with caution because of unknown trapping efficiencies and uncontrolled migration of insects across the landscape (Greenslade 1964, Southwood 1966, Luff 1975). In 2000 there were no physical barriers used to separate the treatment areas. For trapping areas that had significantly higher beetle catches, it is not clear what caused the increased catch. Gist and Crossley (1975) found estimates made with pitfall trapping showed good agreement with hand sorting techniques. The experiment in 2001 controlled for migration of carabids between plots and the results from that experiment will help in determining the overall effects observed in the activity-densities of the species tested in 2000.

Insecticide and refuge habitat effects on predator populations. A total of 2,911 carabids representing 25 species was captured in pitfall traps in 2001 (Table 4). *A. aenea*, *A. sanctaecrucis*, *B. quadrimaculatum*, *E. anceps*, *Harpalus affinis* (Schr.), *P. chalcites*, *P. melanarius*, and *S. comma* each accounted for >5% of the total catch. Seasonal mean carabids captured per trap within the treatment strips ranged from 6-10 beetles per trap, while trap catches within the adjacent crop areas ranged from 9-18 beetles per trap (Table

13). The most beetles captured per trap was in traps located in crop areas treated with cyromazine and adjacent to a refuge strip.

The number of carabids captured per trap within the crop areas was significantly higher with the presence of a refuge strip than for plots without an adjacent refuge strip ($p<0.05$) but was not affected by the insecticide treatments ($p>0.05$) (Table 10) (Figure 12A-B). Both the refuge treatment and the insecticide treatment affected the trap catch. More beetles were captured in the crop areas treated with cyromazine than crop areas treated with chlorpyrifos, however, it was not significant ($p>0.05$) (Figure 12B). *P. chalcites*, *H. affinis*, and *A. aenea* per trap catches were higher in the crop areas adjacent to refuge strips than onion control strips ($p<0.05$) (Figure 13A). The species where catch within the adjacent crop area was affected by insecticide included *E. anceps* and *H. affinis* ($p<0.05$); *E. anceps* trap catch in both the untreated and cyromazine treated crop areas was significantly higher than in the chlorpyrifos treated areas and there was no difference in catch between the untreated or cyromazine treated onions ($p<0.05$) (Figure 15A). H. affinis was significantly higher in the cyromazine treated crop area than in the untreated crop area, however, trap catch was not significantly different than the chlorpyrifos treated crop area ($p<0.05$) (Figure 15A).

The activity-density of carabids within refuge strips and onion control strips were not significantly affected by the presence of a refuge strip or by the application of insecticides ($p>0.05$) (Table 11) (Figure 12A-B). At the species level, trap catches for *P. melanarius* were significantly higher within the refuge strips than in the onion control strips ($p<0.05$) (Table 12) (Figure 13B). The number of *P. melanarius* captured per trap within the refuge treatments was unaffected by the insecticide treatment ($p>0.05$) (Figure

15B). *A. aenea* was the only species captured within the refuge strips affected by the treated adjacent crop area ($p<0.05$) (Table 12) (Figure 15B). Significantly more beetles were captured within the refuge strips that were adjacent to the untreated (control) crop areas than in refuge strips adjacent to chlorpyrifos treated areas ($p<0.05$) (Table 12).

The total number of beetles captured within an entire plot containing a refuge strip was higher than in plots having an onion control strip but the difference was not statistically significant ($p=0.07$) (Table 9) (Figure 12A). Chlorpyrifos appeared to reduced the number of carabids captured per trap within entire plots when compared to catches in plots containing untreated or cyromazine treated crop areas, however, the differences were not significant ($p>0.05$) (Figure 12B). The activity-densities for *H. affinis*, *A. aenea*, *A. sanctaecrucis*, and *P. chalcites* were significantly higher in plots containing refuge strips than in plots with onion control strips ($p<0.05$) (Table 12) (Figure 13C). Fewer *E. anceps* were captured per trap within plots where the crop areas were treated with chlorpyrifos than in cyromazine treated or untreated (control) plots ($p<0.05$) (Figure 15C). B. quadrimaculatum was also affected by the insecticide treatment. Fewer beetles were captured in chlorpyrifos treated plots than in untreated plots, however, it was not significantly lower than cyromazine treated plots ($p<0.05$) (Figure 15C).

The total number of carabids captured over the entire season within crop areas and within entire plots were significantly different between plots treated with refuge strips or plots treated with onion control strips ($p<0.05$) (Figure 14A,C). During the month of August, significantly more beetles were captured within the crop areas adjacent to refuge strips than in crop areas adjacent to onion control strips ($p<0.05$). In general,

activity-densities of captured carabids were higher throughout the entire trapping period, but this is not the case when comparing trap catches within refuge strips. Trap catches were significantly higher within the refuge strips at the beginning of the season and then numbers start to decline (Figure 14B). This same trend was also observed in 2000 (Figure 11B). Although there were differences observed between insecticide treatments, no general trends or patterns could be concluded when examining the trap catches at different times during the trapping period (Figure 16A-C). Significantly more beetles were captured at the beginning of August within plots containing cyromazine treated crop areas than in untreated or chlorpyrifos treated plots ($p<0.05$) (Figure 16C). *P. melanarius* and *B. quadrimaculatum* were the only two species that exhibited differences at specific trap periods during the 2001 field season. *B. quadrimaculatum* activity-density was generally higher within the onion control strip for almost the entire season (Figure 17), while *P. melanarius* activity-density was generally greater in systems that contained refuge strips (Figure 18).

Entire plots containing refuge strips had significantly more carabid species captured than systems containing onion control strips ($p<0.05$) (Table 14). Insecticide treatments had no effect on the total number of species captured ($p>0.05$). However, there was significant interaction between refuge and insecticide treatments. Trap catches from the entire plot comprised of refuge strips and crop areas treated with cyromazine had significantly more species than systems comprised of onion control strips and crop areas treated with chlorpyrifos ($p<0.05$) (Table 14). There were no significant differences observed between the other treatment combinations ($p>0.05$). Refuge strips exhibited significantly greater diversity (greater H' value) than the onion control strips ($p<0.05$)

(Table 15); there were no other differences observed for insecticide effects or interaction between refuge and insecticide effects ($p>0.05$).

Both refuge and insecticide treatments significantly affected the mean number of onions and harvested weight ($p<0.05$) (Table 16). Number of small (<4 cm diam.) and medium (4-10 cm diam.) sized onions were higher in plots with onion control strips than in plots with refuge strips ($p<0.05$) (Figure 19A). Harvested weights were only marginally higher ($p=0.09$) for small sized onions in plots containing onion control strips (Figure 19B). Plots treated with chlorpyrifos had significantly higher onion numbers and weights for small and medium sized onions than in plots cyromazine or untreated (control) plots and the total number of onions harvested were also significantly higher in the chlorpyrifos treated plots ($p<0.05$) (Figure 20A-B). There were no differences observed between the untreated (control) or cyromazine treated plots ($p<0.05$) (Table 16). In a field study comparing cyromazine, chlorpyrifos and untreated onions, no significant onion maggot damage was present at the MSU Muck Research Farm during 2001 (McCornack et al. 2001).

My results indicate that carabid populations can be manipulated with refuge strip habitats and certain species of carabids (*A. aenea* and *E. anceps*) can be conserved with the use of a low spectrum insecticide like cyromazine. It is well documented that carabids are very sensitive to disturbances in the environment and are easily affected by cultivation practices (Kromp 1999). It has been shown that refuge strips can increase the numbers and activity of carabids and other biological control agents in corn and soybeans (Carmona 1998, Menalled and Landis 1997, Lee et al. 2001). Critchely (1972) showed carabids that burrowed into soil treated with insecticides were more susceptible than

those that didn't burrow. Brust et al. (1985) correlated an increase in cutworm-damage to corn plants with a decrease in predator densities in insecticide treated plots. Application of an insecticide only affected a couple of species captured in the onion field (*A. aenea* and *E. anceps*) but harvest weights were higher in chlorpyrifos treated plots. Future studies that would address the issue of plant damage or stand loss (% onion damage) during the growing season would help explain this relationship. However, in this field study, if the onion maggot population at the MSU Muck Soils Research Farm was high, I would expect biological control to be reduced due in chlorpyrifos treated plots to high insecticide activity. This does not appear to be the case. I saw greater beetle numbers and lower harvest weights and onion numbers in plots treated with refuges than in plots without refuge strips.

Michigan onion growers must be able to effectively and economically control onion maggot to remain in business. Registration of new and effective chemicals is just one part of this task. There is a need for an effective, safe, and environmentally sound pest management system that includes all aspects of integrated pest management (chemical, biological, cultural, etc.), so growers can prevent future development of insecticide resistance and reduce the potential impact of onion maggot on onion yields. Currently, there are few management options available to growers. Development of new control tactics and increased effectiveness of biological control agents such as carabids will benefit growers by increasing the stability of the onion production system while reducing the risks associated with crop loss. Conserving natural enemies natural enemies in an agroecosystem is an effective way to increase biological control in the targeted system (Hull and Beers 1985). As the role conservation biological control in an onion

agroecosystem is better defined, the use of carabids for control of onion maggot may become a crucial component to onion pest management programs.

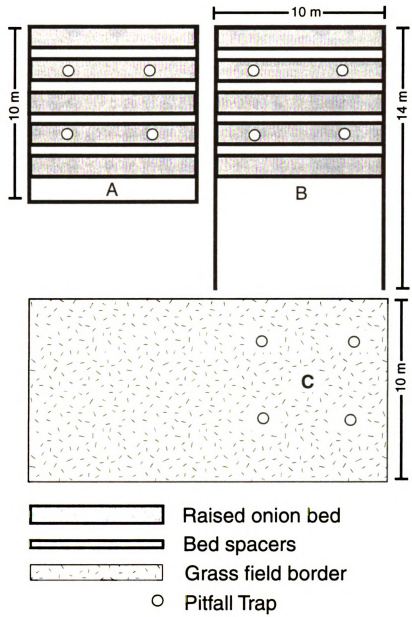


Figure 4. Plot layout for evaluating the effects of a grassy field edge on carabid beetle populations in 1999 at the MSU Muck Soils Research Farm in Clinton County, MI. A) Full-enclosure plot, B) partial-enclosure plot, and C) a grassy field edge.

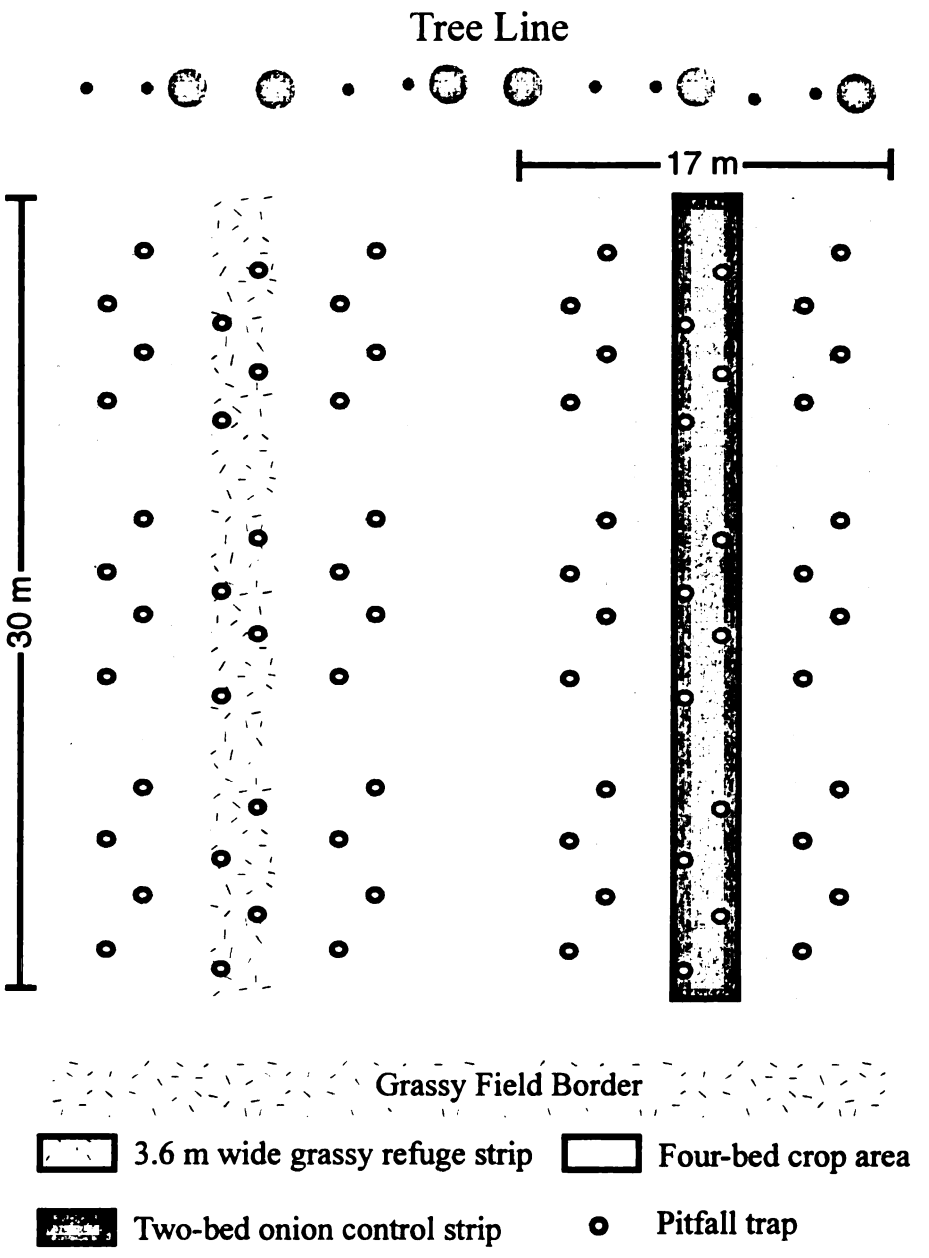


Figure 5. Plot layout for evaluating the effects of newly established refuge strips on carabid beetle populations at the MSU Muck Soils Research Farm in Clinton County, MI in 2000.

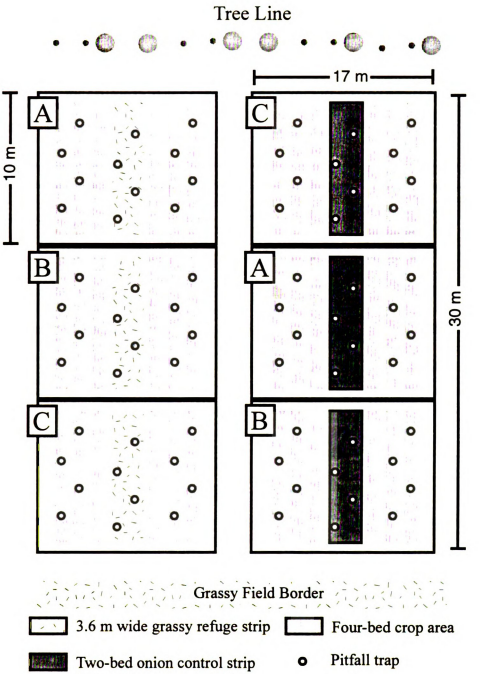


Figure 6. Generalized plot layout of one block for evaluating the effects of established refuge strips, insecticide treatments (A-untreated, B-cyromazine, and C-chlorpyrifos) and interaction between refuge and insecticide on carabid beetle populations at the MSU Muck Soils Research Farm, Clinton County MI in 2001. Pitfall traps were used to monitor beetle activity-densities.

Table 3. Analysis of variance for activity-densities of common carabid species captured in enclosure plots at the Michigan State University Muck Soils Research Farm, Clinton County MI in 1999. Tests for enclosure effects on carabid activity-densities are shown.

Species	d.f.	F	P
Amara aenea	2,6	73.03	<0.0001
Harpalus pennsylvanicus	2,6	9.77	0.013
Poecilus chalcites	2,6	25.51	0.0012
Pterostichus melanarius	2,6	42.39	0.0003
Total	2,6	34.55	0.0005

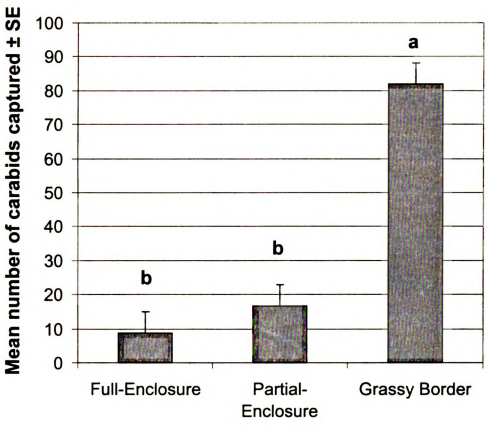


Figure 7. Grassy field border effects on all carabids captured within an onion field in 1999. Mean number of carabids captured during the trapping period are shown. Means with a different letter are significantly different: Fisher's protected LSD test, ($P<0.05$).

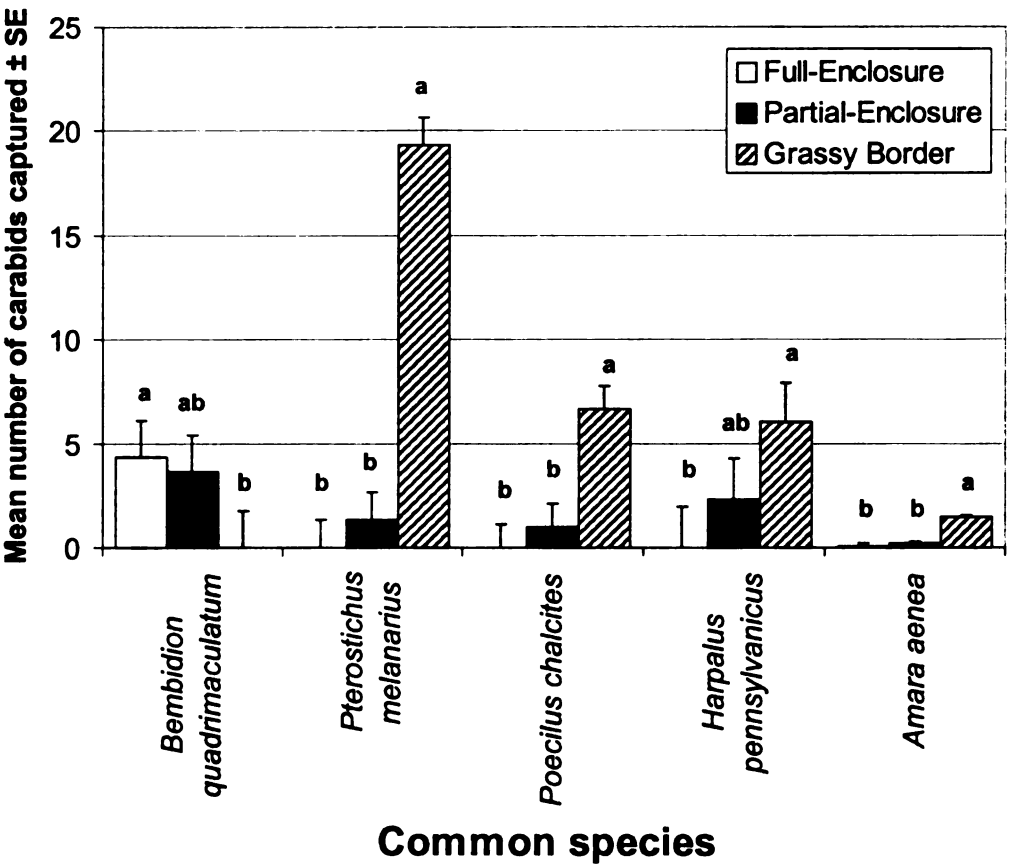


Figure 8. Grassy field border effects on trap catch of common carabid species within an onion field in 1999. Mean number of carabids captured during the trapping period are shown. Means within a species followed by a different letter are significantly different: Fisher's protected LSD test, ($P<0.05$).

Table 4. Carabid species captured during the 2000 (30 May-18 September) and 2001 (6 June-17 September) trapping periods at the Michigan State University Muck Soils Research Farm, Clinton County MI.

	Year 2000		Year 2001	
Carabidae	**Number**	**%Total**	**Number**	**%Total**
Carnivores				
Poecilus chalcites (Say)	627	10.1%	147	5.0%
Bembidion quadrimaculatum L.	519	8.4%	336	11.5%
Pterostichus melanarius (Ill.)	397	6.4%	114	3.9%
Poecilus lucublandus (Say)	173	2.8%	44	1.5%
Chlaenius tricolor Dej.	21	0.3%	0	0.0%
Chlaenius sericeus (Forster)	13	0.2%	0	0.0%
Scarites quadriceps Chd.	8	0.1%	0	0.0%
Bembidion inaequale Say	6	0.1%	2	0.1%
Agonum cupripenne (Say)	0	0.0%	5	0.2%

Table 4 (cont'd).

Agonum placidum (Say)	0	0.0%	4	0.1%
Phytophagous or Omnivorous				
Anisodactylus sanctaecrusis (F.)	1279	20.6%	334	11.5%
Amara aenea (DeG.)	841	13.6%	672	23.1%
Stenolophus comma (F.)	677	10.9%	459	15.8%
Clivina impresifrons LeC.	85	1.4%	13	0.4%
Harpalus herbivagus (Say)	76	1.2%	12	0.4%
Harpalus affinis (Schr.)	59	1.0%	379	13.0%
Harpalus pennsylvanicus (DeG.)	42	0.7%	20	0.7%
Pterostichus permundus LeC.	33	0.5%	21	0.7%
Anisodactylus rusticus (Say)	0	0.0%	2	0.1%
Unknown Diets				
Elaphropus anceps (LeC.)	539	8.7%	224	7.7%

Table 4 (cont'd).

Stenolophus ochropezus (Say)	334	5.4%	57	2.0%
Bembidion versicolor (LeC.)	135	2.2%	29	1.0%
Clivinia bipustulata (F.)	33	0.5%	10	0.3%
Amara obesa	12	0.2%	5	0.2%
Bembidion patruele Dejean	6	0.1%	1	0.0%
Bembidion rapidum (LeConte)	196	3.2%	7	0.2%
Dyschirius integer (LeConte)	83	1.3%	14	0.5%
Total Number of Species	25		25	
Total:	6194		2911	

Table 5. Analysis of variance for traps catches within the entire plot at the MSU Muck Soils Research Farm, Clinton Co MI in 2000.

Source	d.f.	SS	MS	F	p-value
Total	287	9.25			
Block	3	1.569	0.523		
Refuge Effect	1	0.018	0.018	0.15	0.72
Experimental Error	3	0.353	0.118		
Observational Error	280	7.31	0.026		

Table 6. Analysis of variance for trap catches within the crop areas adjacent to refuge or control strips at the MSU Muck Soils Research Farm, Clinton Co MI in 2000.

Source	d.f.	SS	MS	F	p-value
Total	191	5.981			
Block	3	1.181	0.394		
Refuge Effect	1	0.131	0.131	1.02	0.39
Experimental Error	3	0.385	0.128		
Observational Error	184	4.284	0.023		

Table 7. Analysis of variance for traps within refuge or control strips at the MSU Muck Soils Research Farm, Clinton Co MI in 2000.

Source	d.f.	SS	MS	F	p-value
Total	95	3.243			
Block	3	0.419	0.14		
Refuge Effect	1	0.078	0.078	0.81	0.44
Experimental Error	3	0.291	0.097		
Observational Error	88	2.455	0.028		

Table 8. Per trap analysis of variance for activity-densities of common carabid species captured in 2000. Tests for refuge effects on carabid activity-densities within refuge or control strips, within the adjacent crop area, or the entire system is shown.

Species	Pitfall Trap Location	d.f.	F	P
Amara aenea	Treatment Strip	1,3	2.04	0.25
	Adjacent Crop Area	1,3	1.56	0.30
	Entire Plot	1,3	0.30	0.62
Anisodactylus sanctaecrucis	Treatment Strip	1,3	0.41	0.57
	Adjacent Crop Area	1,3	0.95	0.40
	Entire Plot	1,3	0.09	0.78
Bembidion quadrimaculatum	Treatment Strip	1,3	8.03	0.07
	Adjacent Crop Area	1,3	0.89	0.42
	Entire Plot	1,3	1.01	0.39
Elanphrus anceps	Treatment Strip	1,3	22.64	0.02
	Adjacent Crop Area	1,3	0.44	0.56
	Entire Plot	1,3	11.81	0.04

Table 8 (cont'd).

Poecilus chalciites	Treatment Strip	1,3	2.28	0.23
	Adjacent Crop Area	1,3	9.57	0.050
	Entire Plot	1,3	1.40	0.32
Poecilus lucublandis	Treatment Strip	1,3	0.20	0.69
Pterostichus melanarius	Treatment Strip	1,3	40.19	0.01
	Adjacent Crop Area	1,3	0.51	0.53
	Entire Plot	1,3	4.64	0.12
Stenolophus comma	Treatment Strip	1,3	0.45	0.55
	Adjacent Crop Area	1,3	0.19	0.69
	Entire Plot	1,3	0.35	0.59
Stenolophus ochrapezus	Treatment Strip	1,3	0.46	0.54
	Adjacent Crop Area	1,3	4.03	0.14
	Entire Plot	1,3	1.49	0.31
Total Carabids	Treatment Strip	1,3	0.81	0.44

Table 8 (cont'd).

Adjacent Crop Area	1,3	1.02	0.39
Entire Plot	1,3	0.15	0.72

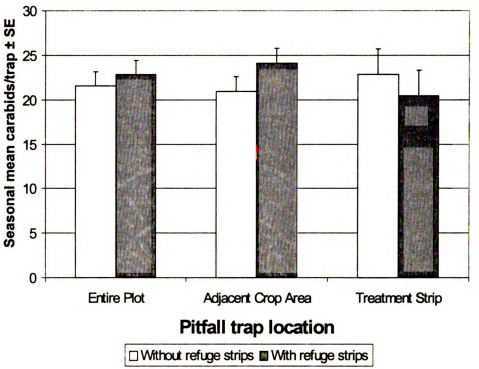
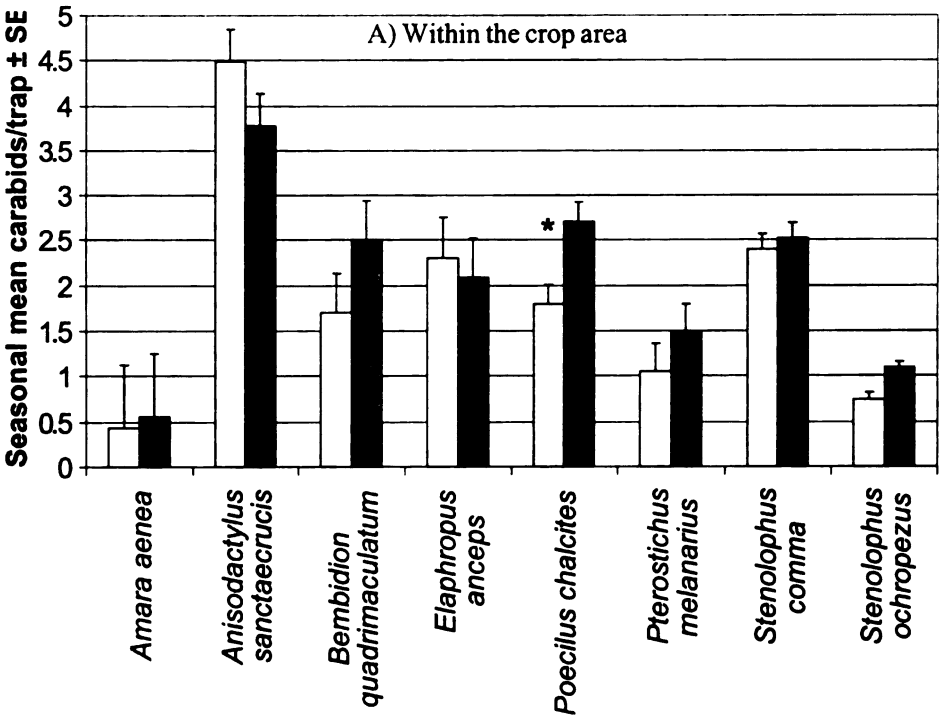
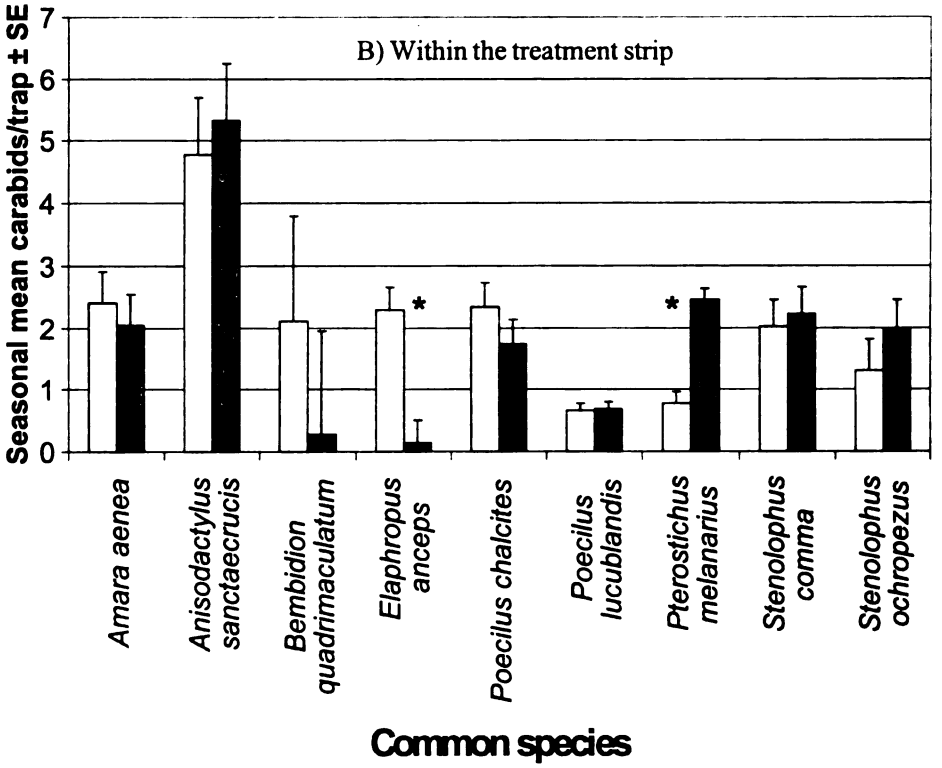


Figure 9. Seasonal activity-density for all carabid beetles captured per trap during the 2000 field season. *Means within a pitfall trap location are statistically significant: Fisher's protected LSD test, ($P<0.05$).


A) Within the crop area
Seasonal mean carabids/trap ± SE
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
*
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Poecilus chalcites
Pterostichus melanarius
Stenolophus comma
Stenolophus ochropezus


B) Within the treatment strip
Seasonal mean carabids/trap ± SE
7
6
5
4
3
2
1
0
*
*
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Poecilus chalcites
Poecilus lucublandis
Pterostichus melanarius
Stenolophus comma
Stenolophus ochropezus
Common species

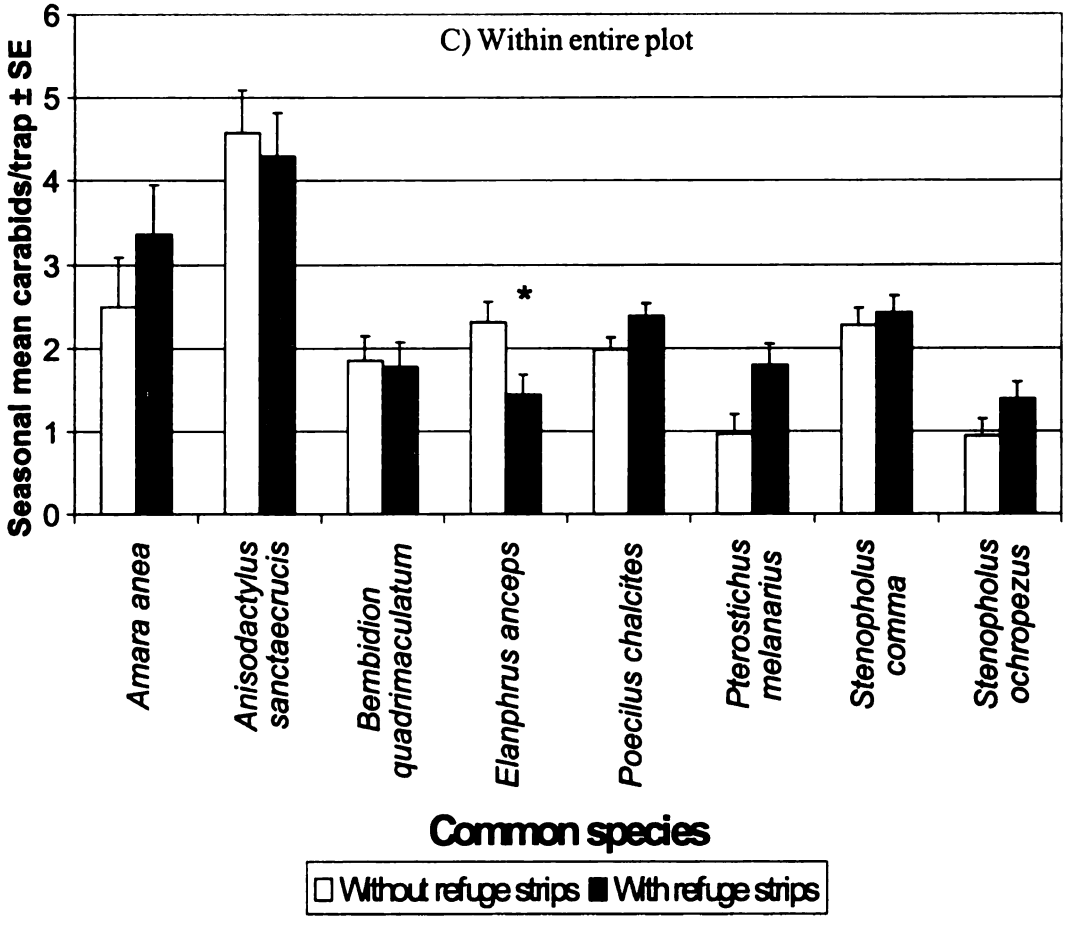
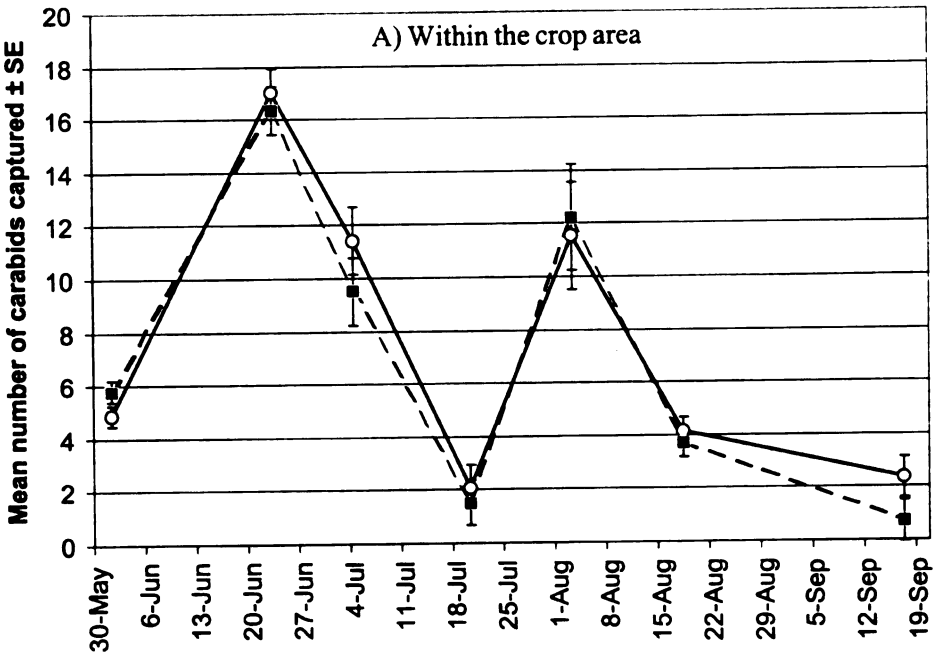
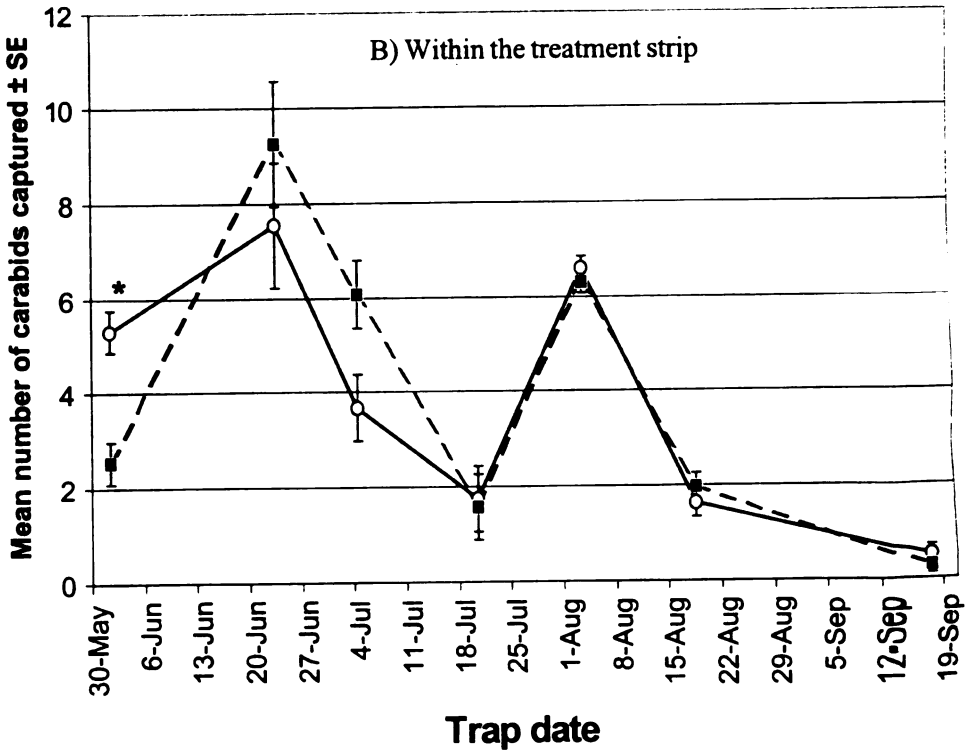


Figure 10. Grassy refuge effects on carabid activity-densities of common carabid species captured within an onion field in 2000. Mean number of carabids captured within a location are shown: A) within the crop area, B) within the refuge strip or onion control strip, and C) within the entire plot. *Means within a species are statistically significant: Fisher's protected LSD test, ($P<0.05$).


A) Within the crop area
Mean number of carabids captured ± SE
0
2
4
6
8
10
12
14
16
18
20
30-May
6-Jun
13-Jun
20-Jun
27-Jun
4-Jul
11-Jul
18-Jul
25-Jul
1-Aug
8-Aug
15-Aug
22-Aug
29-Aug
5-Sep
12-Sep
19-Sep


B) Within the treatment strip
Mean number of carabids captured ± SE
0
2
4
6
8
10
12
*
30-May
6-Jun
13-Jun
20-Jun
27-Jun
4-Jul
11-Jul
18-Jul
25-Jul
1-Aug
8-Aug
15-Aug
22-Aug
29-Aug
5-Sep
12-Sep
19-Sep
Trap date

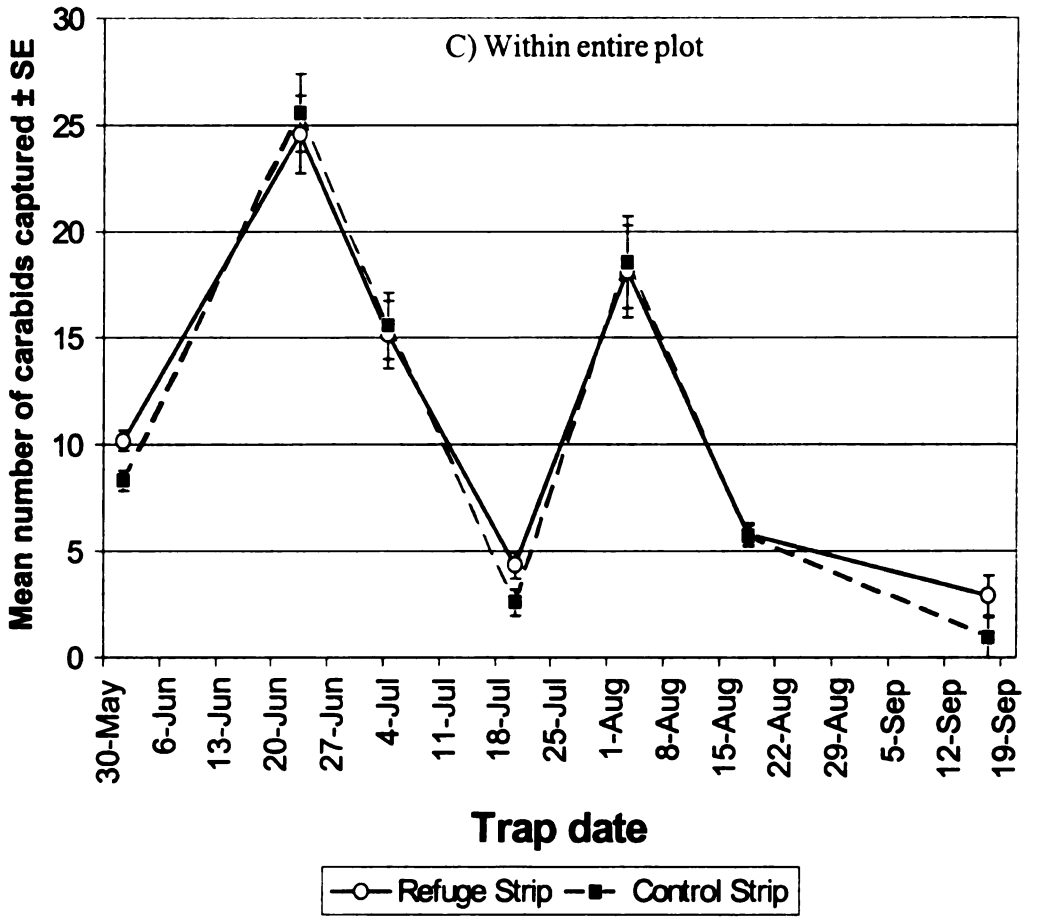


Figure 11. Grassy refuge effects on activity-densities of carabids captured throughout the 2000 trapping period (30 May-18 September) within an onion field. Mean number of carabids captured per trap date: A) within adjacent crop area, B) within the refuge or onion control strips, and C) within the entire plot. *Means within a trapping period are statistically significant: Fisher's protected LSD test, ($P<0.05$).

Table 9. Analysis of variance for traps catches within the entire plot at the MSU Muck Soils Research Farm, Clinton Co MI in 2001.

Source	d.f.	SS	MS	F	p-value
Total	23	959.53			
Block	3	609.27	203.09		
Refuge	1	152.09	152.09	7.74	0.07
Block*Refuge	3	58.95	19.65		
Insecticide	2	30.12	15.06	2.06	0.17
Refuge*Insecticide	2	21.21	10.61	1.45	0.27
Error	12	87.88	7.32		

Table 10. Analysis of variance for trap catches within the crop areas adjacent to refuge or control strips at the MSU Muck Soils Research Farm, Clinton Co MI in 2001.

Source	d.f.	SS	MS	F	p-value
Total	23	1498			
Block	3	884.27	294.76		
Refuge	1	373.08	373.08	32.11	0.01
Block*Refuge	3	34.85	11.62		
Insecticide	2	41.06	20.53	1.77	0.21
Refuge*Insecticide	2	25.33	12.67	1.09	0.37
Error	12	139.36	11.61		

Table 11. Analysis of variance for traps within refuge or control strips at the MSU Muck Soils Research Farm, Clinton Co MI in 2001.

Source	d.f.	SS	MS	F	p-value
Total	23	546.83			
Block	3	226.65	75.55		
Refuge	1	2.67	2.67	0.04	0.86
Block*Refuge	3	205.69	68.56		
Insecticide	2	24.54	12.27	2.02	0.18
Refuge*Insecticide	2	14.47	7.23	1.19	0.34
Error	12	72.82	6.07		

Table 12. Analysis of variance for activity-densities of common carabid species captured in refuge and insecticide treated plots in 2001. Tests for refuge, insecticide, and refuge*insecticide effects on carabid activity-densities within refuge or control strips, within the adjacent crop area, or the entire system are shown.

Species	Pitfall Trap Location	Effect	d.f.	F	P
Amara aenea	Refuge or Control Strip	refuge	1,15	0.09	0.79
		insecticide	2,15	3.52	0.03
		refuge*insecticide	2,15	0.72	0.49
	Adjacent Crop Area	refuge	1,15	25.45	0.02
		insecticide	2,15	0.30	0.74
		refuge*insecticide	2,15	0.10	0.90
	Entire System	refuge	1,15	23.22	0.02
		insecticide	2,15	0.30	0.74
		refuge*insecticide	2,15	0.36	0.70
Anisodactylus sanctaecrucis	Refuge or Control Strip	refuge	1,15	3.68	0.15
		insecticide	2,15	0.10	0.90

Table 12 (cont'd).

		refuge*insecticide	2,15	2.25	0.11
	Adjacent Crop Area	refuge	1,15	89.34	0.003
		insecticide	2,15	0.40	0.67
		refuge*insecticide	2,15	0.64	0.53
	Entire System	refuge	1,15	44.00	0.01
		insecticide	2,15	0.31	0.74
		refuge*insecticide	2,15	0.18	0.84
Bembidion quadrimaculatum	Refuge or Control Strip	refuge	1,15	2.48	0.21
		insecticide	2,15	2.24	0.11
		refuge*insecticide	2,15	0.60	0.55
	Adjacent Crop Area	refuge	1,15	14.48	0.03
		insecticide	2,15	1.94	0.15
		refuge*insecticide	2,15	2.77	0.07
	Entire System	refuge	1,15	0.14	0.73
		insecticide	2,15	2.09	0.13

Table 12 (cont'd).

		refuge*insecticide	2,15	2.91	0.06
Elanphros anceps	Refuge or Control Strip	refuge	1,15	14.13	0.03
		insecticide	2,15	0.80	0.45
		refuge*insecticide	2,15	3.49	0.04
	Adjacent Crop Area	refuge	1,15	22.03	0.02
		insecticide	2,15	8.43	0.0003
		refuge*insecticide	2,15	3.84	0.02
	Entire System	refuge	1,15	0.01	0.92
		insecticide	2,15	7.48	0.001
		refuge*insecticide	2,15	1.53	0.22
Harpalus affinis	Refuge or Control Strip	refuge	1,15	18.07	0.02
		insecticide	2,15	1.27	0.29
		refuge*insecticide	2,15	0.60	0.55
	Adjacent Crop Area	refuge	1,15	47.22	0.01
		insecticide	2,15	2.26	0.20

Table 12 (cont'd).

		refuge*insecticide	2,15	1.98	0.14
		insecticide	2,15	0.36	0.70
		refuge*insecticide	2,15	0.34	0.72
Stenolophus comma	Refuge or Control Strip	refuge	1,15	2.01	0.25
		insecticide	2,15	1.48	0.23
		refuge*insecticide	2,15	0.13	0.88
	Adjacent Crop Area	refuge	1,15	0.34	0.60
		insecticide	2,15	4.10	0.02
		refuge*insecticide	2,15	0.58	0.56
	Entire System	refuge	1,15	1.07	0.38
		insecticide	2,15	2.02	0.14
		refuge*insecticide	2,15	0.54	0.58
Total Carabids	Refuge or Control Strip	refuge	1,15	0.04	0.86
		insecticide	2,15	2.02	0.17
		refuge*insecticide	2,15	1.19	0.34

Table 12 (cont'd).

Adjacent Crop Area	refuge	1,15	32.11	0.01
	insecticide	2,15	1.77	0.21
	refuge*insecticide	2,15	1.09	0.38
Entire System	refuge	1,15	7.74	0.07
	insecticide	2,15	2.06	0.17
	refuge*insecticide	2,15	1.45	0.23

Table 13. Effects of refuge treatment and insecticide on seasonal mean carabids/trap in 2001.

Trap Location	Treatement	carabids/trap ± SE
Treatment strip	Control Strip + untreated	10.00 ± 1.35
	Control Strip + cyromazine	7.13 ± 1.35
	Control Strip + chlorpyrifos	6.13 ± 1.35
	Refuge Strip + untreated	7.19 ± 1.35
	Refuge Strip + cyromazine	7.94 ± 1.35
	Refuge Strip + chlorpyrifos	6.13 ± 1.35
Adjacent crop areas	Control Strip + untreated	11.08 ± 1.79
	Control Strip + cyromazine	8.88 ± 1.79
	Control Strip + chlorpyrifos	5.83 ± 1.79
	Refuge Strip + untreated	14.25 ± 1.79
	Refuge Strip + cyromazine	18.06 ± 1.79
	Refuge Strip + chlorpyrifos	13.88 ± 1.79
Entire plot	Control Strip + untreated	9.35 ± 1.63
	Control Strip + cyromazine	7.60 ± 1.63
	Control Strip + chlorpyrifos	5.81 ± 1.63
	Refuge Strip + untreated	11.90 ± 1.63
	Refuge Strip + cyromazine	14.69 ± 1.63
	Refuge Strip + chlorpyrifos	11.29 ± 1.63

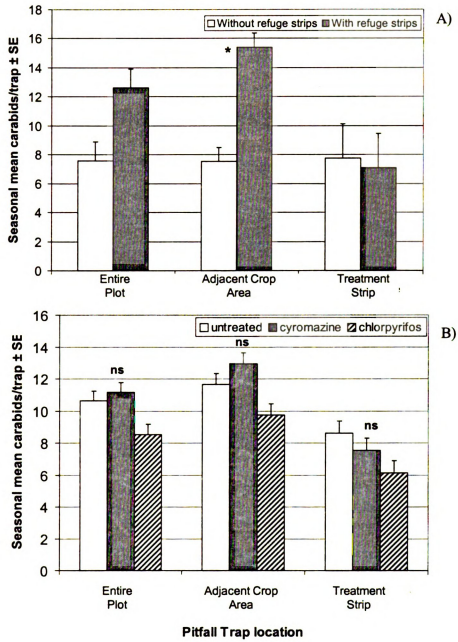
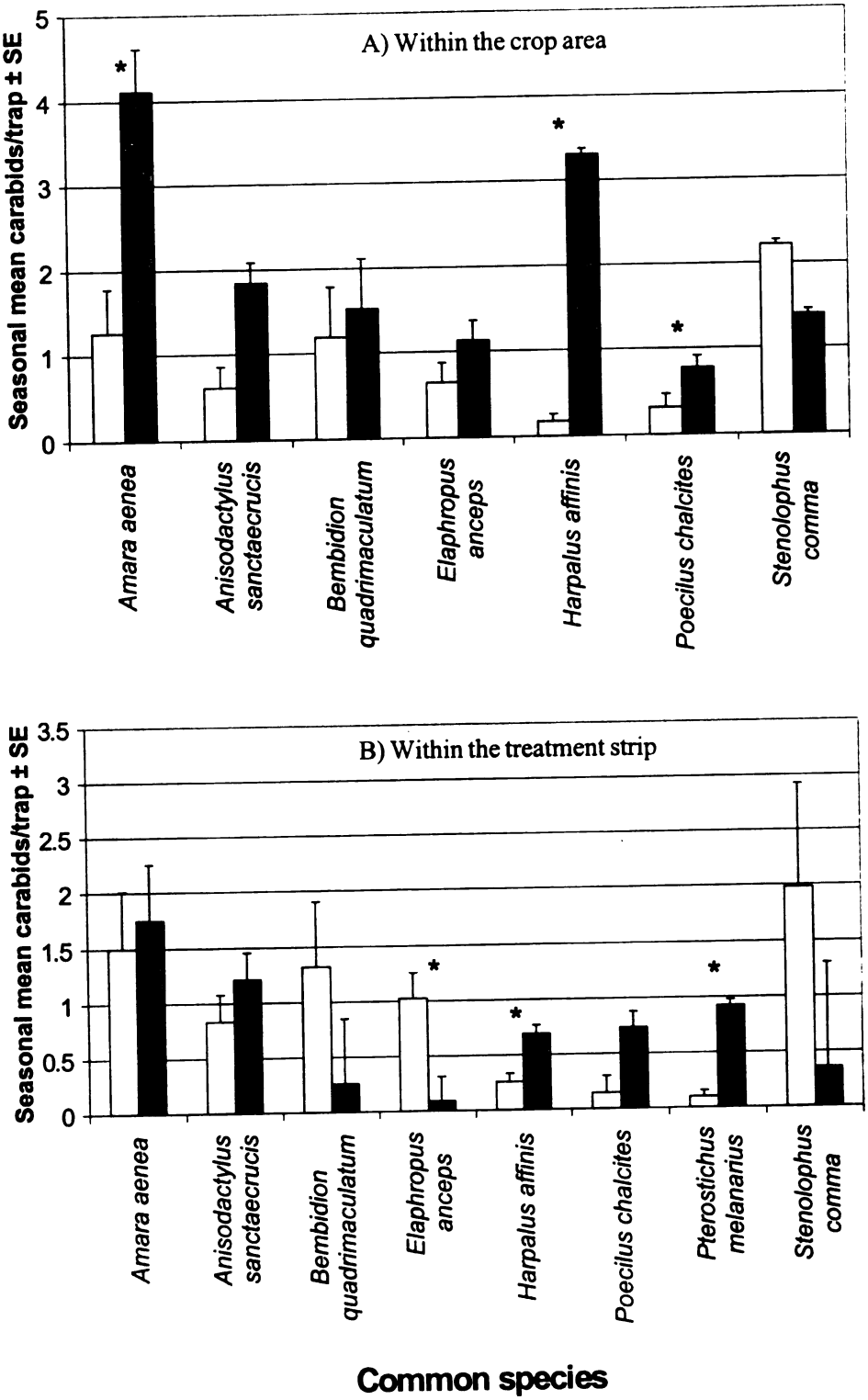


Figure 12. Seasonal mean carabid beetles per trap captured during 2001. A) Effect of refuge strip habitats (*means within a location are statistically significant: Fisher's protected LSD test, $P<0.05$), and B) insecticide treatments on carabid beetles captured in the total plot, within the crop areas, and within the refuge strips (different letters denote significant differences within a location, Fisher's LSD tests, $P<0.05$). ns=no significant differences.


A) Within the crop area
Seasonal mean carabids/trap ± SE
0
1
2
3
4
5
*
*
*
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Harpalus affinis
Poecilus chalcites
Stenolophus comma
B) Within the treatment strip
Seasonal mean carabids/trap ± SE
0
0.5
1
1.5
2
2.5
3
3.5
*
*
*
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Harpalus affinis
Poecilus chalcites
Pterostichus melanarius
Stenolophus comma
Common species

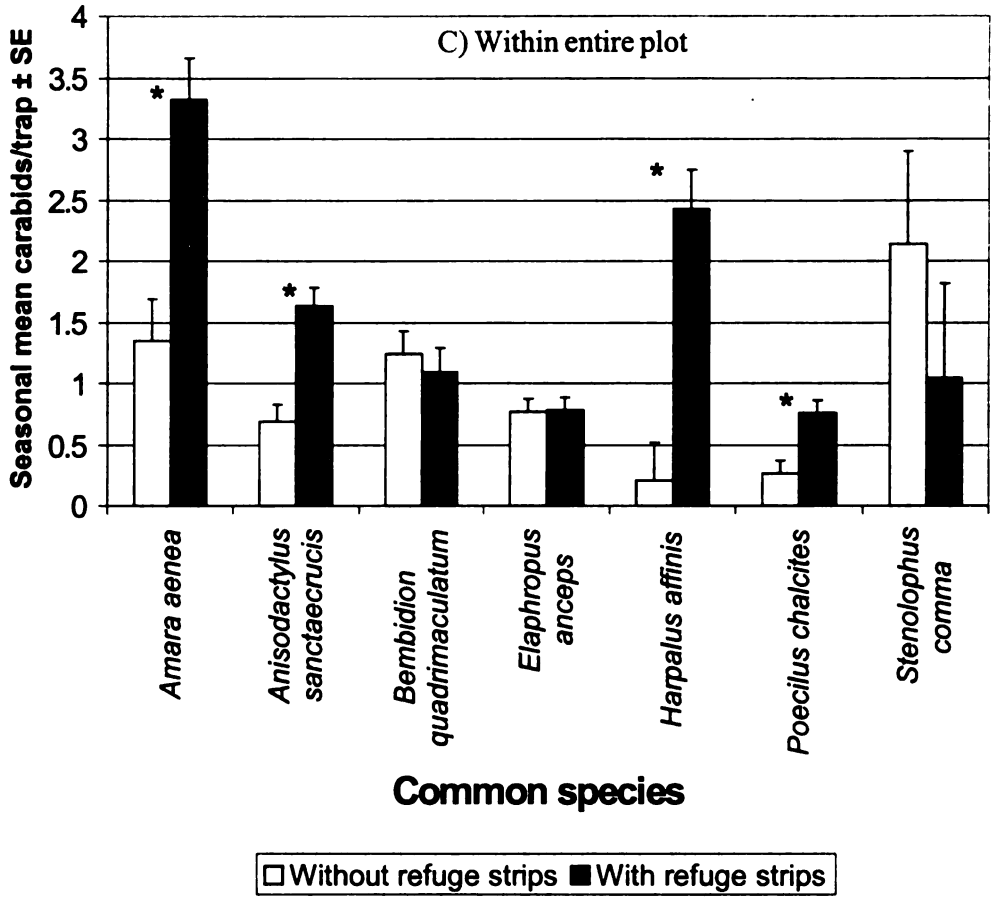
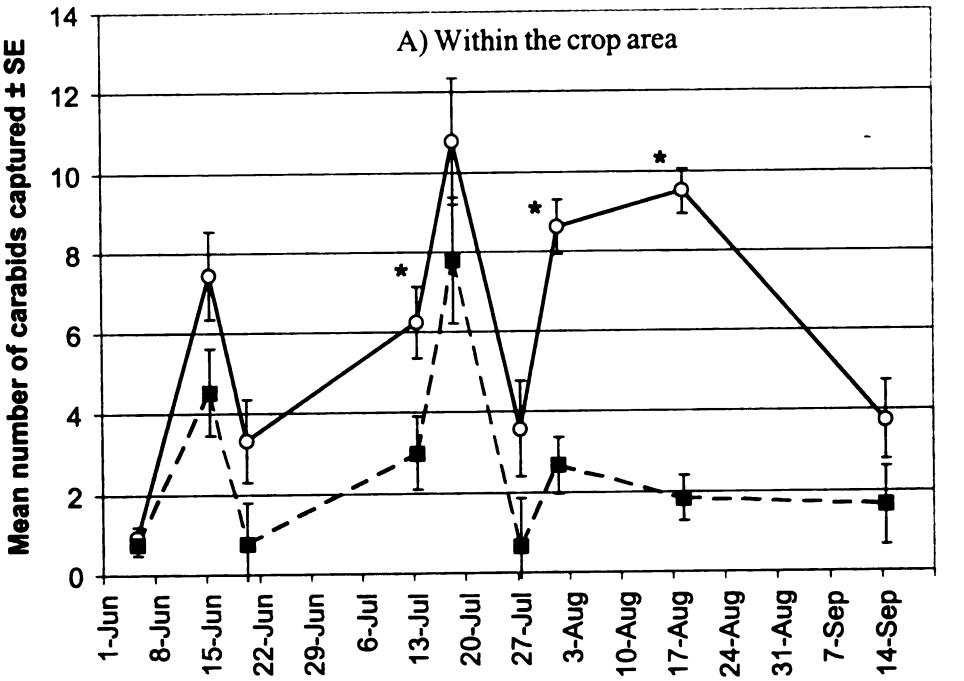
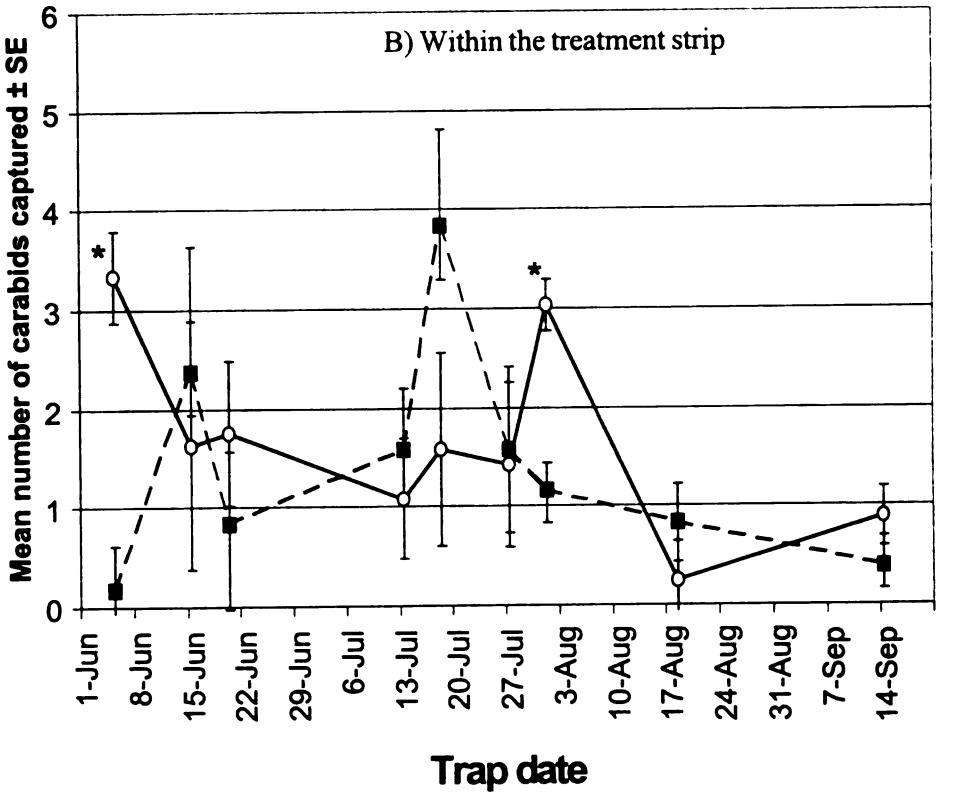


Figure 13. Grassy refuge effects on activity-densities of common carabid species captured within an onion field in 2001. Mean number of carabids captured per location are shown: A) within adjacent crop area, B) within refuge or onion control strips, and C) within the entire plot. *Means within a species are statistically significant: Fisher's protected LSD test, ($P<0.05$).


A) Within the crop area
Mean number of carabids captured ± SE
0
2
4
6
8
10
12
14
1-Jun
8-Jun
15-Jun
22-Jun
29-Jun
6-Jul
13-Jul
20-Jul
27-Jul
3-Aug
10-Aug
17-Aug
24-Aug
31-Aug
7-Sep
14-Sep


B) Within the treatment strip
Mean number of carabids captured ± SE
0
1
2
3
4
5
6
1-Jun
8-Jun
15-Jun
22-Jun
29-Jun
6-Jul
13-Jul
20-Jul
27-Jul
3-Aug
10-Aug
17-Aug
24-Aug
31-Aug
7-Sep
14-Sep
Trap date

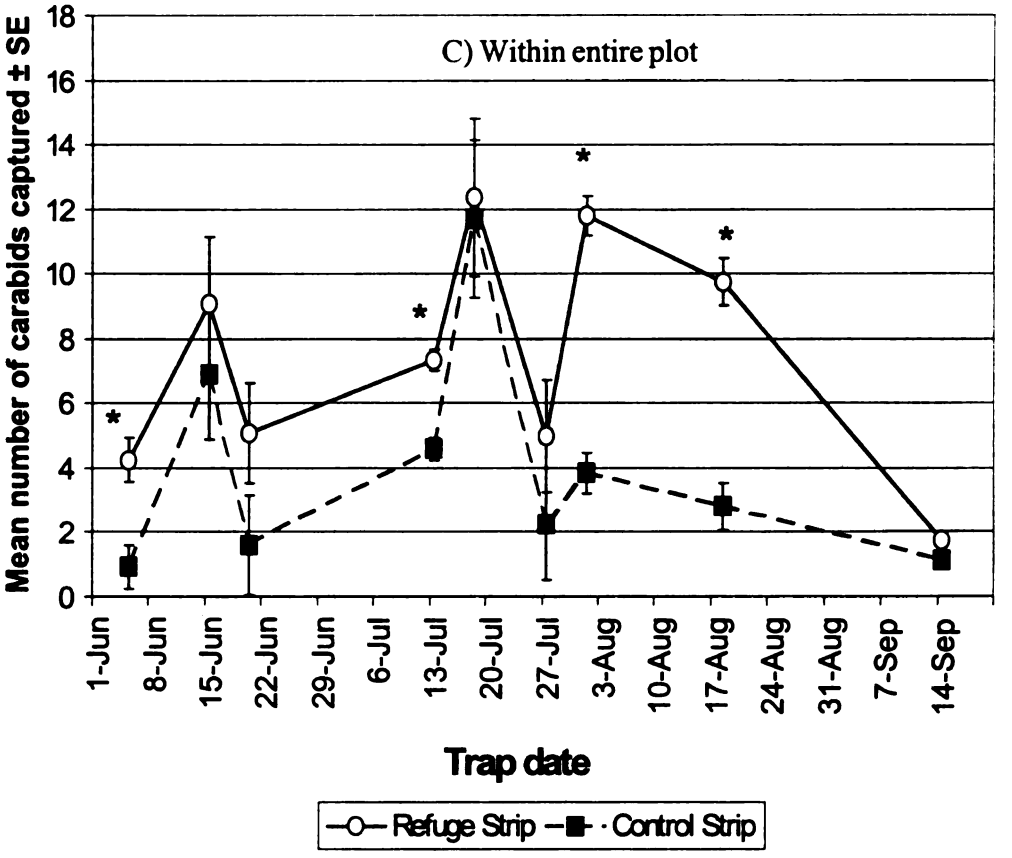
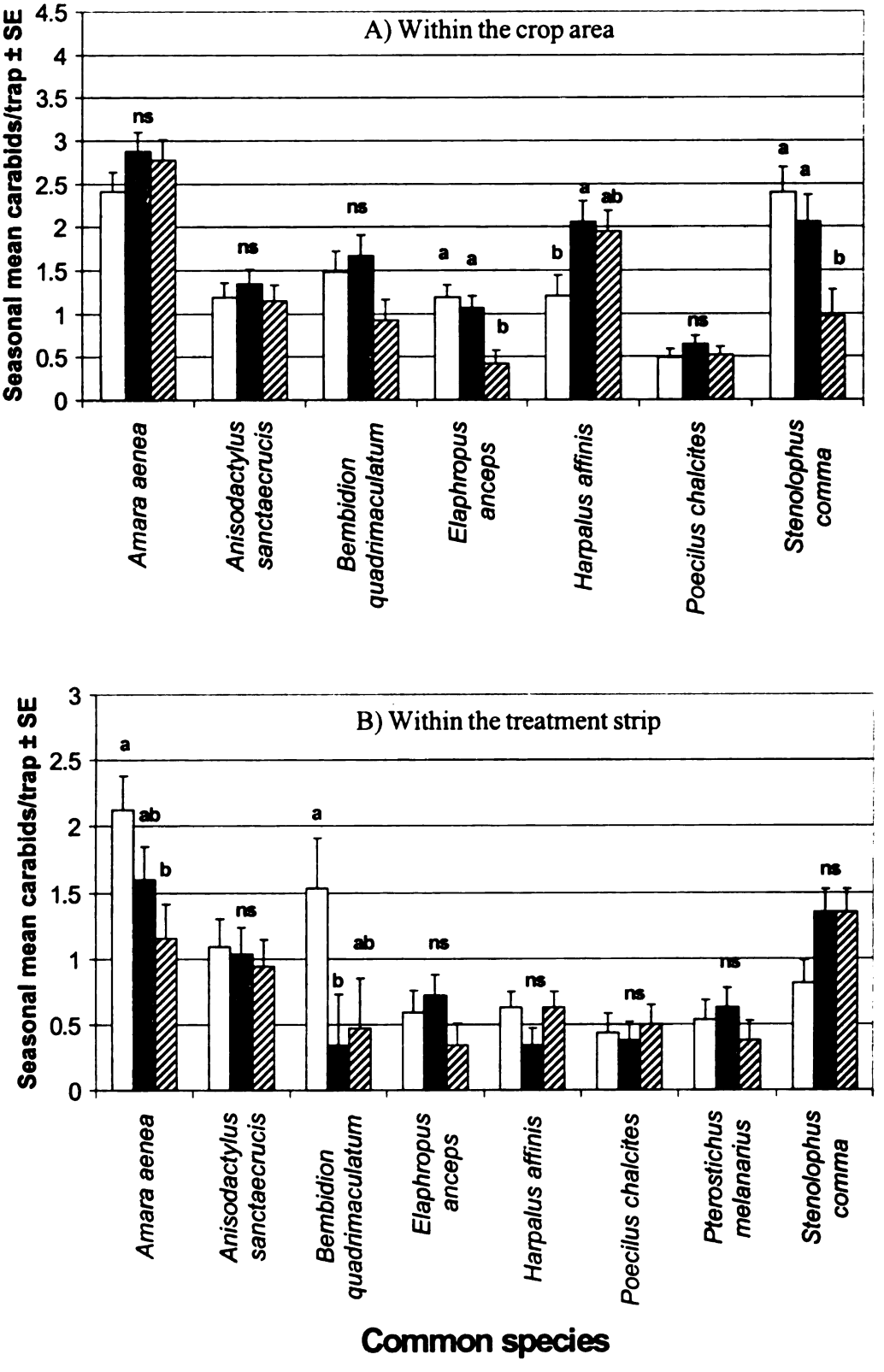


Figure 14. Grassy refuge effects on activity-densities of all carabids captured throughout the 2001 trapping period (6 June - 17 September). Mean number of carabids captured per trap date: A) within adjacent crop area, B) within the refuge or onion control strips, and C) within the entire plot. *Means within a trapping period are statistically significant: Fisher's protected LSD test, ($P<0.05$).


A) Within the crop area
Seasonal mean carabids/trap ± SE
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ns
ns
ns
a
a
b
b
a
ab
ns
a
a
b
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Harpalus affinis
Poecilus chalcites
Stenolophus comma
B) Within the treatment strip
Seasonal mean carabids/trap ± SE
3
2.5
2
1.5
1
0.5
0
a
ab
b
ns
a
b
ab
ns
ns
ns
ns
ns
Amara aenea
Anisodactylus sanctaecrucis
Bembidion quadrimaculatum
Elaphropus anceps
Harpalus affinis
Poecilus chalcites
Pterostichus melanarius
Stenolophus comma
Common species

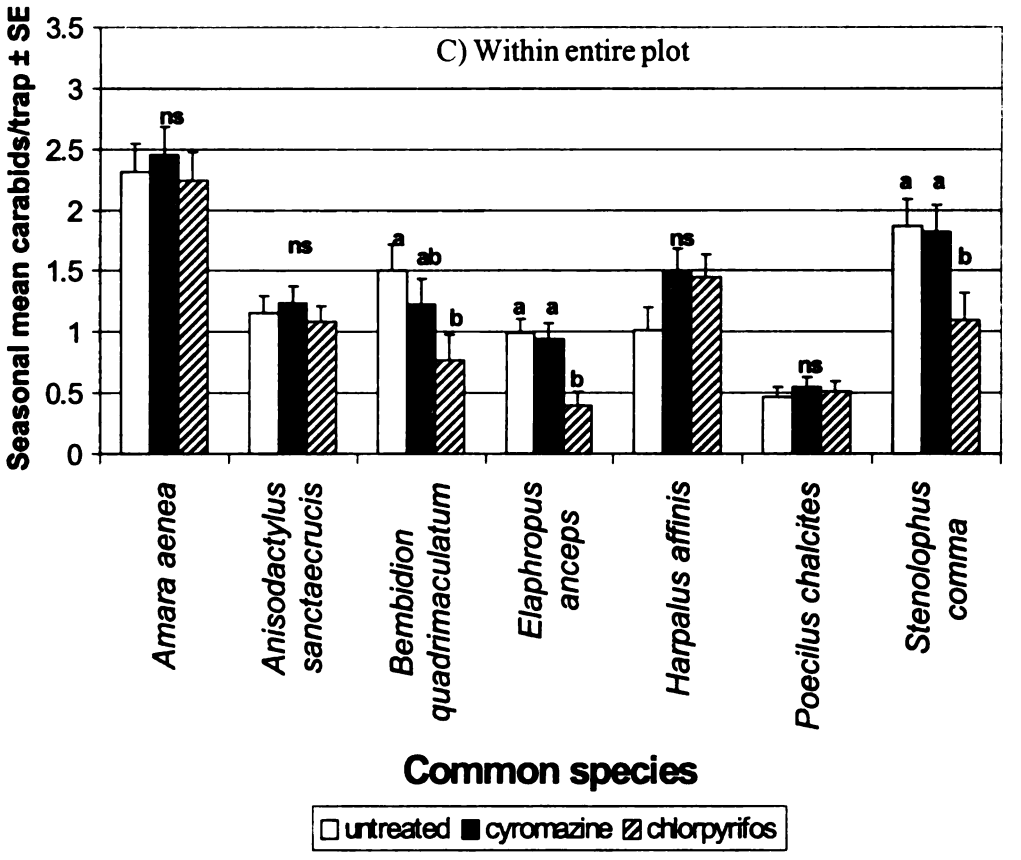
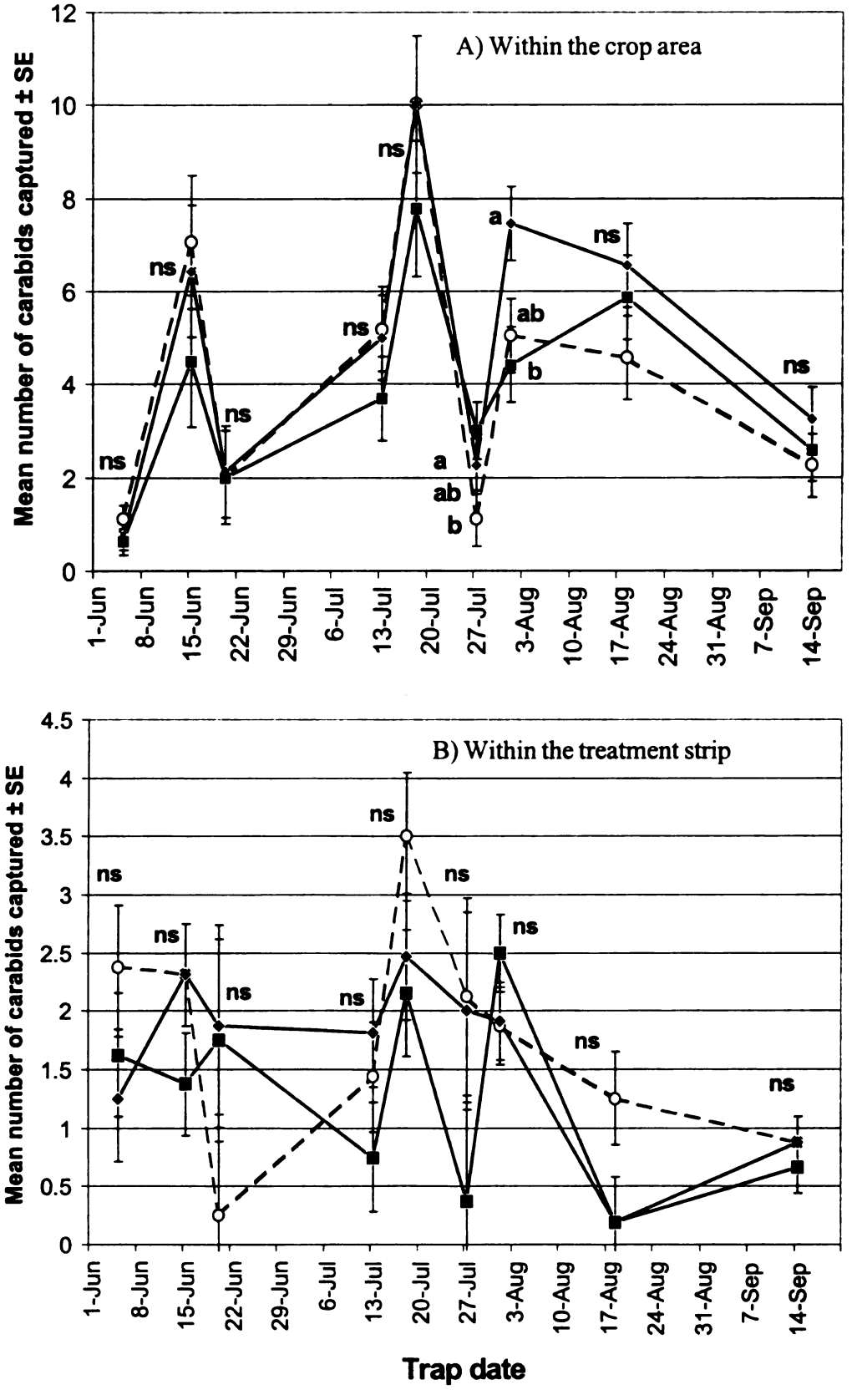


Figure 15. Insecticide effects on activity-densities of common carabid species captured within an onion field in 2001. Mean number of carabids captured per location are shown: A) within adjacent crop area, B) within refuge or onion control strips, and C) within the entire plot. Different letters within a species denote significant differences using Fisher's protected LSD tests, $P<0.05$. ns = no significant differences.


A) Within the crop area
Mean number of carabids captured ± SE
12
10
8
6
4
2
0
ns
ns
ns
ns
ns
a
ab
b
a
ab
b
ns
ns
1-Jun
8-Jun
15-Jun
22-Jun
29-Jun
6-Jul
13-Jul
20-Jul
27-Jul
3-Aug
10-Aug
17-Aug
24-Aug
31-Aug
7-Sep
14-Sep
B) Within the treatment strip
Mean number of carabids captured ± SE
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
ns
ns
ns
ns
ns
ns
ns
ns
ns
1-Jun
8-Jun
15-Jun
22-Jun
29-Jun
6-Jul
13-Jul
20-Jul
27-Jul
3-Aug
10-Aug
17-Aug
24-Aug
31-Aug
7-Sep
14-Sep
Trap date

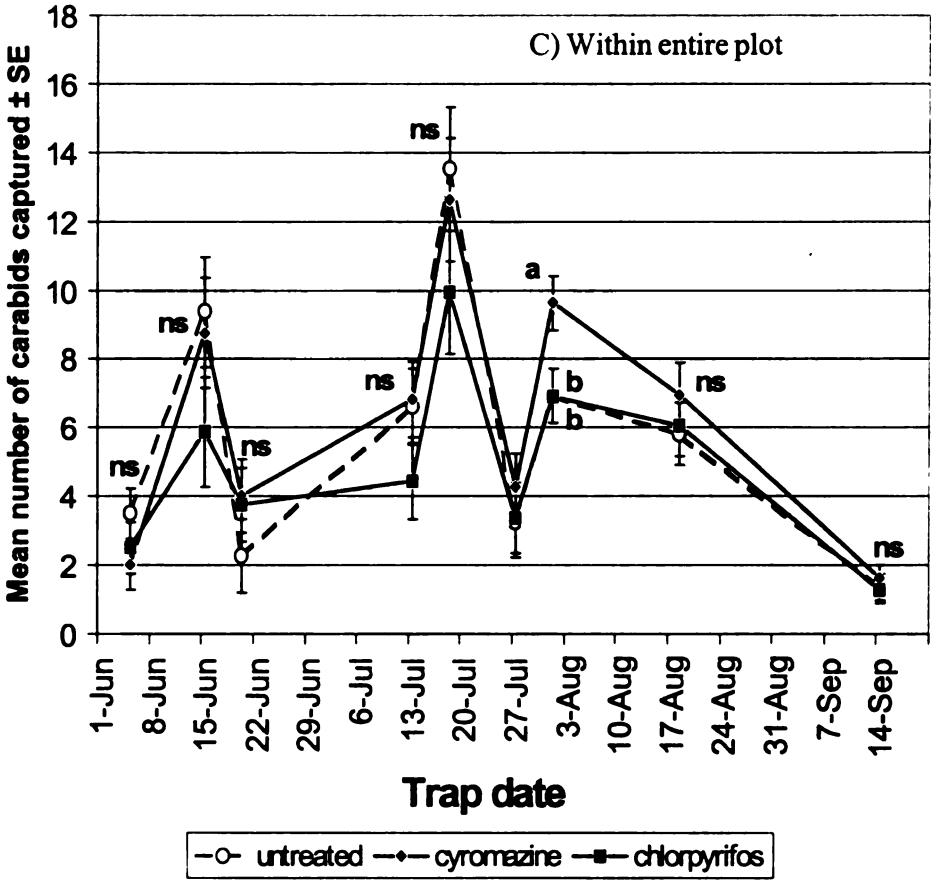


Figure 16. Insecticide effects on on activity-densities of all carabids captured throughout the 2001 trapping period (6 June - 17 September). Mean number of carabids captured per trap date: A) within adjacent crop area, B) within the refuge or onion control strips, and C) within the entire plot. *Means within a trapping period are statistically significant: Fisher's protected LSD test, ($P<0.05$).

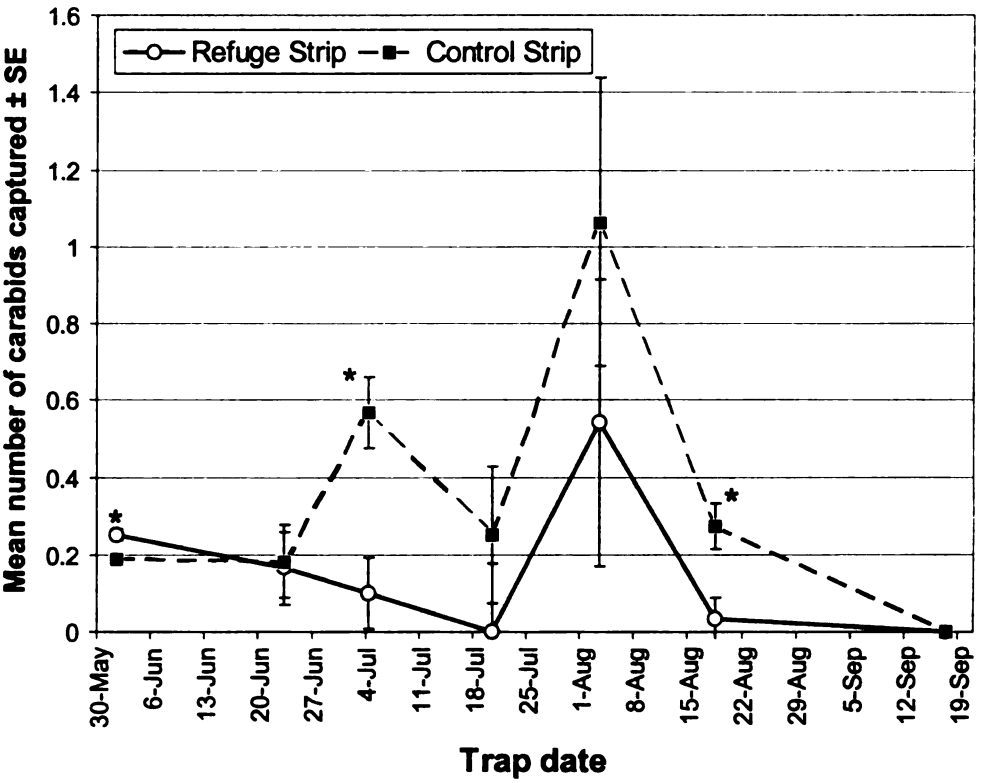


Figure 17. Mean number of *Bembidion quadrimaculatum* L. captured within the refuge strip or onion control strip during the 2001 field season. *Means within a trap date are statistically significant: Fisher's protected LSD test, ($P<0.05$).

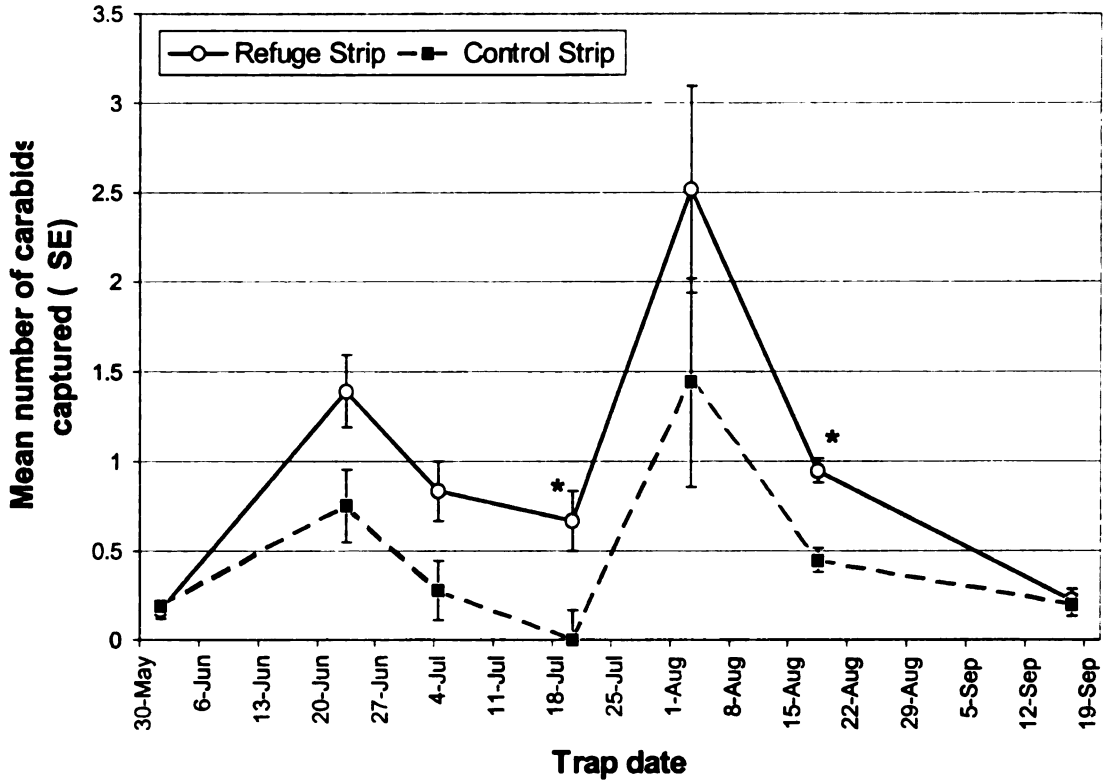


Figure 18. Mean number of *Pterostichus melanarius* (Ill.) captured within the entire plot affected by the presence of refuge or onion control strip during the 2001 field season.

*Means within a trap date are statistically significant: Fisher's protected LSD test, ($P<0.05$).

Table 14. Mean number of species captured per plot within the refuge or control strip, within the adjacent crop area, or within the entire system ! S.E. in 2001. Means for refuge, insecticide, and interaction between refuge*insecticide are shown.

Effect	Trap location	Treatment Factor	Species[1] ± SE
Refuge			
	Within Refuge or Control Strip	Control Strip	7.42 ± 0.67 a
		Refuge Strip	8.92 ± 0.67 a
	Adjacent Crop Area	Control Strip	10.58 ± 0.68 a
		Refuge Strip	12.33 ± 0.68 a
	Entire Plot	Control Strip	11.67 ± 0.63 b
		Refuge Strip	13.58 ± 0.63 a
Insecticide			
	Within Refuge or Control Strip	untreated	8.38 ± 0.83 a
		cyromazine	8.50 ± 0.83 a
		chlorpyrifos	7.63 ± 0.83 a
	Adjacent Crop Area	untreated	11.13 ± 0.83 a

Table 14 (cont'd).

		cyromazine	12.00 ± 0.83 a
		chlorpyrifos	11.25 ± 0.83 a
	Entire Plot	untreated	12.38 ± 0.78 a
		cyromazine	13.63 ± 0.78 a
		chlorpyrifos	11.88 ± 0.78 a
Refuge*Insecticide			
	Within Refuge or Control Strip	Control Strip + untreated	8.50 ± 1.17 ns
		Control Strip + cyromazine	7.75 ± 1.17 ns
		Control Strip + chlorpyrifos	6.00 ± 1.17 ns
		Refuge Strip + untreated	8.25 ± 1.17 ns
		Refuge Strip + cyromazine	9.25 ± 1.17 ns
		Refuge Strip + chlorpyrifos	9.25 ± 1.17 ns
	Adjacent Crop Area	Control Strip + untreated	10.75 ± 1.17 ns
		Control Strip + cyromazine	10.75 ± 1.17 ns
		Control Strip + chlorpyrifos	10.25 ± 1.17 ns

Table 14 (cont'd).

	Refuge Strip + untreated	11.50 ± 1.17	ns
	Refuge Strip + cyromazine	13.25 ± 1.17	ns
	Refuge Strip + chlorpyrifos	12.25 ± 1.17	ns
Entire Plot	Control Strip + untreated	12.00 ± 1.10	ab
	Control Strip + cyromazine	12.25 ± 1.10	ab
	Control Strip + chlorpyrifos	10.75 ± 1.10	b
	Refuge Strip + untreated	12.75 ± 1.10	ab
	Refuge Strip + cyromazine	15.00 ± 1.10	a
	Refuge Strip + chlorpyrifos	13.00 ± 1.10	ab

[1] Mean number of species within a column followed by a different letter are significantly different: Fisher's protected LSD test ($P<0.05$).

Table 15. Shannon Weaver indices (H') for diversity of species captured per plot within the refuge or control strip, within the adjacent crop area, or within the entire system ! S.E. in 2001. Means for refuge, insecticide, and interaction between refuge*insecticide are shown.

Effect	Trap location	Treatment Factor	H' [1] ± SE
Refuge			
	Within Refuge or Control Strip	Control Strip	1.68 ± 0.08 b
		Refuge Strip	1.91 ± 0.08 a
	Adjacent Crop Area	Control Strip	1.95 ± 0.04 a
		Refuge Strip	1.94 ± 0.04 a
	Total Plot	Control Strip	1.98 ± 0.04 a
		Refuge Strip	2.05 ± 0.04 a
Insecticide			
	Within Refuge or Control Strip	untreated	1.85 ± 0.09 a
		cyromazine	1.78 ± 0.09 a
		chlorpyrifos	1.75 ± 0.09 a
	Adjacent Crop Area	untreated	1.95 ± 0.05 a

Table 15 (cont'd).

		cyromazine	1.94 ± 0.05 a
		chlorpyrifos	1.94 ± 0.05 a
	Total Plot	untreated	2.06 ± 0.04 a
		cyromazine	2.02 ± 0.04 a
		chlorpyrifos	1.96 ± 0.04 a
Refuge*Insecticide			
	Within Refuge or Control Strip	Control Strip + untreated	1.88 ± 0.13 ns
		Control Strip + cyromazine	1.66 ± 0.13 ns
		Control Strip + chlorpyrifos	1.50 ± 0.13 ns
		Refuge Strip + untreated	1.82 ± 0.13 ns
		Refuge Strip + cyromazine	1.91 ± 0.13 ns
		Refuge Strip + chlorpyrifos	2.01 ± 0.13 ns
	Adjacent Crop Area	Control Strip + untreated	1.94 ± 0.07 ns
		Control Strip + cyromazine	1.96 ± 0.07 ns
		Control Strip + chlorpyrifos	1.93 ± 0.07 ns

Table 15 (cont'd).

	Refuge Strip + cyromazine	1.93 ± 0.07	ns
	Refuge Strip + chlorpyrifos	1.94 ± 0.07	ns
Total Plot	Control Strip + untreated	2.04 ± 0.06	ns
	Control Strip + cyromazine	2.00 ± 0.06	ns
	Control Strip + chlorpyrifos	1.91 ± 0.06	ns
	Refuge Strip + untreated	2.07 ± 0.06	ns
	Refuge Strip + cyromazine	2.05 ± 0.06	ns
	Refuge Strip + chlorpyrifos	2.02 ± 0.06	ns

[1] Mean H' within a column followed by a different letter are significantly different: Fisher's protected LSD test ($P<0.05$).

Table 16. Analysis of variance of onion harvest weights and number of onions s in 2001. Tests for refuge, insecticide, and refuge*insecticide effects are shown.

Bulb Category	Effect	d.f.	F	P
Small weight (<4 cm)	refuge	1,12	6.01	0.09
	insecticide	2,12	5.88	0.02
	refuge*insecticide	2,12	0.65	0.54
Small count (<4 cm)	refuge	1,12	10.01	0.05
	insecticide	2,12	4.45	0.04
	refuge*insecticide	2,12	0.38	0.69
Medium weight (4-10 cm)	refuge	1,12	2.59	0.21
	insecticide	2,12	3.03	0.09
	refuge*insecticide	2,12	1.21	0.33
Medium count (4-10 cm)	refuge	1,12	5.09	0.11
	insecticide	2,12	3.81	0.05
	refuge*insecticide	2,12	1.21	0.33
Large weight (>10 cm)	refuge	1,12	0.07	0.81
	insecticide	2,12	0.46	0.64
	refuge*insecticide	2,12	2.20	0.15
Large count (>10 cm)	refuge	1,12	0.01	0.91
	insecticide	2,12	0.43	0.66
	refuge*insecticide	2,12	2.31	0.14

Table 16 (cont'd).

Total weight	refuge	1,12	0.75	0.45
	insecticide	2,12	1.67	0.23
	refuge*insecticide	2,12	1.78	0.21
Total count	refuge	1,12	4.00	0.14
	insecticide	2,12	3.91	0.05
	refuge*insecticide	2,12	1.57	0.25

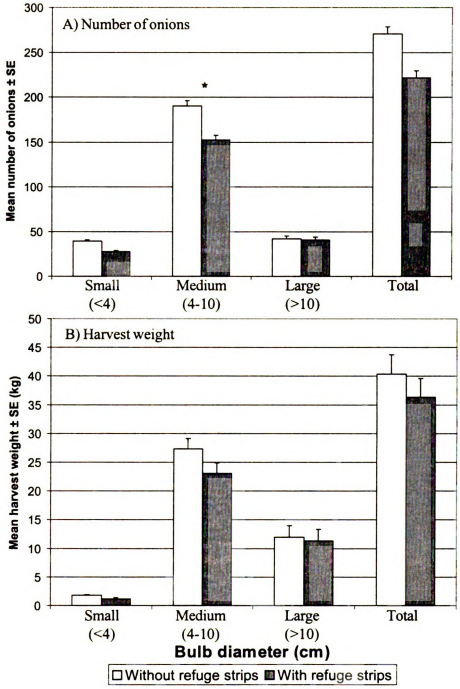


Figure 19. Grassy refuge or control strip effects on onion yield in 2001. A) Number of onions and B) harvest weight. *Mean onion weights are significantly different: Fisher's protected LSD test ($P<0.05$).

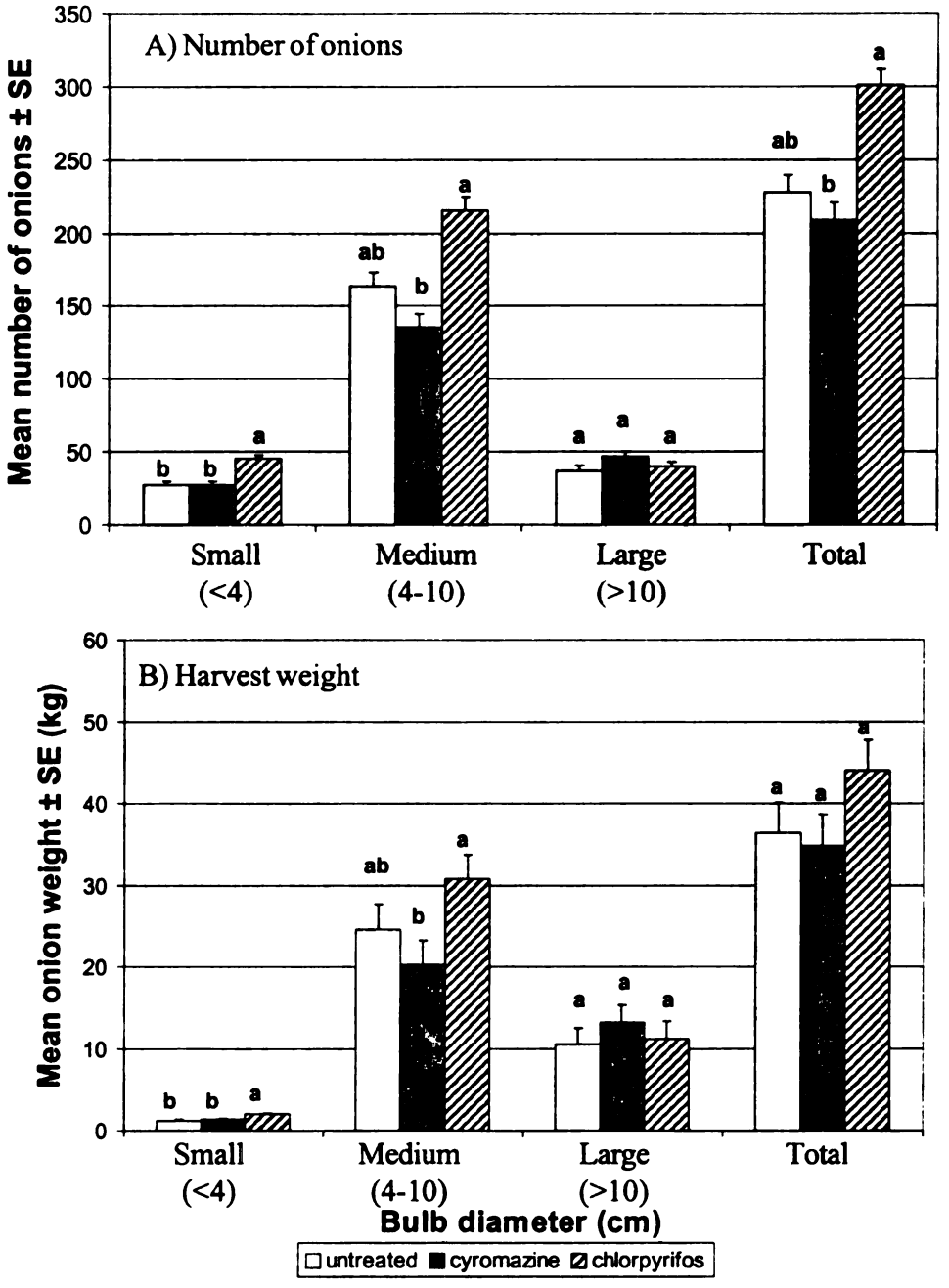


Figure 20. Insecticide treatment effects on onion yield in 2001. A) Number of onions and B) harvest weight. *Mean onion weights with different letters are significantly different: Fisher's protected LSD test ($P<0.05$).

CONCLUSIONS

Despite its economic importance, management options for this pest are limited. Heavy reliance on a single broad-spectrum insecticide by growers generates a cause for concern. Chlorpyrifos has been withdrawn from use in all urban markets and from minor uses in other crops. Even if use on onions is not restricted, development of resistance by onion maggot to chlorpyrifos is a concern. Conservation and augmentation of onion maggot natural enemies requires an integrative approach to onion maggot control. The incorporation of narrow spectrum insecticides can help conserve existing predator populations (Grafius et al. 1997), while preservation of refuge habitats such as field margins and hedgerows (Menalled and Landis 1997) could potentially augment carabid communities in onion fields, thus increasing the importance of biological control. Integrating multiple aspects of onion maggot control will provide a more efficient and sustainable approach to managing onion maggot populations in Michigan onions.

Carabids have significant potential for biological control of onion maggot. In field observations, high activity-densities for *P. chalcites*, *P. lucublandis*, and *P. melanarius* appear to coincide temporally with onion maggot oviposition and larval development (Figure 3). In my experiments I was successful at conserving and augmenting carabid populations in the field. However, this is not enough to merit them as a good biological control agents of onion maggot. Research focused on describing the species that contribute most to the biological control of onion maggot is needed. Finch et al. (1986) found in a related prey species (*D. radicum*) that beetle size was correlated with prey size; medium-sized beetles consumed more eggs than larger beetles. If the important carabid species are egg predators, chances are it will be small in size (i.e such as the predator B. quadrimaculatum). In my field experiments, larger beetles (i.e. *P. melanarius* and *P. chalcites*) were more affected by the presence of refuge strips than smaller species (i.e. *B. quadrimalucatum* and *E. anceps*). Defining the role of immature carabids is also

important to the understanding of their importance in controlling various pests in the field. The next step would be to incorporate refuges in commercial farms and evaluating onion maggot control in the field.

Though the integrative approach to managing onion maggot is much needed in Michigan, growers are in need of new and immediate forms of control that would bring onion maggot populations below some economic threshold. Creating a more stable system with the use of stable habitats like refuge strips and increasing the abundance of generalist predators like carabids is just one part of the picture.

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APPENDIX 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.: 2002-02

Title of thesis or dissertation (or other research projects):

Increasing biological control of onion maggot, Delia antiqua (Meigen), with integrative approaches and methods.

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

Entomology Museum, Michigan State University (MSU)

Other Museums:

Investigator's Name(s) (typed)
Brian P. McCornack

Date 22 March 2002

*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 1.1

Voucher Specimen Data

Page 1 of 3 Pages

Species or other taxon	Label data for specimens collected or used and deposited from MICHIGAN Clinton Co., Muck Soils Research Farm - 5 mi NE of Bath on the date:	Number of: Eggs	Larvae	Nymphs	Pupae	Adults	Adults ♀	Adults ♂	Museum where deposited
Agonum cupripenne (Say)	2 June 2000, 22 June 2000, 23 June 2000					3			
Agonum placidum (Say)	31 May 2000, 1 June 2000, 6 July 2000					3			
Amara aenea (DeGeer)	(3) 5 June 2001					3			
Anisodactylus sanctaecrucis (Say)	(3) 28 June 1999					3			
Bembidion inaequale Say	31 May 2000					1			
Bembidion patruele Dejean	31 May 2000, (2) 1 June 2000					3			
Bembidion quadrimaculatum L.	1 June 2000, 26 June 2000					2			
Bembidion rapidum (LeConte)	31 May 2000, (2) 1 June 2000					3			
Bembidion versicolor (LeConte)	(3) June 2000					3			

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Brian P. McCornack

Date 03/22/2002

Voucher No. 2002-02

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

Curator 26 MAR 2002 Date

Appendix 1.1

Voucher Specimen Data

Page 2 of 3 Pages

Species or other taxon	Label data for specimens collected or used and deposited from MICHIGAN Clinton Co., Muck Soils Research Farm - 5 mi NE of Bath on the date:	Number of: Eggs	Larvae	Nymphs	Pupae	Adults	Adults ♀	Adults ♂	Museum where deposited
Chlaenius sericeus (Forster)	30 May 2000, 1 June 2000, 8 July 1999					3			
Chlaenius tricolor Dejean	30 May 2000, (2) 2 June 2000					3			
Clivina bipustulata (Fabricius)	2 June 2000					1			
Clivina impressifrons LeConte	1 June 2000, (2) 2 June 2000					3			
Dyschirius integer (LeConte)	31 May 2000, 1 June 2000					2			
Elanphropus anceps (LeConte)	(3) 1 June 2000					3			
Harpalus affinis (Schrank)	(2) 4 August 2000					2			
Harpalus herbivgus Say	(2) 31 May 2000, 1 June 2000					3			
Harpalus pennsylvanicus (DeGeer)	(2) 8 July 1999, 8 August 2001					3			

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Brian P. McCormack

Date 03/22/2002

Voucher No. 2002-02

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

Curator Date

Appendix 1.1

Voucher Specimen Data

Page 3 of 3 Pages

Species or other taxon	Label data for specimens collected or used and deposited from MICHIGAN Clinton Co., Muck Soils Research Farm - 5 mi NE of Bath on the date:	Number of: Eggs	Larvae	Nymphs	Pupae	Adults	Adults ♀	Adults ♂	Museum where deposited
Poecilus chalcites (Say)	13 July 1999, (2) 28 July 1999					3			
Poecilus lucublandis (Say)	31 May 2000, (2) 25 June 2000					3			
Pterostichus melanarius (Illiger)	7 July 1999, 8 July 1999, 5 August 2000					3			
Pterostichus permundus (Say)	13 July 1999, (2) 5 August 2000					3			
Scarites quadriceps Chandoir	25 June 1999					1			
Stenolophus comma (Fabricius)	(2) 28 June 1999					2			
Stenolophus ochropezus (Say)	(3) 31 May 2000					3			

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Brian P. McCormack

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Curator Date