Bembidion quadrimaculatum L. PREDATION ON THE EGGS OF THE ONION MAGGOT (Delia antiqua (Meigen))

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ABSTRACT

Bembidion quadrimaculatum
PREDATION ON THE
EGGS OF THE ONION MAGGOT
(Delia antiqua (Meigen))

By

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Bembidion quadrimaculatum L. is a small (2.7-3.8 mm), diurnal ground beetle that preys on the eggs of the onion maggot, Delia antiqua (Meigen) and other arthropods. This study investigates the role these beetles can play in the Michigan onion agroecosystem in the absence of insecticides. In addition, the relative impact of pesticides on B. quadrimaculatum and onion maggot eggs and adults was examined.

B. quadrimaculatum overwinter as adults in the soil and under plant debris. They become active in the spring and peak activity occurs in June, with a second peak in August or September. These activity peaks correspond roughly with spring and fall generation D. antiqua egg laying.

B. quadrimaculatum adults can consume up to 25 onion maggot eggs per day in the laboratory. These beetles forage actively on the soil surface but are not very effective predators if eggs are laid in the soil. In a field experiment, B. quadrimaculatum adults reduced D. antiqua larval numbers by 57% compared to the controls (absence of beetles).

B. quadrimaculatum adults are highly intolerant to foliar insecticides and are almost completely absent from commercial fields. Concentrations sufficient to kill onion maggot eggs and adults in the laboratory, killed these carabids quickly. However, soil insecticides do not appear to be very toxic to the adults in the field.

In conclusion, B. quadrimaculatum adults presently appear to play no role in reducing onion maggot numbers in commercial fields. However, if allowed to reach natural population densities, they are capable of reducing maggot numbers.

Bembidion quadrimaculatum L. PREDATION ON THE EGGS OF THE ONION MAGGOT (*Delia antiqua* (Meigen))

By

Frederick W. Warner

A THESIS

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To my parents,
for their financial and moral support
and to my wife, Glenys, and son, Steve,
for backing all of my endeavors

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INTRODUCTION

There has typically been a heavy reliance on chemicals for control of soil insect pests (Harris et al. 1981). Extreme measures have been taken to control the onion maggot (Delia antiqua (Meigen)) in North America. As a result, the onion maggot frequently indicates problems that probably will arise with other soil insect species (Harris et al. 1981).

Insecticides have been used to control the onion maggot since the 1930's (Kendall 1932). Until the 1950's, however, 30-80% control was typical (Harris et al. 1981). At that time (1950's), the development of the chlorinated hydrocarbon complex (DDT, aldrin, heptachlor, dieldrin) revolutionized soil insect control. Unfortunately for onion growers, the effectiveness of the cyclodiene insecticides was short-lived. By the late 1950's, the onion maggot had become resistant to all cyclodiene insecticides in the northern U.S. and Canada (Drew and Guyer 1958). Resistance to these insecticides occurred in England in the late 1960's (Gostick, Powell and Slough 1971).

Organophosphorus (OP) compounds were then employed to control the onion maggot. These insecticides were very effective from 1960 until the early 1970's. By 1972, the onion maggot had become somewhat resistant to all OP insecticides and carbofuran (a carbamate) although the latter was rarely applied for maggot control (Harris and Svec 1976). Resistance levels have continued to increase (Harris et al. 1981). Due to these resistance problems, growers sprayed for adults more frequently and at higher application rates. Some growers were applying 20 applications of parathion and diazinon during the growing season by 1975 (Harris et al. 1981). Presently, moderate spray programs in Michigan consist of 7-10 sprays during the growing season, even though foliar sprays are not effective in reducing maggot damage (Warner and Grafius 1981, Whitfield 1981). Recently, the effects of a post-harvest spray of naled for adults have been studied (Chambers 1984).

Future control of the onion maggot by the use of agrochemicals seems precarious at best. The development of new soil insecticides aimed at onion maggot control does not seem to be a primary objective of the pesticide industry (Harris et al. 1981). Due to the high costs associated with pesticide production, screening and registration, companies are interested in developing new products for corn, cotton, small grains, soybeans and tobacco only (Matsumura 1983). Therefore, it appears that future onion maggot control will be obtained with limited or no chemical input. Future control will rely heavily on cultural practices aimed at reducing pest populations and increasing the population of natural enemies and/or on the use of non-insecticidal tactics such as sterile insect releases.

The carabid, Bembidion quadrimaculatum L. was felt to be highly intolerant to insecticides due to its extremely low numbers in commercial compared to organic fields (Motyka and Edens 1984). Ground beetles, as a rule, are highly intolerant to insecticides applied at normal concentrations (Freitag 1979). However, insecticides are known to produce differential kills of ground beetles when applied at equal concentrations (Mowat and Coaker 1967, Critchley 1972, Tomlin 1975, Thiele 1977). For this reason, the relative toxicities of various insecticides to ground beetles (as well as other predators and parasitoids) and noxious insect species should be investigated. When this information is available, sound management decisions can be made concerning chemical input into an agroecosystem.

Predators, such as B. quadrimaculatum, and parasitoids are less likely to become tolerant to insecticides than pests. Because of this, a common phenomenon associated with buildup of insecticide resistance by a pest is an increase in damage in chemically treated plots as opposed to untreated areas (Mowat and Coaker 1967, Chapman and Eckenrode 1973). This increase in damage is usually correlated with a decrease in predator and parasitoid numbers in the treated plots. Therefore, it appears that, unwarranted insecticide use can be detrimental by destroying beneficial species.

The preservation of beneficial insect species should be a major concern when implementing pest management spray programs. In the onion agroecosystem, B. quadrimaculatum is felt to be a beneficial insect species although its role at this time is not fully understood. These beetles are known to be predators on the eggs of D. antiqua (Perron 1972, Drummond 1982). Therefore, management practices aimed at increasing their abundance in onion fields should be advantageous.

RESEARCH OBJECTIVES

1. Study the feeding habits of <u>Bembidion</u> <u>quadrimaculatum</u> adults in the laboratory.
2. Investigate the impact these carabids have on onion maggot larvae numbers in the field.
3. Examine the relative impact of pesticides on <u>B</u>. <u>quadrimaculatum</u> and onion maggot eggs and adults.

LITERATURE REVIEW

Onion Maggot

The onion maggot, Delia (=Hylemya) antiqua (Meigen) is an important pest of onions in Michigan as well as other parts of the United States and Canada. It has been a major pest in onions for over 100 years (Fitch 1867). Annually, in Michigan, crop loss due to the onion maggot is estimated to be 1-20%. Losses can be as high as 95% if onions are left untreated or insecticides fail. This insect is only known to attack Allium species, with the bulbing onion, Allium cepa L., the preferred host (Ellis and Eckenrode 1979).

There are three distinct generations of the onion maggot per year in Michigan, although the generations do overlap (Carruthers 1979). It overwinters as a pupa in the soil. As the soil warms in the spring, adults emerge. Fifty percent emergence occurs at approximately 400 $DD_{4.4^oC}$ (Eckenrode, Vea and Stone 1975, Carruthers 1979, Whitfield 1981).

Newly emerged flies require a day to dry and harden (Carruthers 1981). A preovipositional period follows and the flies forage. They are commonly found in field borders visiting dandelions, Taraxacum officinale Weber (Baker 1927) or other wild flowers (Carruthers 1981).

After the preovipositional period (about 10 days, 103 $DD_{3.88^oC}$, Carruthers 1979), flies mate. Gravid females lay their eggs in the soil around the base of onion plants, on the leaves, or in the leaf axils (Doane 1953, Workman 1958). Females from this spring generation have the highest reproductive potential (Perron and LaFrance 1961). In field cages in Quebec, the mean numbers of eggs laid per female of each generation were 57.8, 36.2 and 24.3 respectively for the three generations.

The placement of eggs, especially early in the growing season, is often dictated by the presence of volunteer onions (onion bulbs left in the field after harvest the previous fall that sprout and grow the next spring). These volunteer onions attract onion maggot females (Whitfield 1981, Chambers 1984). Females alight on the volunteers and lay their eggs on these sprouting onions or on nearby seedlings. Cull onions were suggested as a trap crop in Wisconsin as early as 1924 (Dudley 1925). He felt large numbers of onion maggot larvae could be eliminated by destroying these cull onions after maggots had infested them.

Onion maggot eggs require 50 $DD_{3.88}$ to hatch (Carruthers 1979). After eclosion, first instar larvae feed directly on onion tissue, usually initiating feeding at the root zone. Positioning of the eggs adjacent to the host plant appears to be extremely important because first instar larvae have a migration distance and detection radius of only ca. 2.5 cm. (Drummond 1982). Drummond suggested that 60-80% larval mortality could be induced if the eggs could be dislodged from the plant in some manner.

One onion seedling may not be sufficient to sustain a developing larva. One maggot destroys an average of 28 small seedlings (onions in the loop stage with a diameter at the soil surface of 1 mm.) before completing development (Workman 1958). The larger the onion, the more larvae it can support (Workman 1958, Loosjes 1976, Carruthers 1979). One larva can sustain itself on an onion with a diameter of 4-5 mm. (Workman 1958) and onion maggot adults actually prefer to oviposit on onion plants with a stem diameter of 4-8 mm. and heights of 10 cm. or more (Harris 1982). Larval population densities can be reduced up to 95% by late plantings of onions compared to early plantings, with or without insecticide treatment (Chambers 1984).

Developmental times of the three instars are 37, 89 and 161 $DD_{3.88}$, respectively (Carruthers 1979). Carruthers (1979) found pupae from the spring (and summer) generation 0 to 15 cm. deep in muck soil. Fifty percent emergence of summer generation adults is correlated with the accumulation of approximately 990 $DD_{4.4}$ (Whitfield 1981).

The summer generation larvae cause little or no damage to the existing onion crop. Ninety-six percent of summer generation flies reinfest previously infested onions (Kendall 1932). This behavior probably increases larval survival because first instar larvae are frequently unable to penetrate and establish themselves on healthy bulbs (Drummond 1982).

Fifty percent emergence of fall generation adults is correlated with the accumulation of 1769 $DD_{4.4}$ (Whitfield 1981). However, 10-67% of summer generation pupae enter diapause and remain in the ground until the following spring (Perron and LaFrance 1961, Ellington 1963, Loosjes 1976, Whitfield 1981).

A large proportion of the overwintering onion maggot population develops in cull onions left in the field (Drummond 1982). He demonstrated the importance of cut and sprouted culls as attractants to onion maggot adults. He also reported onion maggot pupae of the fall generation to pupate at deeper depths (up to 28 cm.) than reported for the spring and summer generations (Carruthers 1979).

Ground Beetles

The immature stages of the onion maggot are very susceptible to predation by various species of Carabidae and Staphylinidae. The impact the staphylinid, Aleochara bilineata (Gyll.) has on Michigan onion maggot populations has been well documented (Whitfield 1981, Groden 1982). Carabids, however, have received little attention.

Ball (1960) lists approximately 2500 species of Carabidae in America north of Mexico. Allen (1979) states that the majority of North American carabids can best be described as opportunistic. Depending on what is available they may act as general predators, herbivores, or scavengers. However, a few species specialize as predators on specific taxa. Lindroth (1969) lists carabid larvae as being predatory with very few exceptions. Two North American ground beetle genera, however, are known to have species that are host specific ectoparasitoids as larvae.

Ground beetles are present in most, if not all, agricultural croplands (Allen 1979). Although little is known about the biology of North American carabids or their role in cultivated fields (Kirk 1971a, Thiele 1977), there has been an increased interest in ecological and biological studies on the Carabidae within the past several years (Allen 1979).

Carabids are generally regarded in the literature as being beneficial. They have been known, however, to be minor pests of some crops such as strawberries (Johnson and Cameron 1969) and corn (Pausch and Pausch 1980). Their usefulness comes from their consumption of vegetable and animal material. They have been shown to consume the seeds of many noxious weed species of cultivated land (Johnson and Cameron 1969, Lund and Turpin 1977). As predators, they feed principally on the eggs and larvae of many forest and agricultural pests (Davies 1953, Best and Beegle 1977, Allen 1979).

Much of the literature concerning the usefulness of carabids in agroecosystems deals with their predation of root maggots, Delia spp. (Treherne 1916, Wishart, Doane and Maybee 1956, Hughes 1959, Wright, Hughes and Worrall 1960, Mitchell 1963, Coaker and Williams 1963, Coaker 1965, Wyman, Libby and Chapman 1976, Drummond 1982, Andersen et al. 1983, Andersen and Sharman 1983). Treherne (1916) demonstrated in the laboratory that carabids found in cabbage fields consumed eggs of the cabbage maggot, Delia radicum L. (=Hylemya brassicae (Bouche)). Carabids have also been shown to be very important predators of D. radicum eggs in the field (Wishart et al. 1956). Hughes (1959) listed five species of carabids (along with three species of staphylinids) as predators of D. radicum eggs. He found that predation accounted for over 90% of the mortality experienced by cabbage maggot eggs during the first generation. Wright et al. (1960) demonstrated that the number of carabids (of the most abundant species) was inversely proportional to the number of surviving D. radicum eggs and larvae. Mitchell (1963) found two carabid species feeding on cabbage maggot eggs and determined that the stage of crop growth affected the densities of the two beetle species. Coaker and Williams (1963) estimated the daily intake of four common carabid species to be a minimum of 16 D. radicum eggs, larvae or pupae per day. They felt, however, that staphylinids were more effective predators than carabids. Coaker (1965) determined carabids were responsible for up to 33% of the total egg mortality of D. radicum. Wyman et al. (1976) demonstrated that damage occurring in cabbage plots could be significantly reduced by artificially increasing populations of Stenolophus (=Agonoderus) lecontei Chandoir and S. comma (F.) using blacklights. They also reported that these two species can consume large numbers of cabbage maggot eggs. Finlayson et al. (1970) found more D. radicum pupae in plots where the carabid, Bembidion lampros (Herbst) had been removed than in plots where they were present. Andersen et al. (1983) and Andersen and Sharman (1983) also showed carabids and staphylinids to be important predators on the eggs of the turnip root fly, Delia floralis Fallen. They concluded, however, that predation alone did not reduce the pest population as greatly as granular insecticides.

Drummond (1982) reported on the importance some carabid species play in the onion agroecosystem. He found six species of ground beetles to feed on the eggs of the onion maggot, D. antiqua. In addition to Drummond (1982), the importance carabids may play in the Michigan onion agroecosystem was exhibited by results obtained in a pitfall trap study during the growing seasons of 1981 and

1982 (Motyka and Edens 1984). The four fields studied ranged in pesticide use from "organic" (no pesticide use for at least three years) to "intensive" (soil insecticide at planting and approximately 15 foliar insecticide applications plus fungicides and herbicides during the growing season). The "organic" field yielded catches of ten times more carabids than any of the other three onion fields, but the combined numbers of trapped adult onion and seedcorn maggots, Delia platura (Rond), were almost two times less in the "organic" field. This strong negative correlation suggests that carabids may play a role in reducing root maggot numbers in Michigan.

The Genus Bembidion

Bembidion is the largest genus of carabids, with 162 species (Lindroth 1969). Adults have a rather uniform appearance, small and slender (< 8.5 mm) with long antennae and legs. Metallic reflection is common and the elytra are often spotted. They move very rapidly.

Lindroth (1969) states that most species of Bembidion live close to water. Thiele (1977) asserts that there are many similarities between littoral regions and cultivated fields, the most important being that both are subject to drastic changes in climatic factors. According to Thiele (1977) then, it should come as no surprise to find large numbers of Bembidion in cultivated fields. Lindroth (1969), however, further states that a few species of Bembidion are rather xenophilous and run about on bare spots in the sunshine. Bembidion eat a variety of living, dying or dead arthropods (Lindroth 1969, Allen 1979). Collembola, Acarina, Araneida, fragments of other arthropods, fungal spores and other plant material comprised the diet of 14 species found in England (Davies 1953). Allen (1979), in his list of materials reportedly consumed by North American Carabidae, lists eight species of Bembidion. All were reported to feed on the eggs of the red-backed cutworm, Euxoa ochrogaster Guenee in the laboratory.

When the consumption rates of insect eggs by various carabids are reported, Bembidion spp. usually receive high rankings (Wishart et al. 1956, Wright et al. 1960, Coaker and Williams 1963, Perron 1972, Drummond 1982, Andersen et al. 1983). Wishart et al. (1956) state that Bembidion quadrimaculatum oppositum Say was the most important carabid attacking D. radicum eggs in the field in Ontario. They assigned it the highest ranking in egg-eating capacity and relative abundance. Another species, Bembidion nitidum (Kby.), received the fifth highest ranking in egg-eating capacity. Wright et al. (1960) report Bembidion lampros (Herbst) to be the most important predator in their experiments in Wellesbourne, England. Coaker and Williams (1963), also in Wellesbourne, gave B. lampros the highest relative predator value during their studies of consumption of cabbage maggot eggs. B. quadrimaculatum was given the fifth highest value. Perron (1972) mentions that B. quadrimaculatum adults can destroy large numbers of onion maggot eggs in Quebec. B. quadrimaculatum adults consumed 8 onion maggot eggs in two days in a greenhouse study at Michigan State University (Drummond 1982). Only one of seven other species of carabid adults tested consumed more. Finally, Andersen et al. (1982) showed B. lampros and B. quadrimaculatum can eat large numbers of turnip root fly eggs in Norway. B. lampros received the highest predator value; B. quadrimaculatum received the fourth highest value compared with eight other carabids and four species of staphylinids.

In addition to Drummond's research (1982), Haynes and co-workers (Haynes, Tummala and Ellis 1980) felt Bembidion spp. may play an important role as predators in the Michigan onion agroecosystem. In their conceptualization of the onion ecosystem (Figure 1) the general nature of predation by these beetles is depicted. They are not only shown to be first order predators of three pest species, but also interact with five beneficial organisms.

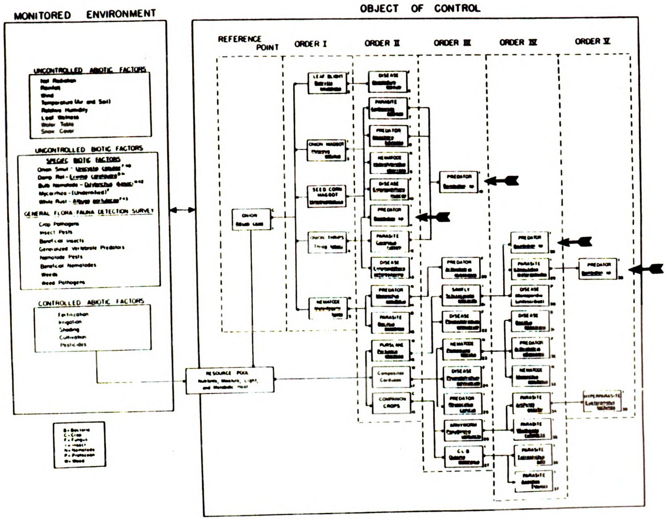

Figure 1. Conceptualization of the onion agroecosystem showing levels of interaction within the object of control and the monitored environment. Numbers refer to footnotes in Appendix A (after Haynes et al., 1980). Arrows highlight role of Bembidion sp.

Bembidion quadrimaculatum

The most common species of Bembidion found in Michigan onion fields is Bembidion quadrimaculatum L. (Drummond 1982, Motyka and Edens 1984). Adult beetles are 2.7-3.8 mm. in length and black with two yellow lateral spots on each elytron. They occur throughout North America (Lindroth 1969) and at least in some European countries (Coaker and Williams 1963, Thiele 1977, Andersen 1982).

There are two recorded subspecies of B. quadrimaculatum, B. quadrimaculatum oppositum Say and B. quadrimaculatum dubitans LeConte. B. quadrimaculatum oppositum occurs east of the Rocky Mountains and B. quadrimaculatum dubitans occurs west of the Rockies (Lindroth 1969). Lindroth (1969) states, however, that he is unable to find any difference between the two subspecies other than color. Since the two forms are almost allopatric and their occurrence is apparently not governed by climate (both occurring in humid coastal as well as in dry inland country), Lindroth (1969) felt that the two forms were genetically fixed and regarded both as subspecies of B. quadrimaculatum.

B. quadrimaculatum adults are commonly found on bare or almost bare soil, usually fine-sand or clay that is dry or slightly damp (Rivard 1964a, Lindroth 1969). Andersen (1982), however found that they preferred clay soils over sandy soils. This is not unusual and is a general phenomenon associated with carabids (Thiele 1977). Clay generally has higher plant productivity which in turn ensures a better food supply of herbivores and detritivores. In addition, Perron (1972) found populations of predators and parasitoids to be almost ten times higher on organic soil (e.g. muck) than on clay soils.

B. quadrimaculatum are often common in cultivated fields (Lindroth 1969). Esau and Peters (1975) actually collected more adults in pitfall traps placed in disturbed habitats (cornfields) than fence rows or prairies in Iowa. B. quadrimaculatum frequently occur in large numbers in cultivated fields (Wishart et al. 1956, Rivard 1964a, Frank 1971, Kirk 1971a, Perron 1972, Pimentel and Wheeler 1973, Esau and Peters 1975, Hsin, Sellers and Dahm 1979, Drummond 1982, Andersen 1982, Los and Allen 1983). Frank (1971a) recorded a density of 20 B. quadrimaculatum adults per square meter from an arable field in central Alberta. In these agricultural settings, B. quadrimaculatum adults are reported to be predators on the eggs of several Delia spp. (Wishart et al. 1956, Perron 1972, Drummond 1982, Andersen et al. 1983), the eggs of the western corn rootworm, Diabrotica virgifera virgifera LeConte, the northern corn rootworm, D. longicornis (Say) (Kirk 1982) and the eggs of the red-backed cutworm, Euxoa ochrogaster Guenee (Frank 1971b).

Similar to almost all other Bembidion spp., B. quadrimaculatum overwinters as an adult. As the soil warms in the spring, they become active, although the time of peak activity is uncertain. Perron (1972) reports that they do not build up to significant numbers in Quebec until late June or early July. Drummond (1982) reports peak captures of adults in Michigan from mid-April through early June. He mentions, however, that the activity response is unclear, possibly due to low population densities. Andersen (1982) shows peak activity ranging from mid-May to late July in Norway. The most reliable indication of the activity response in Michigan comes from the M.S.U. pitfall trap study (Motyka and Edens 1984). Results of trap catches from the organic field showed the first activity peak to occur from mid-June to early July.

Egg laying occurs in the spring (Rivard 1964b, Lindroth 1969, Frank 1971a, Andersen 1982). Rivard (1964b) reports only one breeding period and collected gravid females in May, June and July in eastern Ontario, with the highest percentage of gravid females taken in early July. Frank (1971a) also records collecting gravid females only during May-July but he reports two distinct breeding periods in central Alberta. He states this is a common phenomenon associated with beetles in the genus Bembidion.

From dissections, Rivard (1964b) found that the maximum number of eggs present per gravid female was 16. He used a maximum of ten eggs per female as a cutoff point to separate carabid species with a high reproductive potential from those having a low reproductive potential. Although not recorded specifically for B. quadrimaculatum adults, carabid females frequently lay their eggs singly in the soil at random, a few centimeters below the soil surface (Allen 1979).

Teneral B. quadrimaculatum adults occur in the fall (Andersen 1982), another indication of spring and early summer reproduction (Goulet 1976). The second adult activity peak ranges from early August to early September in Michigan (Motyka and Edens 1984). These adults eventually overwinter.

Most adult Bembidion are reported to be excellent fliers (Lindroth 1969). However, the wings of B. quadrimaculatum adults are not always functional, although these beetles have been observed flying in Europe (Lindroth 1969). Thus, B. quadrimaculatum may have limited dispersal capabilities.

Very little is known about carabid immature stages in general (Lindroth 1969, Kirk 1972). Little information is available concerning the larvae of B. quadrimaculatum. The larvae were described by Kirk (1972). They typically occur from mid-August through October (Lindroth 1969).

For carabids in general, eggs usually hatch in three to ten days depending on environmental factors (Kirk 1972, Allen 1979). There are generally three instars with the duration of each stadium varying with the species and environmental factors (Allen 1979). They are subterranean (Kirk 1972) and generally predaceous (Lindroth 1969). Third instars construct a cell in the soil prior to pupation (Kirk 1972). The duration of the pre-pupal and pupal stages also vary with environmental temperature and species involved. Adults upon emerging are extremely soft-bodied and require a period to harden. At this time, they are relatively inactive and are very susceptible to predation by other carabid adults (Goulet 1976).

Pitfall Traps

Pitfall traps are the most commonly used instrument to study ground beetle populations. They are inexpensive, quick and easy to operate and they yield large amounts of data (Southwood 1978). Also, because ground beetles are frequently present in low numbers in certain habitats and have secretive habits, daytime searching and collecting activities are tedious and inefficient (Durkis and Reeves 1981). In an evaluation of various trapping devices available, pitfall traps were found to be superior to all other methods for sampling populations of Carabidae (Thiele 1977).

There are also numerous disadvantages associated with the use of pitfall traps and data obtained with these traps must be interpreted with caution. They do not yield an accurate assessment of the density of a population (unless other techniques such as mark-recapture techniques are employed), but measure the activity density of a population (Andersen 1982) (i.e. pitfall trap catches are not only dependent on the population density of a species, but also on its activity, Thiele 1977). The activity of soil dwelling arthropods is affected by many factors such as temperature, soil moisture and other weather conditions, food supply, the characteristics of the habitat (e.g. the amount of impedance by vegetation) and the sex, age, behavior and condition of the individuals (Greenslade 1964, Thomas and Sleeper 1977, Southwood 1978).

Pitfall trap designs and trapping methods have been shown to affect trap catches. Comparison of trap catch data from different habitats or between various researchers is therefore difficult. For example, the type of trap used, greatly influences trap catches, especially when no preserving fluid (e.g. ethylene glycol) is used in the traps. Glass and plastic traps have a higher retaining efficiency than metal ones (Luff 1975). The diameter of the traps is also important. Traps are generally circular and catch size should be theoretically related to the length of the perimeter (Southwood 1978). However, it has been demonstrated that smaller aperture traps seemed to have higher efficiencies for smaller beetles while larger traps caught a higher proportion of the larger beetles that encountered the trap boundary (aperture) (Luff 1975).

Trapping methods that have been found to influence trap catches are plentiful. The number of traps used and the distance between traps are important. Traps standing close together will overlap in their effective catching-area and thus catch less than traps farther apart (Andersen 1982). The use of barriers has been shown to increase trap catches (Durkis and Reeves 1982). The number of times a trap is replaced also affects catches. The catches immediately after a pitfall trap is placed in position are commonly found to be higher than those subsequently achieved ("digging-in effects", Greenslade 1973).

It seems that the adoption of a universally accepted pitfall trapping scheme would be beneficial so that trap data obtained by different researchers could be more adequately compared. Inferences could be made about the size of a carabid population in a particular habitat compared to a similar habitat if the number of traps, the size of the traps and the distances between them within each location were identical.

ACTIVITY OF BEMBIDION QUADRIMACULATUM L.[1] AND PREDATION ON EGGS OF THE ONION MAGGOT, DELIA ANTIQUA (MEIGEN)[2]

Abstract

Bembidion quadrimaculatum L. (Coleoptera: Carabidae), one of the most common ground beetles in Michigan onion fields, feeds on the eggs of the onion maggot (Delia antiqua (Meigen) (Diptera: Anthomyiidae)). Laboratory and field experiments were conducted to determine how well B. quadrimaculatum prey on D. antiqua eggs. In the laboratory, these carabids consume up to 25 onion maggot eggs per day. D. antiqua larval numbers were reduced more by B. quadrimaculatum when eggs were on the soil surface (70% reduction) than when eggs were under the soil surface (17.5% reduction). In a field cage study, B. quadrimaculatum reduced onion maggot larval numbers 57%. B. quadrimaculatum, therefore, may be an effective biological control agent of D. antiqua.

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[1]Coleoptera: Carabidae

[2]Diptera: Anthomyiidae

Introduction

Bembidion quadrimaculatum L. is one of the most abundant carabid species found in onion fields in Michigan (Motyka and Edens 1984). The adults prey on root maggot (Delia spp.) eggs, reducing pest populations (Wishart et al. 1956, Coaker and Williams 1963, Coaker 1965, Perron 1972, Drummond 1982, Andersen et al. 1983, Andersen and Sharman 1983). The onion maggot, Delia antiqua (Meigen), is a major pest of onions in the northern United States and Canada. B. quadrimaculatum preys on eggs of D. antiqua (Perron 1972, Drummond 1982) and might be a potential biological control agent of this pest.

The objectives of this study were to study B. quadrimaculatum feeding and the impact these beetles have on onion maggot numbers in the field. Information is also presented on dispersal and activity of these insects.

Materials and Methods

Feeding Studies. Bembidion quadrimaculatum adults were collected from the soil surface at the M.S.U. Muck Soils Experimental Farm (Laingsburg, MI) and kept in the laboratory at 20-25^{o}C (15hL:9hD) in cake pans (34 cm x 24 cm x 5.7 cm) filled with muck soil or a vermiculite and silica sand mix. Fifty to one hundred beetles were placed in each pan. They were fed and given water three times a week. The diet consisted of onion maggot eggs and first instar larvae, sections of Tenebrio larvae, and small pieces of boiled ham.

Food Preference. In a preliminary study, B. quadrimaculatum adults were housed in petri dishes for ten days with radish (Rapharus sativus (L.)), barnyard-grass (Echinochloa crusgalli (L.) Beauv.) and redroot pigweed (Armaranthus retroflexus (L.)) seeds -- none were fed on. B. quadrimaculatum adults also did not feed on lettuce leaves, although B. rapidum LeConte (found in moderate numbers at the M.S.U. Muck Soils Experimental Farm) did.

Seventy-five Bembidion quadrimaculatum adults were individually housed at 20°C in petri dishes (100 mm x 15 mm) containing moist filter paper. Six food items: Delia antiqua eggs, one-day-old D. antiqua larvae, a section of Tenebrio sp. larva, onion bulb mites (Rhizoglyphus echinopus (Fumouze and Robin)), green peach aphid adults (Myzus persicae (Sulzer)), and pea aphid adults (Acyrthosiphon pisum (Harris)), were offered simultaneously to each beetle. The beetles were checked 48 hours later and the remaining food was recorded.

Feeding Rate Study. Beetle adults were individually housed in petri dishes (100 mm x 15 mm) with moist filter paper at 15°, 20°, and 25°C (fifteen beetles per temperature). Each received a known number (15, 20, 25, or 30) of onion maggot eggs daily for 60 days. The eggs were fertile and viable and often hatched. Eggs and first instar larvae consumed were recorded daily.

Foraging Ability. A piece of chemically untreated onion (15 mm x 15 mm x 3-4 mm) was placed at the bottom of 40 petri dishes (60 mm x 15 mm) and covered with 1 cm of field-collected muck soil. Twenty D. antiqua eggs were placed in each dish in two clumps of ten, ca. 1.5 cm apart. They were placed adjacent to the onion, (covered with 1 cm of soil) or left on top of the soil. Beetles were collected three days before the experiment, stored at 25° and not fed. One B. quadrimaculatum adult was placed in half the dishes; the other half served as controls to estimate maggot survival in the absence of predation. The onion sections were kept at 25°C for 96 hours, and then examined for the presence of first instar larvae.

Dispersal & Activity. B. quadrimaculatum populations were sampled with pitfall traps. (See Durkis and Reeves 1982 and Warner 1986 for the use of these traps.) Glass canning jars (Mason jars, 473 ml, 7.6 cm ID) were used as pitfall traps in 1982. They were modified in 1983 by placing a plastic cup (414 ml) inside each jar.

A roof (aluminum flashing material, 11.4 cm x 14.0 cm) was constructed ca. 8 cm above each trap to keep rain out. The beetles were trapped alive, identified in the field, and brought to the laboratory for further studies.

Periods of Activity. Fifteen pitfall traps were placed in an onion plot (22.86 m x 15.24 m in 1982 and 30.48 m x 15.24 m in 1983) at the M.S.U. Muck Soils Experimental Farm during May of 1982 and 1983. The traps were placed in a 3 x 5 grid measuring 10.98 m (each trap 5.49 m apart) by 12.2 m (each trap 3.05 m apart). The traps were checked three times a week and remained in position until beetle activity had ceased. They were removed temporarily if field activities necessitated their removal.

Population Density Estimates and Dispersal Measures. Mark-recapture techniques were used to study the fall population levels of *B. quadrimaculatum* during 1983. Before releasing marked beetles in the field, the marking procedure was evaluated in the laboratory.

Thirty *B. quadrimaculatum* adults were marked on the right elytron with model airplane paint (Testors®) in the laboratory the previous spring. The paint was applied with a No. 2 Entomological pin. After the mark dried, the beetles were housed individually in petri dishes (60 x 15 mm) containing muck soil for 21 days. Thirty unmarked beetles were individually housed and served as controls.

To obtain the desired estimates in the field, a release point was chosen on September 6 in a fallow area (30.48 m x 15.24 m) adjacent to an onion plot. Eighteen pitfall traps were placed in three concentric rings around this release point (4 traps 3 m from the release point, 6 traps 7.6 m from the position of release, and 8 traps 15.2 m from the release point).

100 marked *B. quadrimaculatum* adults were released at 5 p.m. EDT. The time corresponded to the beginning of a period of inactivity (Drummond 1982). Animals frequently show a high level of activity immediately after release, which could bias dispersal estimates (Southwood 1978).

Estimates of the population density of B. quadrimaculatum adults were derived from collecting beetles at the M.S.U. Muck Soils Experimental Farm during 1983. The collections were made from a fallow area adjacent to two onion plots. Early summer densities were estimated to be 6-9 adults/m^2; fall densities were estimated at 2-5 beetles/m^2. Densities as high as 20/m^2 have been reported (Frank 1971).

Effects of Rainfall and Temperature. The effects of rainfall on B. quadrimaculatum activity were evaluated with pitfall traps and rainfall records. To determine the lower threshold temperatures for activity, 16 beetles were individually housed in petri dishes and placed in an environmental chamber at 15°C. The temperature was lowered 1-2°C every 48 hours. The proportion able to walk at each temperature was recorded.

Habitat Study. Twelve pitfall traps were monitored at the M.S.U. Muck Soils Experiment Farm, 15 August to 9 September, in each of four locations: an onion plot, a windrow comprised of pine trees, a Sudan grass plot, and a large fallow area. The traps were placed in a 2x6 array measuring 5.49 m by 27.45 m and were examined 2x/week.

Overwintering Habitats. Two hundred samples (30.5 cm x 30.5 cm x 10 cm deep) were taken in each of the four locations described above. The samples were taken on 7 to 8 November 1983 when virtually all adult B. quadrimaculatum activity had ceased.

Impact on Onion Maggot Larval Numbers. Four field experiments were conducted at the M.S.U. Muck Soils Experimental Farm during the summer and fall of 1983. Experiments 1 and 2 were conducted during the growing season; experiments 3 and 4 simulated conditions after harvest.

Thirty-six enclosures (clay drainage tile covered with insect screen, 20.32 cm in diameter placed 16 cm beneath the soil surface with 15 cm protruding above) were placed at random in an onion plot. The plot received no soil insecticide treatment at planting and no foliar applications during the growing season.

All arthropods were trapped to extinction within each enclosure before the experiments began. A pitfall trap (Mason jar, 473 ml. 7.6 cm ID), partially filled with antifreeze, was used for this purpose. This trapping was accomplished in 7 to 10 days.

Two to four non-maggot infested onions were transplanted into each enclosure. D. antiqua eggs (obtained from Jim Miller, Dept. of Entomology, M.S.U.) were then placed in clusters of 6-10 (25/enclosure), approximately 1 cm below the soil surface; 0, 1, 3, or 5 B. quadrimaculatum adults were then added randomly to each enclosure (4 treatments, 9 enclosures/treatment). The beetles were field-collected on the day of the experiment except for experiment 4 (collected in mid-September and kept at 15°C).

Six to eleven days later, the onions and surrounding soil within each enclosure were sampled for surviving D. antiqua larvae. Carabid mortality was not monitored during the experiments since soil and plants could not be disturbed.

Placement of Eggs by Onion Maggot Females. To determine the percentage of eggs accessible to B. quadrimaculatum adults, cull onions were sampled from two onion fields in Grant, Michigan, on September 28 and October 11. Eggs were considered available if they were (1) attached to an onion at the soil surface, (2) lying on the soil adjacent to an onion, or (3) under a cull onion at the onion-soil interface.

Only cut or sprouted cull onions were sampled because eggs are most frequently found around them (Drummond 1982). Cut culls were sampled by removing them from the soil and scraping away small portions of soil beneath them to a depth of approximately 5 cm. Sprouted culls were sampled by pulling them from the ground, searching along the stem and bulb and then searching in the cavity left in the ground.

Results and Discussion

Feeding Studies. Delia antiqua eggs, mealworms, and one-day old D. antiqua larvae were the most frequently attacked of the items presented (Figure 1). However, no food was entirely avoided. B. quadrimaculatum adults were never seen killing a healthy green peach or pea aphid during the study, but fed on dead individuals. Furthermore, B. quadrimaculatum were never seen attacking and killing another healthy beetle. If,however, one or more healthy beetles encountered a dead or dying individual, they would quickly overwhelm it. These observations agree with Lindroth (1969) who found the staple food of Bembidion adults to be dead or dying insects, which could include insect stages with limited mobility such as eggs or maggots.

Feeding Rate Study. B. quadrimaculatum adults can consume up to 25 onion maggot eggs per day at 25°C (Table 1). When B. quadrimaculatum adults locate eggs, they usually remain in the vicinity of the eggs and continue feeding, unless disturbed. This behavior is noteworthy because, in the field, onion maggot eggs are typically laid in groups of 2-12 (Doane 1953). Therefore, if these beetles encounter a group of eggs they can consume them all before resuming active foraging.

Foraging Ability. There was no significant difference in larval survival when eggs were on or under the soil surface in the absence of predation (Table 2). In the presence of B. quadrimaculatum, onion maggot larval numbers were significantly

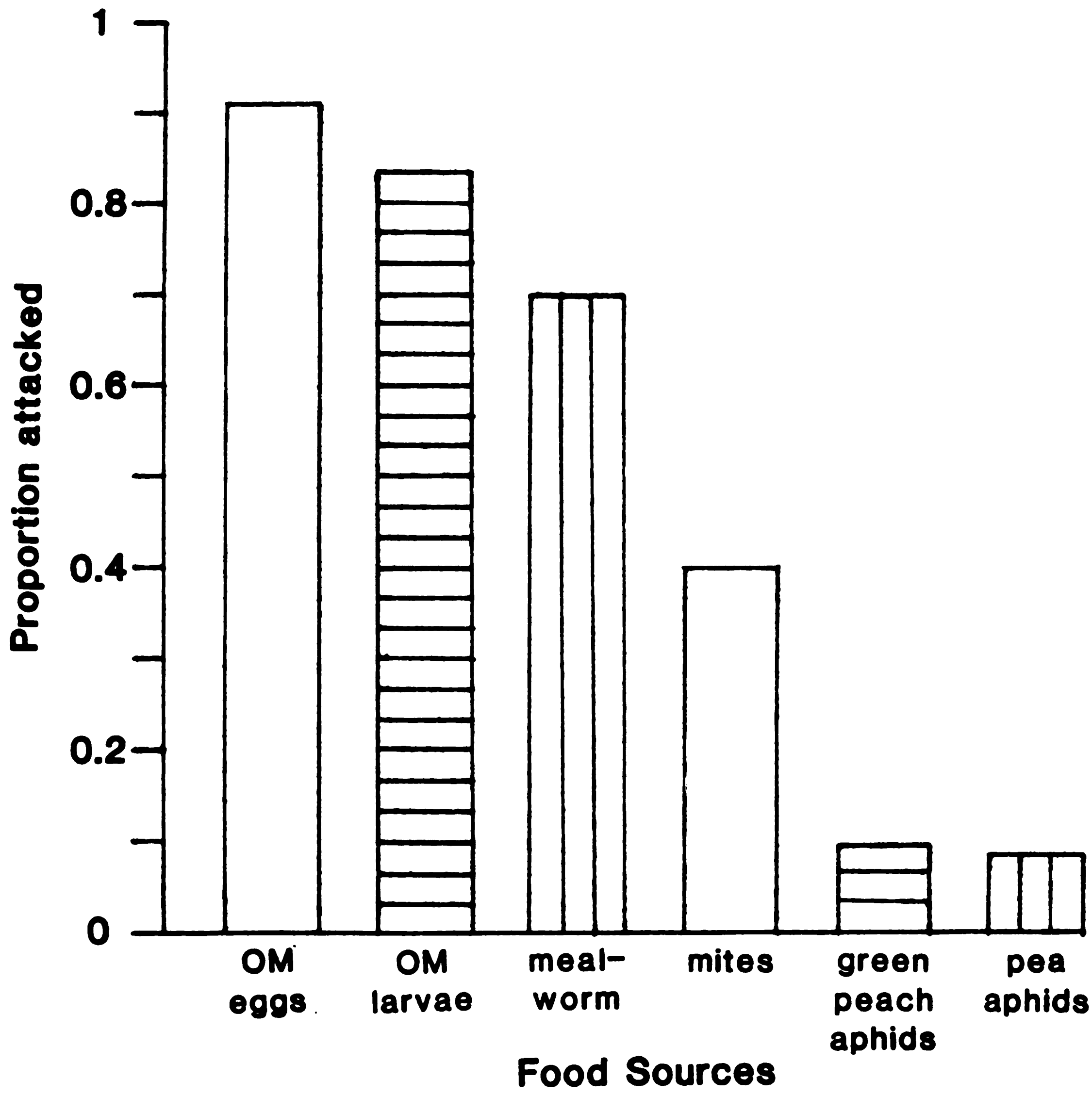


Figure 1. Proportion of attacks (number of times attacked/75) by Bembidion quadrimaculatum adults on 6 food items in a preference study.

Table 1. Numbers of onion maggot eggs and first instar larvae consumed daily by Bembidion quadrimaculatum adults at constant temperatures of 15°, 20° and 25°C over 60 days.

Temperature (°C)	Eggs		Larvae		Eggs and Larvae
	$\bar{x} \pm$ S.E.	Range	$\bar{x} \pm$ S.E.	Range	$\bar{x} \pm$ S.E.
15	.96 ± .12	0-8	1.77 ± .16	0-8	2.73 ± .21
20	1.30 ± .12	0-10	2.78 ± .18	0-9	4.08 ± .24
25	4.53 ± .52	0-25	4.06 ± .24	0-12	8.59 ± .61

reduced (70%)when the eggs were on top of the soil but not when the eggs were under the soil surface (17.5% reduction). This agrees with Kirk (1982) who reported that B. quadrimaculatum adults feed on corn rootworm eggs, but make no effort to dig the eggs out of the soil.

Possible explanations are that the beetles are not effective excavators, or they cannot detect the presence of eggs under the soil surface. B. quadrimaculatum adults forage actively on the soil surface, but randomly. Therefore, they may not possess an effective mechanism for sensing prey at any distance. Searching is undoubtedly more rapid on top than beneath the soil surface (depending on the amount of vegetation to impede their movement).

The surface foraging behavior of B. quadrimaculatum adults may reduce competition between adults and larvae. Most carabid larvae, including B. quadrimaculatum larvae, are subterranean (Kirk 1972). From laboratory obserations and pitfall trap catches, it seems that these larvae rarely forage on the soil surface. Although larvae are felt to outnumber adults in the field by a ratio of 10 to 1 (Tomlin 1982), they are infrequently caught in pitfall traps (Kirk 1971). Thus, this diversification of feeding habits may increase survival of both larvae and adults.

Dispersal and Activity. B. quadrimaculatum adults exhibit two periods of peak activity (Figures 2 and 3). Overwintering adults become active in the spring and breed. The larvae spend the summer in the soil, and the adults become active again in late summer and early fall (Andersen 1982, Motyka and Edens 1984).

B. quadrimaculatum adults are predators of onion maggot eggs, but their impact is limited by low their densities during first generation D. antiqua egg-laying (Perron 1972). Because the onion crop is damaged most at this time (Whitfield 1981), a decrease in onion maggot larvae numbers would be extremely beneficial. During 1982 and 1983, B. quadrimaculatum adults became active in May. Drummond (1982) found these carabids in April of 1979. Therefore, B. quadrimaculatum adults may possess the potential to reduce spring onion maggot larval numbers in Michigan.

Population Density Estimates and Dispersal Measures. No significant difference in mortality was found between marked beetles (13.3% mortality) and the controls (10% mortality). However, 3 of the 26 surviving marked beetles (11.54%) lost their mark, a common occurrence when marking with paints (Southwood 1978). Because other marking procedures were tedious or impossible, paint was still used.

Actual field densities were not obtained because only two marked beetles were captured during the study (2.7% of the total number of B. quadrimaculatum adults collected over 23 days). One marked B. quadrimaculatum adult traveled 7.6 m on the soil surface in a day. B. lampros adults, a species slightly larger than B. quadrimaculatum, wandered an average of 1.6 m/day (maximum 10.0, minimum 0.15 m/day) (Thiele 1977). Although B. quadrimaculatum adults can fly, they seldom do (Lindroth 1969).

Effects of Rainfall and Temperature. Beetle activity decreased significantly (difference test, $p > 0.05$; 1982, $t = 5.13$; 1983, $t = 3.04$) after periods of moderate to heavy rainfall (> 1.25 cm during a trapping period) (Figure 4), which agrees with previous reports (Freitag et. al. 1969). Data analyzed in this study were collected prior to the use of irrigation. The effects of irrigation on B. quadrimaculatum activity were not studied.

The effect of temperature on B. quadrimaculatum is shown in Figure 5. All beetles did not cease being active until 5°C. The lower temperature range for individual beetle activity was 6-11°C, suggesting large individual variability within the population. This may be genetically determined or due to the condition of the beetle (e.g., age and body fat).

Table 2. Foraging ability of Bembidion quadrimaculatum adults.

Placement of Eggs	Beetles Present	Percent Survival[1]
On Soil Surface	No	87.0
	Yes	26.0[2]
Under Soil Surface	No	91.0
	Yes	75.5

1. (#larvae/#eggs) x 100
2. Significantly different from controls (SNK test, P < 0.01)

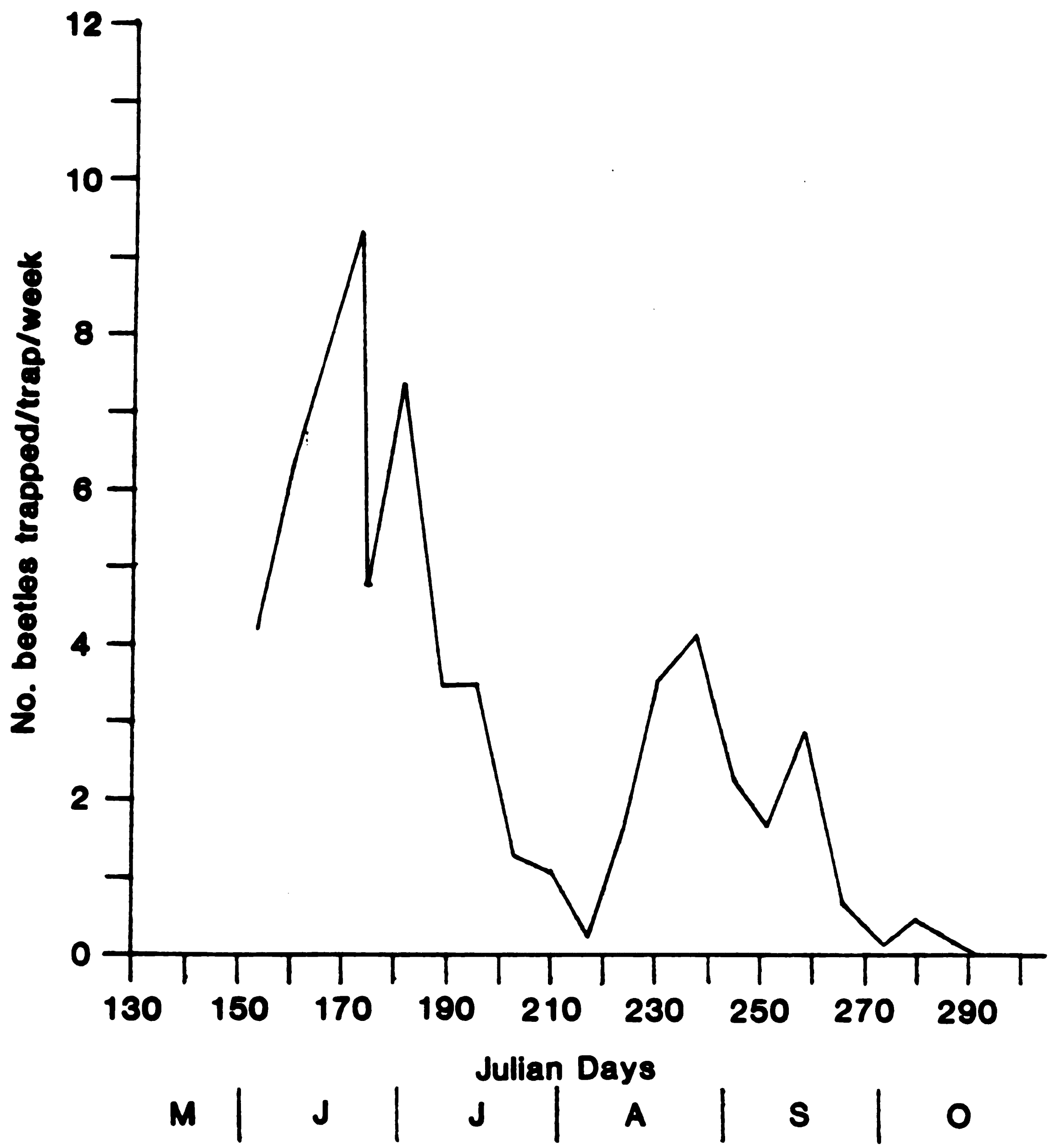


Figure 2. Seasonal trap catch of Bembidion quadrimaculatum adults in an onion plot located at the M.S.U. Muck Soils Experimental farm, 1982.

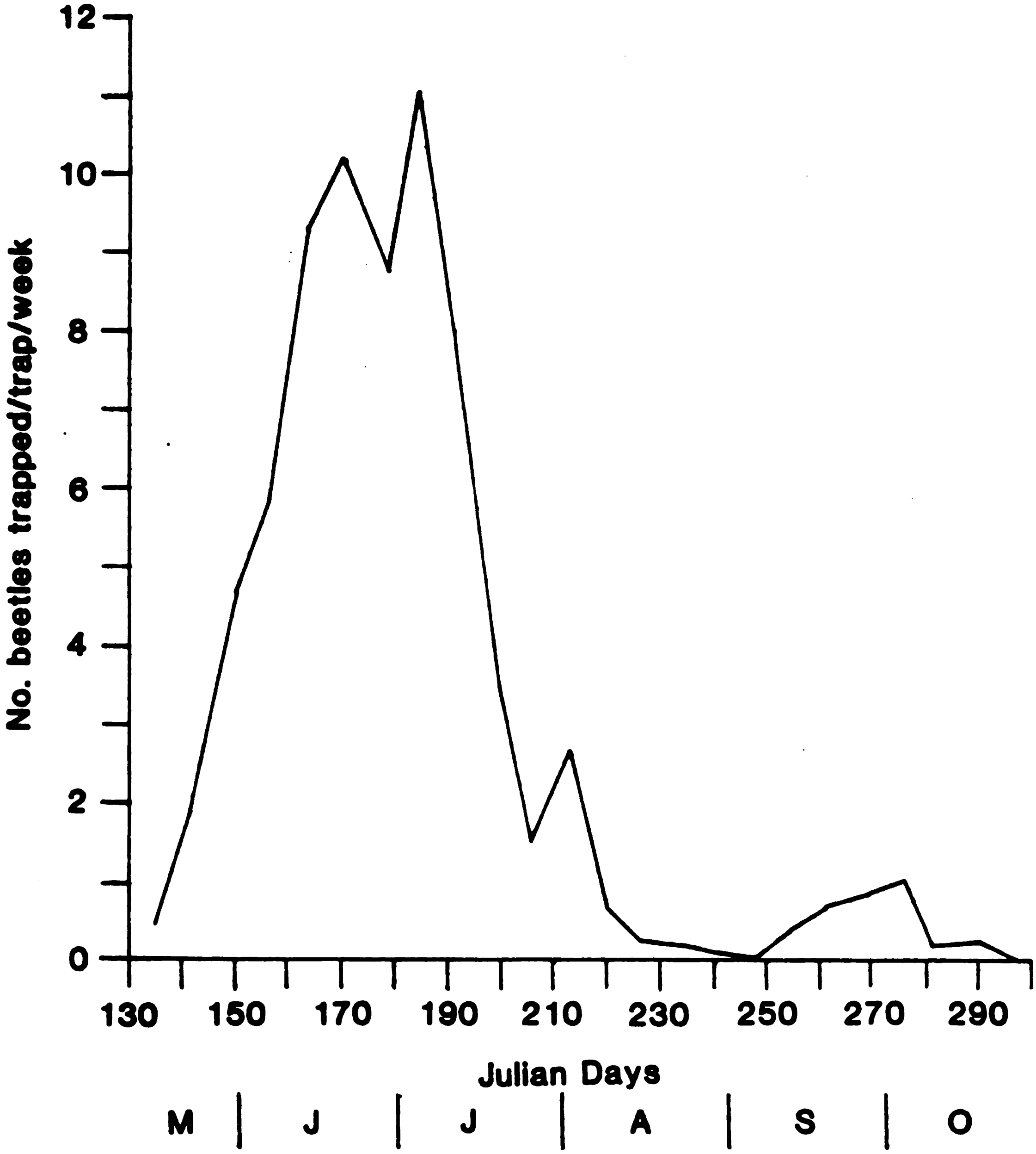
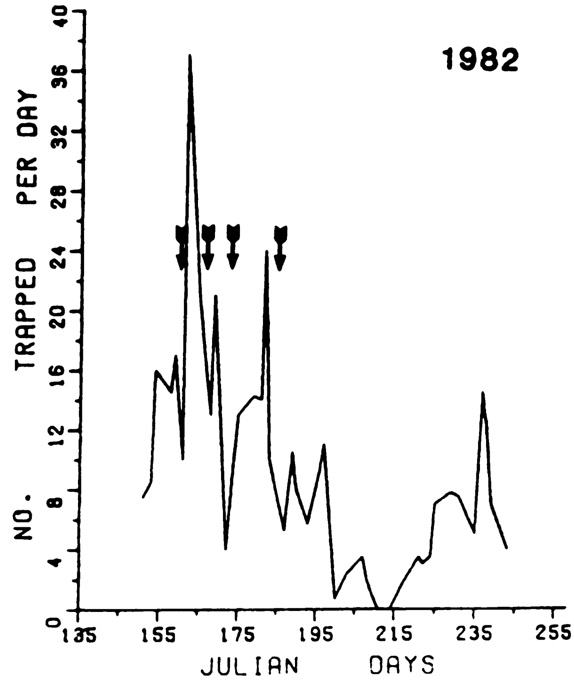


Figure 3. Seasonal trap catch of Bembidion quadrimaculatum adults in an onion plot located at the M.S.U. Muck Soils Experimental farm, 1983.

Habitat Study. More B. quadrimaculatum adults were caught in the windrow (wind break of pine trees) than in other locations. Only 1% of the beetles were collected from the onion plot; 19% were found in the fallow area, 21% in the Sudan grass and 59% in the windrow (n = 269 beetles). These results were unexpected, because carabids have strong habitat preferences (Thiele 1977), and B. quadrimaculatum prefer the relatively dry and sunny nature of a cultivated field with low vegetation (Lindroth 1969). Possible explanations could be (1) extremes in heat (the soil surface temperature of onion fields in Michigan frequently reaches 50^{o}C or higher) and low soil surface moisture killed the beetles or forced them to aestivate, (2) higher larval mortality in onion fields than in adjacent habitats, or (3) adult dispersal from onion fields to more suitable adjacent habitats. Carabids can distinguish small differences in air humidity (Thiele 1977). The humidity level in the windrow may have been more suitable. The low levels of moisture present in the onion plot during this study is best exemplified by the large numbers of cicindelid beetles (they prefer very dry conditions, Thiele 1977) trapped over this period. Thirty-four cicindelids were trapped in the onion plot, whereas they were not trapped in the other 3 habitats.

Overwintering Samples. The number of B. quadrimaculatum adults found overwintering in the four locations were: 0.25 adults/m^2 in the fallow plot, 0.18 adults/m^2 in the Sudan grass plot and 0.15 adults/m^2 in the onion plot and windrow B. quadrimaculatum adults overwinter in the soil and under plant debris. Soil samples were taken to a depth of 10 cm; most adults (77.3%) were taken at 0-6 cm. When found deeper in the soil, they were frequently associated with Stenolophus comma adults. B. quadrimaculatum adults probably followed burrows dug by these beetles.



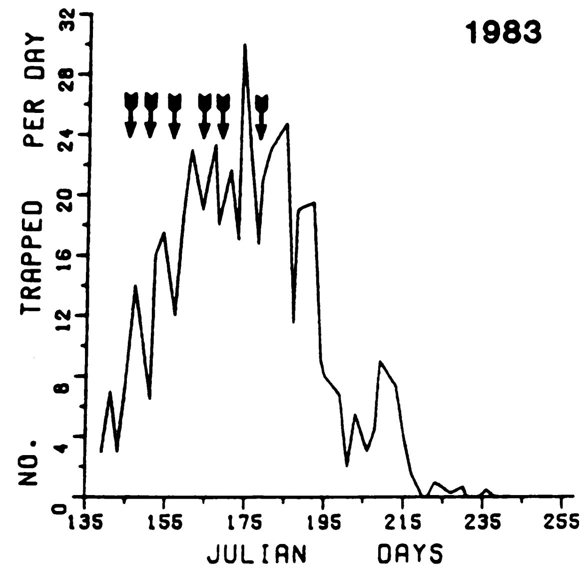


Figure 4. Number of Bembidion quadrimaculatum adults trapped per day during 1982 and 1983 in an onion plot located at the M.S.U. Muck Soils Experimental farm. Arrows indicate periods of moderate to heavy rainfall (> 1.25 cm) during the trapping period.

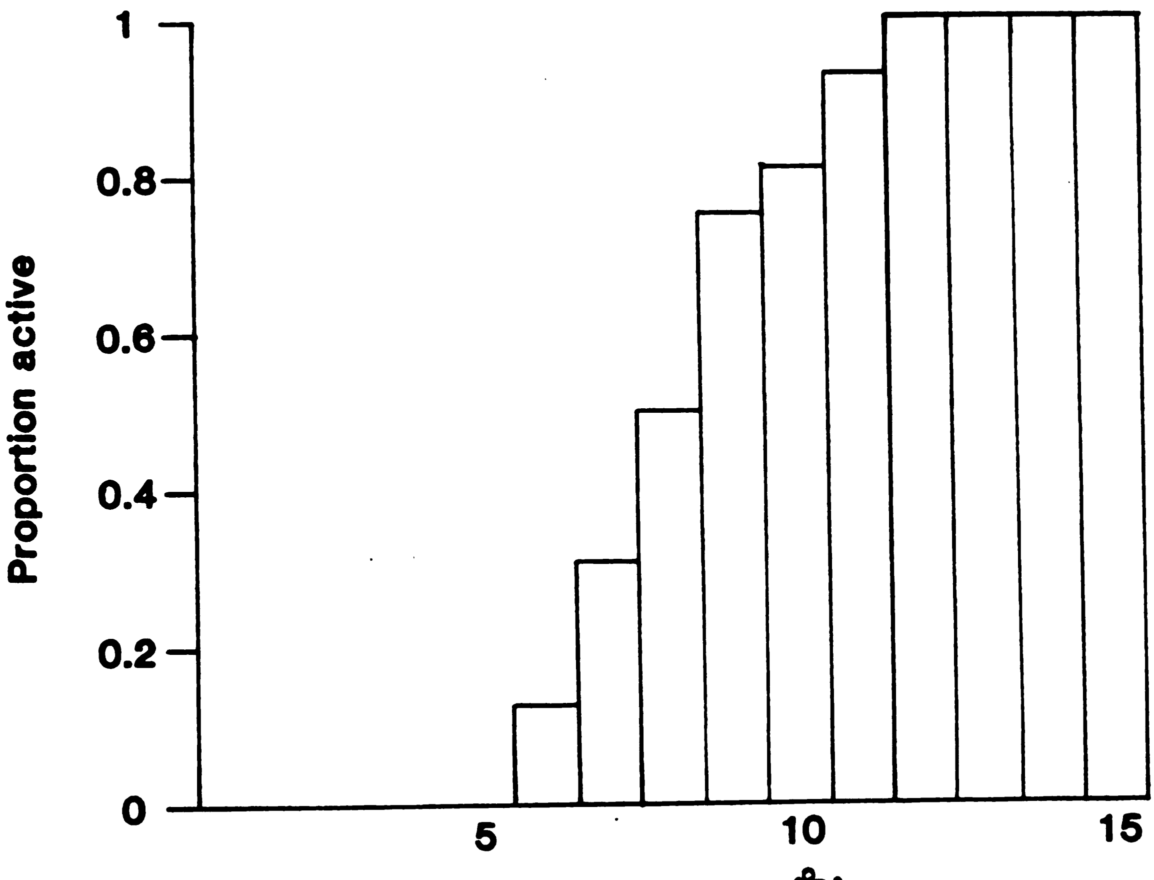


Figure 5. Proportion of Bembidion quadrimaculatum adults active at various temperatures.

Impact on Onion Maggot Larval Numbers. Only experiments 2 and 3 yielded substantial onion maggot survival in the absence of beetles (Table 3). In these experiments, the number of surviving onion maggot larvae was inversely proportional to the number of B. quadrimaculatum adults. The highest beetle density reduced larval numbers by 55% in experiment 2 (Figure 6) and 57% in experiment 3 (Figure 7). Wishart et. al. (1956) found no relation between the number of B. quadrimaculatum adults and Delia radicum L. pupae in a laboratory experiment using cages (17.8 cm x 19 cm x 7.9 cm) with 125 D. radicum eggs placed on and slightly below the soil surface around a turnip. In this study, they used 0, 5, 10, and 20 beetles, but found the largest reduction (91%) in pupal numbers in the cages with 5 beetles. They concluded that 5 predators could devour all the accessible eggs in each cage during the time it took them to hatch (approximately 3 days). Thus, B. quadrimaculatum adults may be able to reduce root maggot numbers more than shown in the two field experiments reported here.

The beetle treatment that best represents a natural field density is unknown because density estimates were unsuccessful. However, B. quadrimaculatum adults are very sparse in commercial onion fields (Motyka and Edens 1984) and are much more common in "organic" fields and at the M.S.U. Muck Soils Experimental farm. Regardless of density, however, all the beetle treatments reduced onion maggot larval numbers. Therefore, B. quadrimaculatum adults, if present, can reduce onion maggot numbers in the field.

Placement of Eggs by Onion Maggot Females. Data obtained from the fall sampling of onion culls is presented in Table 4. The data is similar to Drummond's (1982), except he found fewer eggs on the foliage of sprouted culls (only 5%). The percentage of eggs found on the foliage may increase with increasing soil moisture (Doane 1953, Miles 1953, Workman 1958).

Table 3. Percent survival of onion maggot larvae in the absence of predation in field experiments conducted at the M.S.U. Muck Soils Experimental farm, 1983.

Date	Initial Condition of Onions	# Eggs per tile	Placement of eggs	% Survival
July 14 - July 20	not damaged	25	in soil	3.56
August 11 - August 18	damaged	40	in soil	18.33
September 19 - September 26	damaged	30	on soil	37.41
October 18 - October 29	damaged	30	on soil	1.11

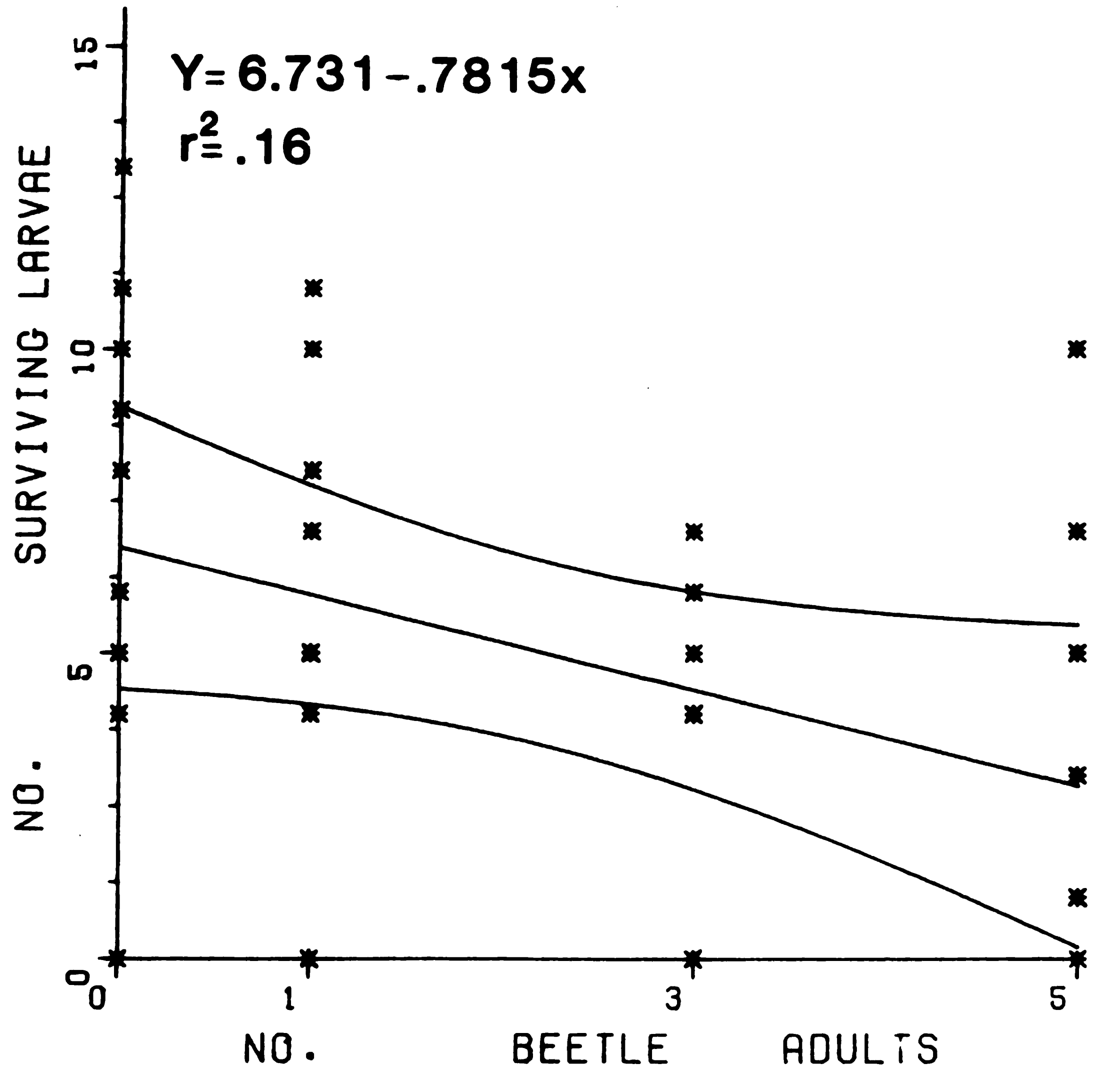


Figure 6. Relationship between the number of Bembidion quadrimaculatum adults and the number of surviving Delia antiqua larvae (with 95% confidence interval) per enclosure in the second of four field experiments, 1983.

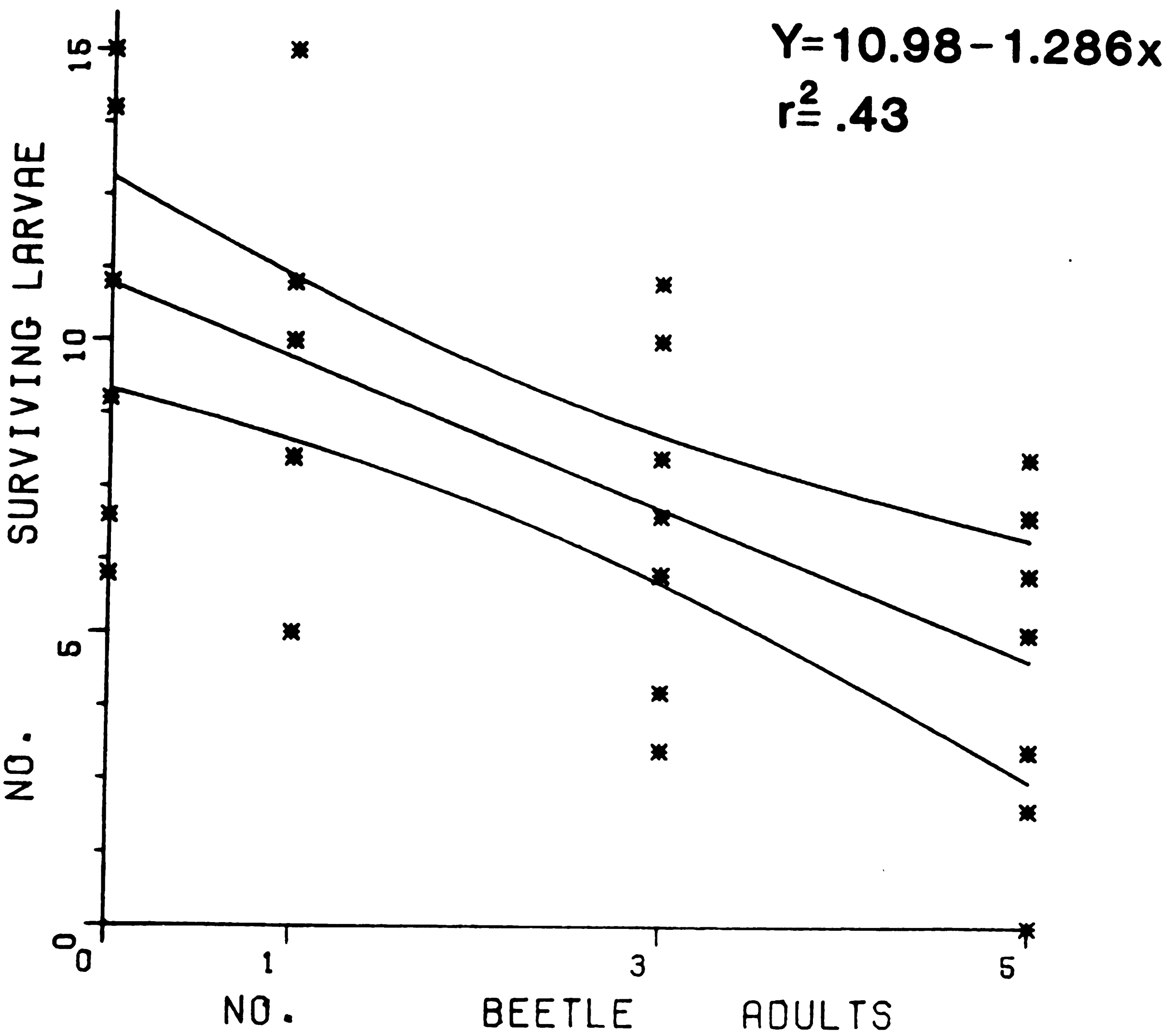


Figure 7. Relationship between the number of Bembidion quadrimaculatum adults and the number of surviving Delia antiqua larvae (with 95% confidence interval) per enclosure in the third of four field experiments, 1983.

On the average, ca. one quarter of the total eggs laid around cut and sprouted culls were deemed accessible to _B_. _quadrimaculatum_ adults. Although these beetles reduced onion maggot larval numbers 17.5% (Table 2) when eggs were placed 1 cm under the soil surface, they are much more efficient predators of eggs on the soil surface. Eggs below the soil surface, however, may be preyed on by _B_. _quadrimaculatum_ larvae. As this aspect was not studied, their impact on onion maggot numbers is unknown.

Onion maggot eggs are felt to be most accessible to _B_. _quadrimaculatum_ adults in the spring and fall. Eggs are often attached to young seedlings at the air-soil interface during the spring; these would be vulnerable to predation by _B_. _quadrimaculatum_ adults. Many eggs (Table 4) are also present on the soil surface in the fall. Therefore, _B_. _quadrimaculatum_ adults should reduce populations of onion maggots to a greater degree at these times, rather than in mid-summer when most eggs are laid beneath the soil surface (Workman 1958) and adults are not so prevalent.

In conclusion, _B_. _quadrimaculatum_ adults are capable of reducing onion maggot numbers in the field. However, this study investigated the role these beetles might play in the Michigan onion agroecosystem in the absence of insecticides. Heavy insecticide pressure is exerted upon _D_. _antiqua_ by commercial growers. The effects of insecticides on these carabids should be determined for a better understanding of the impact _B_. _quadrimaculatum_ have on maggot populations in commercial settings.

Table 4. Egg data obtained from sampling cut and sprouted cull onions from commercial fields in Grant, Michigan, 1983.

	Cut Cull Onions				Sprouted Culls			
Date	n	% with eggs	% eggs in soil	% eggs available[1]	n	% with eggs	% eggs in soil	% eggs available[1]
9/28	131	15.3	65.0	25.0	58	25.9	73.3	13.3
10/11	123	5.7	71.4	42.9	116	29.3	67.6	23.5

[1]Includes eggs attached to an onion at the soil surface, eggs lying on the soil adjacent to an onion or eggs under a cull onion at the onion-soil interface.

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REFERENCES CITED

Andersen, A. 1982. Carabidae and Staphylinidae (Col.) in swede and cauliflower fields in south-eastern Norway Fauna Norv. Ser. B. 29:49-61.

Andersen, A., A. G. Hansen, N. Rydland and G. Oyre. 1983. Carabidae and Staphylinidae (Col.) as predators of eggs of the turnip root fly Delia floralis Fallen (Diptera, Anthomyiidae) in cage experiments. Z. ang. Ent. 95:499-506.

Andersen, A. and J. A. Sharman. 1983. Effect of chlorfenvinphos and isofenphos on Carabidae and Staphylinidae (Col.), and their predation of eggs of Delia floralis Fallen (Diptera, Anthomyiidae) in field experiments. Z. ang. Ent. 95:206-213.

Coaker, J. M. 1965. Further experiments on the effect of beetle predators on the numbers of the cabbage root fly, Erioischia brassicae (Bouche), attacking brassicae crops. Ann. Appl. Biol. 56:7-20.

Coaker, J. M. and D. A. Williams. 1963. The importance of some Carabidae and Staphylinidae as predators of the cabbage root fly, Erioischia brassicae (Bouche). Entomol. Exp. Appl. 6:156-164.

Doane, C. C. 1953. The onion maggot in Wisconsin and its relation to rot in onions. Ph.D. Thesis. University of Wisconsin. 125 pp.

Drummond, F. A. 1982. Post-harvest biology of the onion maggot, Hylemya antiqua (Meigen). M.S. Thesis. Michigan State University. 353 pp.

Durkis, J. J. and R. M. Reeves. 1982. Barriers increase efficiency of pitfall traps. Ent. News 93(1):9-12.

Frank, J. M. 1971. Carabidae (Coleoptera) of an arable field in Central Alberta. Quaest. Entomol. 7(2):237-252.

Freitag, R., G. W. Ozburn and R. E. Leech. 1969. The effects of sumithion and phosphamidon on populations of five carabid beetles and the spider Trochosa terricola in northwestern Ontario and including a list of collected species of carabid beetles and spiders. Can. Entomol. 101:1328-1333.

Johnson, N. E. and R. Scott Cameron. 1969. Phytophagous ground beetles. Ann. Entomol. Soc. Amer. 62(4):909-914.

Kirk, V. M. 1971. Biological studies of a ground beetle, Pterostichus lucublandus. Ann. Entomol. Soc. Amer. 64(3)540-544.

Kirk, V. M. 1972. Identification of ground beetle larvae found in cropland in South Dakota. Ann. Entomol. Soc. Amer. 65(6):1349-1356.

Kirk, V. M. 1975. Biology of Stenolophus (=Agnoderus) comma, a ground beetle of cropland. Ann. Entomol. Soc. Amer. 68(1):135-138.

Kirk, V. M. 1982. Carabids: minimal role in pest management of corn rootworms. Environ. Entomol. 11(1):5-8.

Lindroth, C. M. 1969. The ground beetles of Canada and Alaska-parts 1-6. Opusc. Entomol. Suppl. 20, 24, 29, 33, 34 and 35.

Lund, R. D. and F. T. Turpin. 1977. Carabid damage to weed seeds found in Indiana cornfields. Environ. Entomol. 6(5):695-698.

Miles, M. 1953. Study of British anthomyiid flies. V. The onion fly, Delia antiqua. Bull. Ent. Res. 44:583-588.

Motyka, G. and T. C. Edens. 1984. A comparison of heterogeneity and abundance of pests and beneficials across a spectrum of chemical and cultural controls. Prepared for submission to the E.P.A.

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua (Meig.), under field conditions in Southwestern Quebec. Ann. Ent. Soc. Quebec 17:29-45.

Southwood, T. R. E. 1978. Ecological methods, 2nd ed. Chapman and Hall, London. 524 pp.

Thiele, H. U. 1977. Carabid beetles in their environments. Zoophysiology and Ecology 10. Springer-Verlag, Berlin, Heidelberg, New York. 369 pp.

Tomlin, A. D. 1982. Personal communication. Research Centre, Agriculture Canada. London, Ontario.

Warner, F. 1986. Bembidion quadrimaculatum L. predation on eggs of the onion maggot (Delia antiqua (Meigen)). M. S. Thesis. Michigan State University.

Whitfield, G. H. 1981. Spatial and temporal population analysis of the onion maggot, (Hylemya antiqua (Meig.)) in Michigan. Ph.D. Thesis. Michigan State Univeristy. 379 pp.

Wishart, G., J. F. Doane and G. E. Maybee. 1956. Notes on beetles as predators of eggs of Hylemya brassicae (Bouche) (Diptera: Anthomyiidae). Can. Entomol. 88:634-639.

Workman. R. B., Jr. 1958. The biology of the onion maggot, Hylemya antiqua (Meigen), under field and greenhouse conditions. Ph.D. Thesis. Oregon State College, Corvallis. 82 pp.

EFFECTS OF INSECTICIDES ON BEMBIDION QUADRIMACULATUM L.[1] AND DELIA ANTIQUA (MEIGEN)[2] EGGS AND ADULTS

Abstract

The effects of insecticides on Bembidion quadrimaculatum L., Delia antiqua (Meigen) eggs and D. antiqua adults were studied. Field experiments were conducted to determine the impact of foliar insecticides on B. quadrimaculatum. Laboratory studies were also performed on B. quadrimaculatum adults, D. antiqua eggs, field-collected D. antiqua adults and laboratory-reared adults to obtain LC_{50} values for various pesticides utilized in Michigan onions. In large plots, B. quadrimaculatum numbers were not reduced by insecticides in 1982, but were significantly reduced by diazinon in 1983. In field cages, diazinon killed 100% of B. quadrimaculatum and fenvalerate killed 51% in 2 weeks. All of the insecticides tested were extremely toxic to the beetles in the laboratory. Insecticides (with the exception of fenvalerate) were found to be toxic to D. antiqua eggs, but the adults were quite tolerant. Field-collected D. antiqua adults were 14x more tolerant to diazinon, 8x more tolerant to fenvalerate and 4.7x more tolerant to naled than laboratory-reared flies. Insecticides were 65 - 492x more toxic to B. quadrimaculatum than to field-collected D. antiqua adults.

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[1]Coleoptera: Carabidae

[2]Diptera: Anthomyiidae

Introduction

The onion maggot, Delia antiqua (Meigen) is a major pest of onions in the northern United States and Canada. Insecticides have been used to control this insect since the 1930's due to the extensive damage it may cause (Kendall 1932). Resistance, however, is a primary concern. The onion maggot has become resistant to virtually all insecticides used for its control (Drew and Guyer 1958, Harris and Svec 1976, Harris et. al. 1981). Due to resistance problems, growers spray for adults more frequently and at higher application rates (Harris et. al. 1981). Presently, moderate spray programs in Michigan consist of 7-10 sprays during the growing season, even though foliar sprays are not effective in reducing maggot damage (Warner and Grafius 1981, Whitfield 1981).

Unwarranted insecticide use can be detrimental by destroying beneficial insect species. Ground beetles, as a rule, are highly intolerant to insecticides applied at normal concentrations (Freitag 1979). However, insecticides are known to produce differential kills of ground beetles when applied at equal concentrations (Mowat and Coaker 1967, Critchley 1972, Tomlin 1975, Thiele 1977). Insecticides less toxic to ground beetles (as well as other predators and parasitoids) should be utilized to control pest insect species when implementing pest management spray programs.

The carabid, Bembidion quadrimaculatum L. was felt to be highly intolerant to insecticides due to its extremely low numbers in commercial compared to organic fields (Motyka and Edens 1984). These beetles are predators of onion maggot eggs (Perron 1972, Drummond 1982, Warner 1986), therefore, management practices aimed at increasing their abundance in commercial onion fields should be beneficial.

The primary objective of this study was to examine the relative effects of insecticides on B. quadrimaculatum and D. antiqua eggs and adults. The effects of soil and foliar insecticides on B. quadrimaculatum in the field were observed. Laboratory studies were performed to obtain relative toxicities of various agrochemicals utilized in Michigan onion production to B. quadrimaculatum adults, D. antiqua eggs, field-collected D. antiqua adults and laboratory-reared D. antiqua adults.

Materials and Methods

Field Research. Field research was conducted at the M.S.U. Muck Soils Experimental Farm (Laingsburg, MI) during the summers of 1982 and 1983. A large plot experiment and a cage study were conducted in 1982 and a large plot study was conducted in 1983.

Pitfall traps (Mason® jar, 473 ml, 7.6 cm ID) were used to monitor the activity of B. quadrimaculatum adults. Beetles were trapped alive and returned to their respective plots as far from the traps as possible to reduce the probability of immediate recapture (beetles are known to become "trap happy," Thomas and Sleeper 1977). The traps were checked 3-5 times per week.

Diazinon (.56 kg ai/ha, .417% solution, 280 l/ha) and fenvalerate (.11 kg ai/ha, .139% solution, 280 l/ha) were applied every 7-10 days, similar to commercial programs for onion maggot and onion thrips (Thrips tabaci (Lind)) control. Soil insecticide (fonofos or chlorpyrifos granules) was applied in-row at planting to portions of the plot to reduce D. antiqua damage.

Large Plot Experiment 1982. Plots were separated by placing aluminum flashing (23 cm high) ten centimeters in the ground between plots arranged in a completely randomized design with 6 replications per treatment (Fig. 1). The plots were not enclosed over the top, but B. quadrimaculatum movement from these plots was minimal because they rarely fly. Insecticides were applied as described above.

Cage Study 1982. Nine cages (6.7 cm x 6.7 cm) were constructed of aluminum flashing with 1 mm mesh screen tops, and placed into the ground. All vegetation (weeds and onions) was removed from the cages.

All insects present when the cages were placed in the ground were removed or killed by drenching the soil with a 15% Clorox® mixture followed by pitfall trapping (with ethylene glycol) for approximately three weeks. Ten or fifteen field-collected B. quadrimaculatum adults were then placed in each cage. The beetles were fed onion maggot eggs and given water daily with a small sponge. Insecticides were applied with a hand sprayer August 3, 10 and 18.

B. quadrimaculatum adults were monitored daily using one pitfall trap per cage and by disturbing the top two centimeters of soil. The number of living and dead beetles was recorded, although dead beetles were difficult to locate.

Large Plot Experiment 1983. Plots were arranged in a randomized complete block design with 4 replications per treatment (Fig. 1). The treatments were not separated using aluminum flashing as in 1982. This allowed beetles to move freely from treated to untreated plots. The insecticides were applied as before on July 28, August 4 and August 18.

Laboratory Studies. Laboratory LC_{50} values were obtained with various pesticides for B. quadrimaculatum adults, D. antiqua eggs, field-collected D. antiqua adults and laboratory-reared adults. Pesticides tested were: diazinon, fenvalerate (Pydrin), naled (Dibrom), chlorpyrifos (Lorsban), fonofos (Dyfonate), maneb (a fungicide) and glyphosate (Roundup, an herbicide). LC_{50} values were not obtained for every chemical tested due to the limited numbers of insects available.

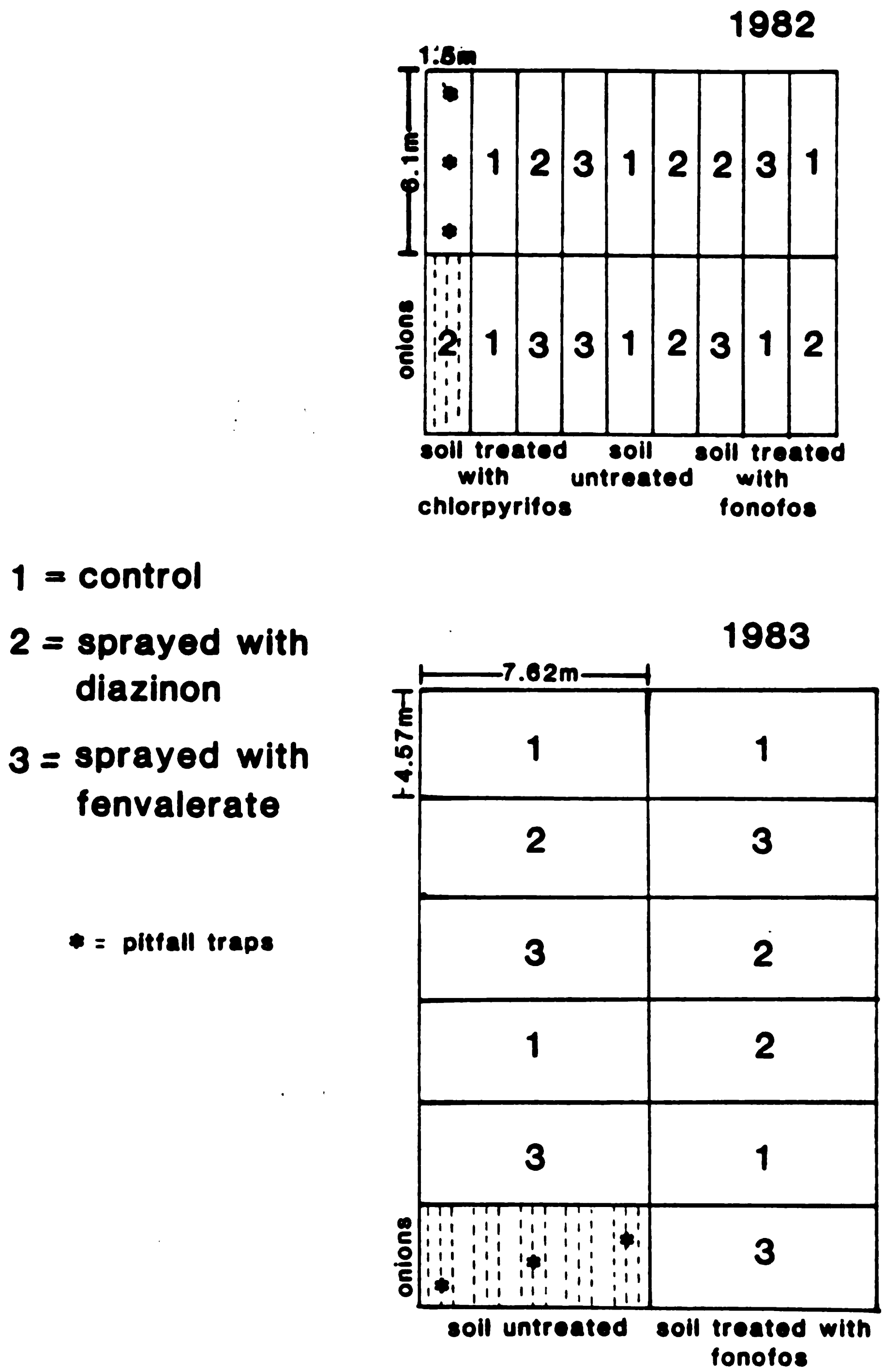

Figure 1. Plot diagrams of large plot insecticide experiments at the M.S.U. Muck Soils Experimental farm during the summers of 1982 and 1983.

Pesticide solutions were prepared using commercial pesticide formulations and distilled water. Filter papers (Whitman® #2) were then dipped into the respective solutions for five seconds and allowed to dry for ten minutes (when testing D. antiqua eggs, the filter papers were only allowed to drip dry). After drying, the papers were placed into containers and insects or eggs added. The tests were conducted at 25°C. Containers were checked every 24 hours for four days.

Effects of Pesticides on B. quadrimaculatum Adults. Beetles used in these tests were collected at the M.S.U. Muck Soils Experimental farm and stored in the laboratory for 2-3 weeks at 25°C. These beetles were fed and watered three times a week.

Testing was performed by placing an insecticide-treated filter paper (5.5 cm) in a baby food jar (130 ml) covered with screen. Thirty adults (6 replications (jars); 5 beetles/rep) were tested at each concentration (Table 1). The beetles were fed D. antiqua eggs and watered after 24 hours.

Effects of Pesticides on D. antiqua Eggs. Eggs used in these tests were obtained from a laboratory culture of D. antiqua maintained by the staff of Dr. Jim Miller, located at the Pesticide Research Center, M.S.U. These flies, collected from Guelph, Ontario, have completed approximately 20 generations in the lab.

Testing was performed by placing an insecticide-tainted filter paper (5.5 cm) in a petri dish (60 mm x 15 mm). One hundred and fifty eggs (6 replications; 25 eggs/rep) were tested at each concentration (Table 2).

An additional experiment was completed to determine if insecticide resistance is present in the eggs of D. antiqua. For this study, eggs collected from the aforementioned laboratory culture were compared to eggs oviposited by flies recently captured (0 generations removed from the field) from Grant, Michigan.

Table 1. Treatment levels (percent solution) for onion production pesticides applied to Bembidion quadrimaculatum in laboratory studies.

diazinon (I)	fenvalerate (I)	naled (I)	chlorpyrifos (I)	maneb (F)	glyphosate (H)
.125	.04	.0025	.5	.1	1.25
.025	.01	.001	.25	.01	
.01	.001	.0005	.125	.001	
.005	.00015	.00025	.025		
.0025	.0001	.0001	.0025		
.001		.000025	.00025		
.0005			.000025		
.00025					
.0001					
.00005					
.000025					
.417[f]	.139[f]	.417[f]		.375[f]	1.25[f]
.250[d]	.083[d]		.500[d]		

d = normal drench treatment concentration at 467 l/ha

f = normal foliar application concentraton at 280 l/ha

I = insecticide

F = fungicide

H = herbicide

Table 2. Treatment levels (percent solution) for onion production pesticides applied to Delia antiqua eggs and adults in laboratory studies.

diazinon (I)	fenvalerate (I)	naled (I)	chlorpyrifos (I)	fonofos (I)	maneb (F)	glyphosate (H)
2.5^{y}	$.8^{y}$	$.5^{z}$	$.025^{z}$	$.025^{z}$	1.0^{z}	1.0^{z}
.5	$.16^{z}$	.25	$.0025^{z}$	$.0025^{z}$	$.1^{z}$	$.25^{z}$
$.25^{z}$	.08	$.125^{z}$	$.00025^{z}$	$.00025^{z}$	$.01^{z}$	$.025^{z}$
.125	$.04^{z}$	.025	$.000025^{z}$	$.000025^{z}$	$.001^{z}$	$.0025^{z}$
.025	$.01^{z}$	.0025				
.0025	.008	$.00025^{z}$				
$.00025^{z}$	.0008	$.000025^{z}$				
$.000025^{z}$						
$.417^{f}$	$.139^{f}$	$.417^{f}$			$.375^{f}$	1.25^{f}
$.250^{d}$	$.083^{d}$		$.500^{d}$	$.500^{d}$		

d = normal drench treatment concentration at 467 l/ha

f = normal foliar application concentraton at 280 l/ha

y = applied only to field collected D. antiqua adults

z = applied only to D. antiqua eggs

I = insecticide

F = fungicide

H = herbicide

Flies from Grant were chosen because they are known to be resistant to a large number of insecticides (Harris and Svec 1976, Harris et al. 1981). Filter papers were dipped in a .0025% diazinon solution and placed in petri dishes. Two hundred and fifty eggs (10 replications; 25 eggs/rep) of each strain of flies were tested.

Effects of Insecticides on D. antiqua Adults. The testing procedure was identical for the field-collected and laboratory-reared flies. The tests were done by placing an insecticide-tainted filter paper (7.0 cm) in a one pint Mason jar. The jar was covered by insect screen. Forty-five adults (3 replications; 15 flies/rep) from each culture were tested at each insecticide concentration (Table 2). The flies were fed a mixture of 20 parts enzymatically hydrolyzed yeast, 10 parts table sugar and 10 parts powdered milk and given water daily.

Results and Discussion

Large Plot Experiment 1982. The foliar applications of diazinon and fenvalerate produced no significant differences in the mean numbers of B. quadrimaculatum trapped (Table 3). However, more beetles were actually trapped in the sprayed plots than in the unsprayed plots. There were equivalent densities of B. quadrimaculatum adults in all the plots prior to spraying (Table 3). Therefore, there may have been a slight increase in activity of B. quadrimaculatum adults in the insecticide-treated plots, especially the plots sprayed with fenvalerate. Sublethal doses of insecticides are known to stimulate carabid activity (Critchley 1972).

These results were unexpected because the rates of insecticide applied were felt to be toxic to B. quadrimaculatum adults. However, many broad-leaved weed species (e.g. redroot pigweed, Amaranthus retroflexus L. and lambsquarters, Chenopodium album L.) colonized these plots and probably prevented many insecticide droplets from reaching the soil surface. Therefore, it is possible that only a small proportion of the insecticide applied settled on the soil.

Although non-replicated, the soil insecticide may have reduced B. quadrimaculatum numbers (Figure 2). Soil insecticides are known to be toxic to many species of carabids (Mowat and Coaker 1967, Critchley 1972, Tomlin 1975), so these results were not surprising. However, it is unknown whether the adults, larvae or both stages were adversely affected by these insecticides.

Chlorpyrifos and fonofos produce excellent onion maggot control when applied at planting (Grafius, Warner and Mitchell 1983a). However, because fonofos appears to be more toxic to B. quadrimaculatum, chlorpyrifos would be preferable.

Cage Study 1982. The first application of diazinon produced 83% mortality of B. quadrimaculatum adults within 24 hours. Eventually, all of the diazinon-treated beetles succumbed. The first application of fenvalerate produced 33% mortality within 24 hours (calculated after Abbott (1925)). The three applications of fenvalerate caused 51% mortality.

The cage study probably represents an amplification of the results that would be obtained in commercial onion fields. Because all of the vegetation (onions and weeds) was removed from the cages, all of the insecticide droplets probably reached the soil surface. In commercial fields, a great deal of the insecticide applied would settle on the onion foliage and not on the soil. However, weed control in commercial onion fields is intensive so weeds would not be present to intercept the remaining droplets.

Table 3. Mean numbers per replication of Bembidion quadrimaculatum adults trapped in plots sprayed with diazinon and fenvalerate, 1982.

	$\bar{x}$ numbers of B. quadrimaculatum adults trapped[1]	
Treatments	Prior to foliar applications (7-20)	Post applications
diazinon	2.5[a]	11.33[a]
fenvalerate	2.5[a]	21.67[a]
untreated	2.67[a]	10.33[a]

[1]Means followed by the same letter are not significantly different (Student-Newman-Keuls' multiple range test, P > 0.05).

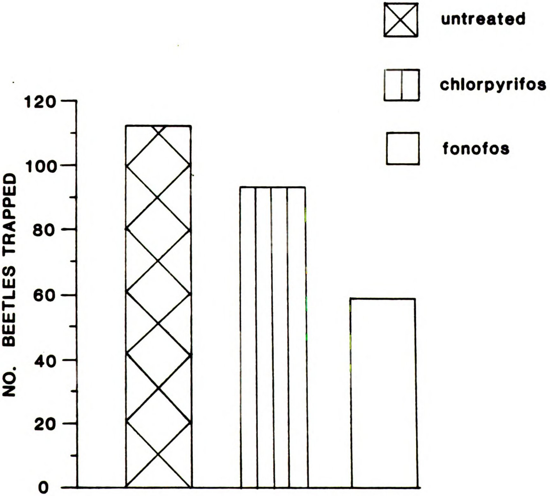

Figure 2. Comparative numbers of Bembidion quadrimaculatum adults trapped from July 13 to August 18, 1982 in plots treated with 2 soil insecticides compared to an untreated plot.

Large Plot Experiment 1983. Fewer B. quadrimaculatum adults were trapped in the plots receiving applications of foliar insecticides than in the untreated plots. Significantly fewer beetles were caught in the diazinon-treated plots than in the untreated plots (Table 4). As in the cage study, diazinon appeared to be more toxic to B. quadrimaculatum than fenvalerate. Both foliar insecticides produce comparable control of onion thrips (Grafius, Warner and Mitchell 1983b), therefore, fenvalerate would be preferable.

It appears that the application of fonofos at planting did not reduce B. quadrimaculatum numbers in this study (Figure 3). However, in this experiment, beetles were allowed to move from one plot to another, unlike the 1982 study. Therefore, although the adults did not appear to be affected by the soil insecticide treatment, the effects on the larvae are uncertain.

Laboratory Studies.

Effects of Pesticides on B. quadrimaculatum Adults. All of the insecticides tested were extremely toxic to B. quadrimaculatum adults (Table 5). The herbicide, glyphosate, produced 100% mortality. This was not unexpected because carabids are known to be intolerant to many herbicides (Thiele 1977, Freitag 1979). Maneb produced only 40% mortality at 0.1% solution, but this dose is 3.75x less than the recommended field rate. Foliar pesticides, in general, are probably extremely detrimental to B. quadrimaculatum adults. Populations of these carabids will almost surely be drastically reduced in fields where these pesticides are routinely applied.

Comparing the LC_{50} values of diazinon, fenvalerate and naled obtained for D. antiqua eggs, field-collected adults and laboratory-reared adults with values found for B. quadrimaculatum adults indicates the relative toxicity of these three

Table 4. Mean numbers per replication of Bembidion quadrimaculatum adults trapped in plots sprayed with diazinon and fenvalerate, 1983.

	$\bar{x}$ numbers of B. quadrimaculatum adults trapped[1]	
Treatments	Prior to foliar applications (8-1)	Post application
diazinon	17.25a	2.5a
fenvalerate	15.25a	4.25ab
untreated	17.5a	5.5b

[1]Means followed by the same letter are not significantly different (Student-Newman-Keuls' multiple range test, P > 0.05).

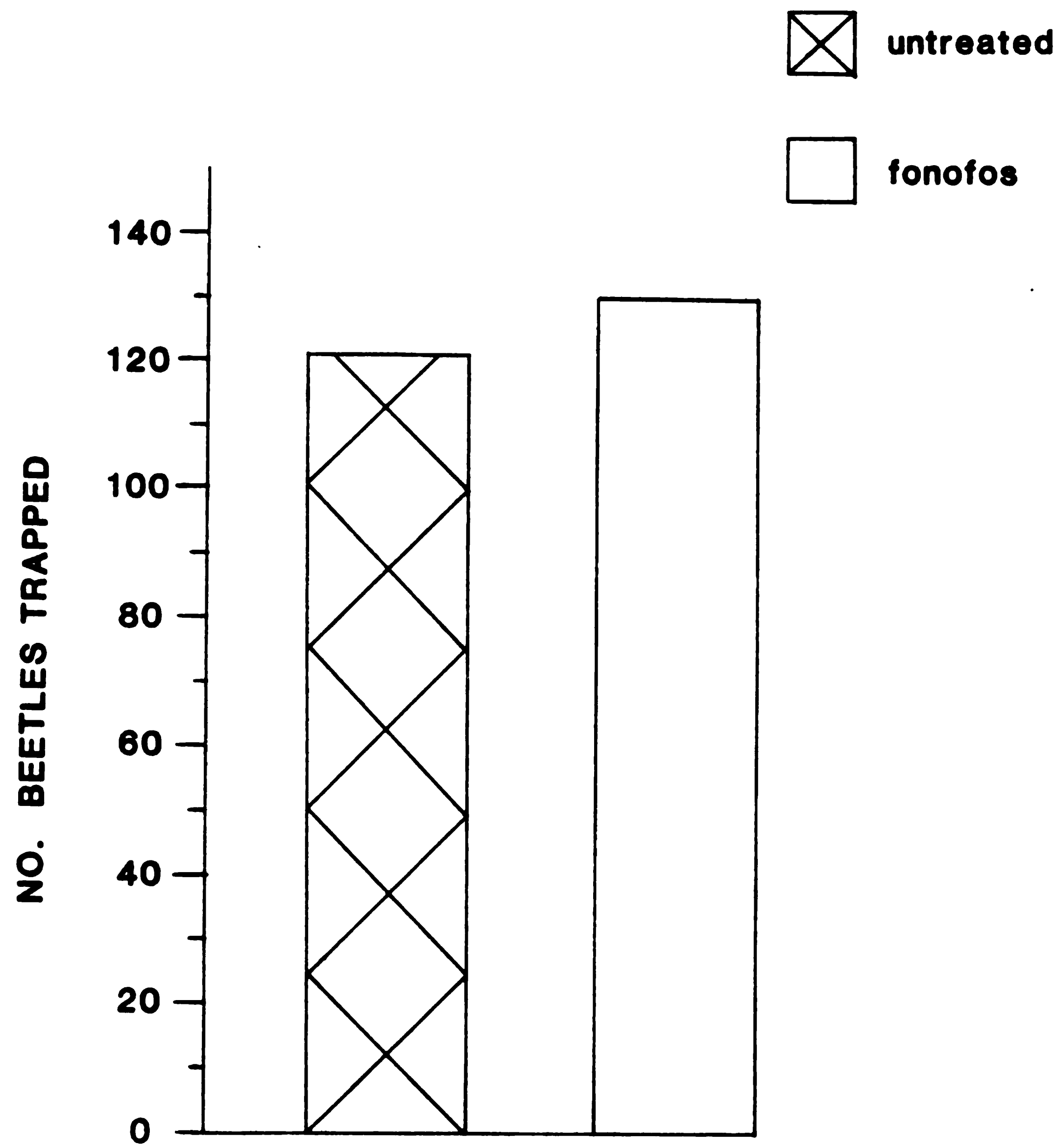

Figure 3. Comparative numbers of Bembidion quadrimaculatum adults trapped from July 16 to August 24, 1983 in an untreated plot and a plot treated with fonofos.

Table 5. Response levels and LC_{50} values with 95% confidence limits (CL) for all pesticide treatments applied in the laboratory studies.

	B. quadrimaculatum		*D. antiqua* eggs		field-collected *D. antiqua* adults		lab-reared *D. antiqua* adults	
	LC_{50} (ml. formulation per l.)		CL formulation		LC_{50} (ml. formulation per l.)		CL formulation	
diazinon	1.8	1.93	11.2	11.5	874	898	63.2	71.9
		1.68		11.0		856		55.7
fenvalerate	3.03	3.52	727	822	1490	1510	186	192
		2.55		646		1480		184
naled	2.98	3.46	7.13	8.02	193	209	41.4	47.8
		2.51		6.30		182		35.3
chlorpyrifos	0.62	0.64	18.4	18.8	n.t.		n.t.	
		0.61		18.2				
fonofos	n.t.		8.25	8.48	n.t.		n.t.	
				8.08				
maneb	a		c		n.t.		n.t.	
glyphosate	b		c		n.t.		n.t.	

n.t. = not tested
a = LC_{50} value not obtained, but produced 40% mortality at .1% solution
b = produced 100% mortality at 1.25% solution
c = not significantly different from control mortality at any solution tested, P = 0.05

insecticides to the pest organisms and the beetle. Some of the ratios are extremely high (Figure 4). For example, fenvalerate was found to be 492x more toxic to B. quadrimaculatum adults than to field-collected onion maggot adults. Obviously, doses of insecticide required to control D. antiqua (especially the adults) are going to kill B. quadrimaculatum adults.

Effects of Pesticides on D. antiqua Eggs. All of the insecticides tested, with the exception of fenvalerate were extremely toxic to D. antiqua eggs (Table 5). However, glyphosate and maneb produced no significant mortality at any solution tested (S.N.K. multiple range test, P = 0.05). From these results, it would seem possible to achieve excellent control of onion maggot populations by the use of well-timed insecticide applications (e.g. drench applications of diazinon) aimed at the eggs. However, only marginal control is obtained in the field (Grafius, et al. 1983a). Insecticide resistance may be present in the eggs of D. antiqua. However, a comparison of eggs obtained from laboratory-reared flies and eggs oviposited by field-collected flies did not support this (Student's t-test, P = 0.01). Therefore, other phenomena (e.g. degradation of the insecticide, binding of the insecticide by soil particles, etc.) account for the less than anticipated onion maggot control achieved by soil drenches.

Effects of Insecticides on D. antiqua Adults. D. antiqua adults, most notably field-collected adults, appear tolerant to the insecticides tested (Table 5). In fact, the field-collected adults were 14x more tolerant to diazinon, 8x more tolerant to fenvalerate and 4.7x more tolerant to naled than the laboratory-reared flies. This was not surprising because flies from Grant, Michigan are known to be resistant to many insecticides and this resistance is rapidly increasing (Harris et al. 1981).

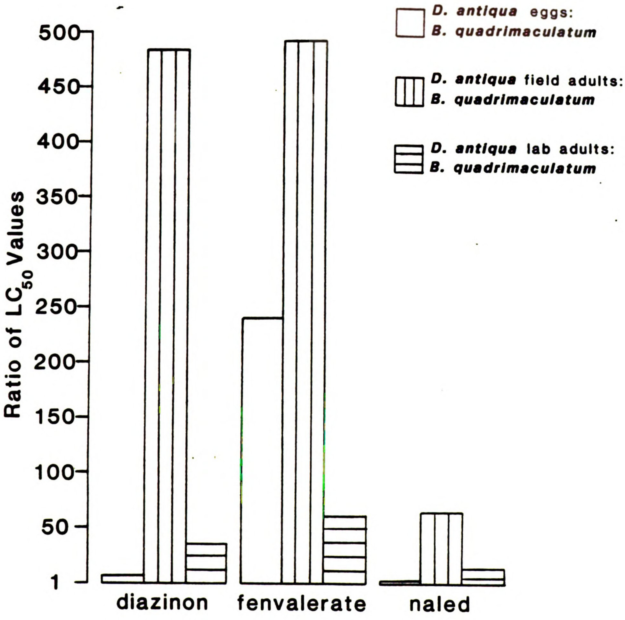

Figure 4. Ratios of LC_{50} values obtained for Bembidion quadrimaculatum, Delia antiqua eggs, D. antiqua eggs, D. antiqua field-collected adults and D. antiqua laboratory-reared adults during laboratory studies.

Examination of the log dose-probit mortality regression equations obtained for the two strains of flies reveals nearly identical slopes (Figures 5-7). This may be an indication that resistance is already a serious problem. Often, when testing insects that are developing insecticide resistance, the slope of the line changes and the line moves to the right compared to a line obtained for a non-resistant strain. If the onset of a resistance problem is detected, resistance management can be employed (Matsumura 1983). However, once resistance has become fixed, management is much more difficult.

It appears obvious that no insecticide spray programs should be employed against D. antiqua adults in the field. The flies are difficult to kill and additional insecticide pressure favors resistance buildup. In fact, the use of foliar sprays to reduce D. antiqua damage has been shown to be ineffective (Warner and Grafius 1981, Whitfield 1981). In addition, this heavy insecticide pressure is detrimental to the natural enemies of the pest such as B. quadrimaculatum, the braconid, Aphaereta pallipes (Say) and the tigerfly, Coenosia tigrina (Fabricus) (Carruthers 1981).

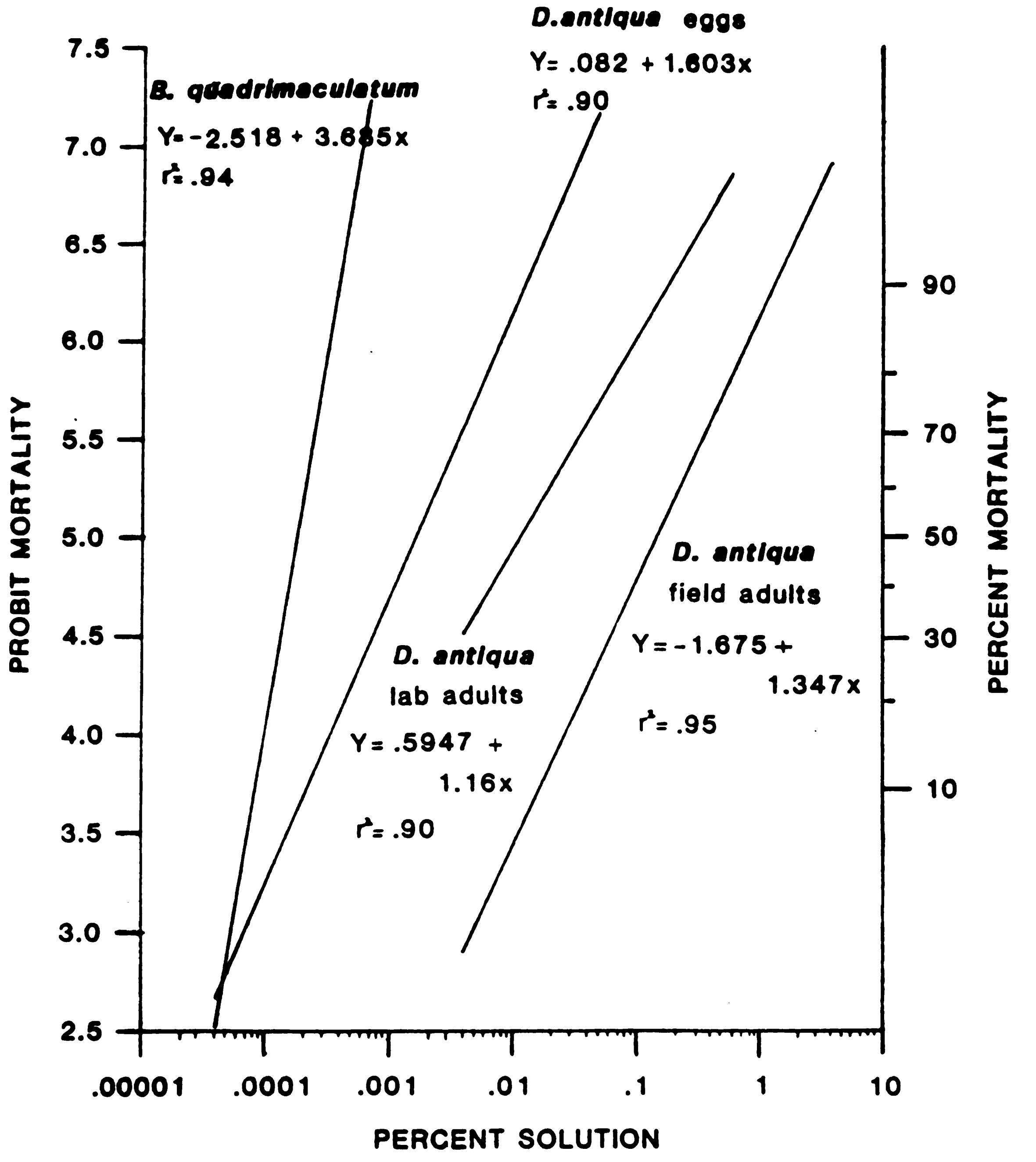

Figure 5. Log dose-probit mortality regressions for Bembidion quadrimaculatum, Delia antiqua eggs, D. antiqua field-collected adults and D. antiqua laboratory-reared adults exposed to diazinon.

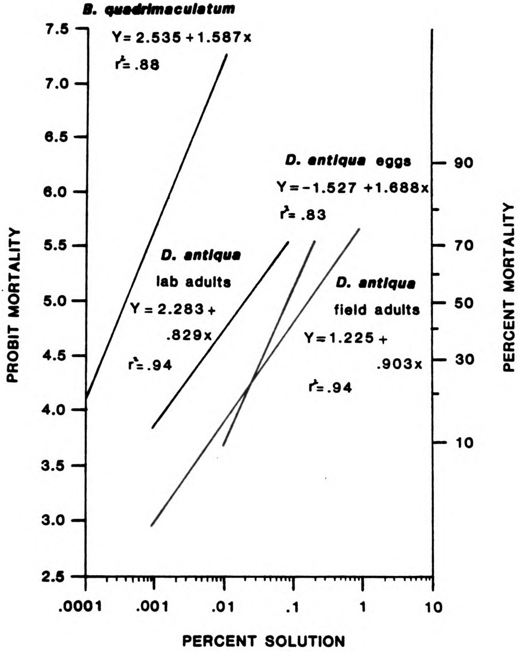

Figure 6. Log dose-probit mortality regressions for Bembidion quadrimaculatum, Delia antiqua eggs, D. antiqua field-collected adults and D. antiqua laboratory-reared adults exposed to fenvalerate.

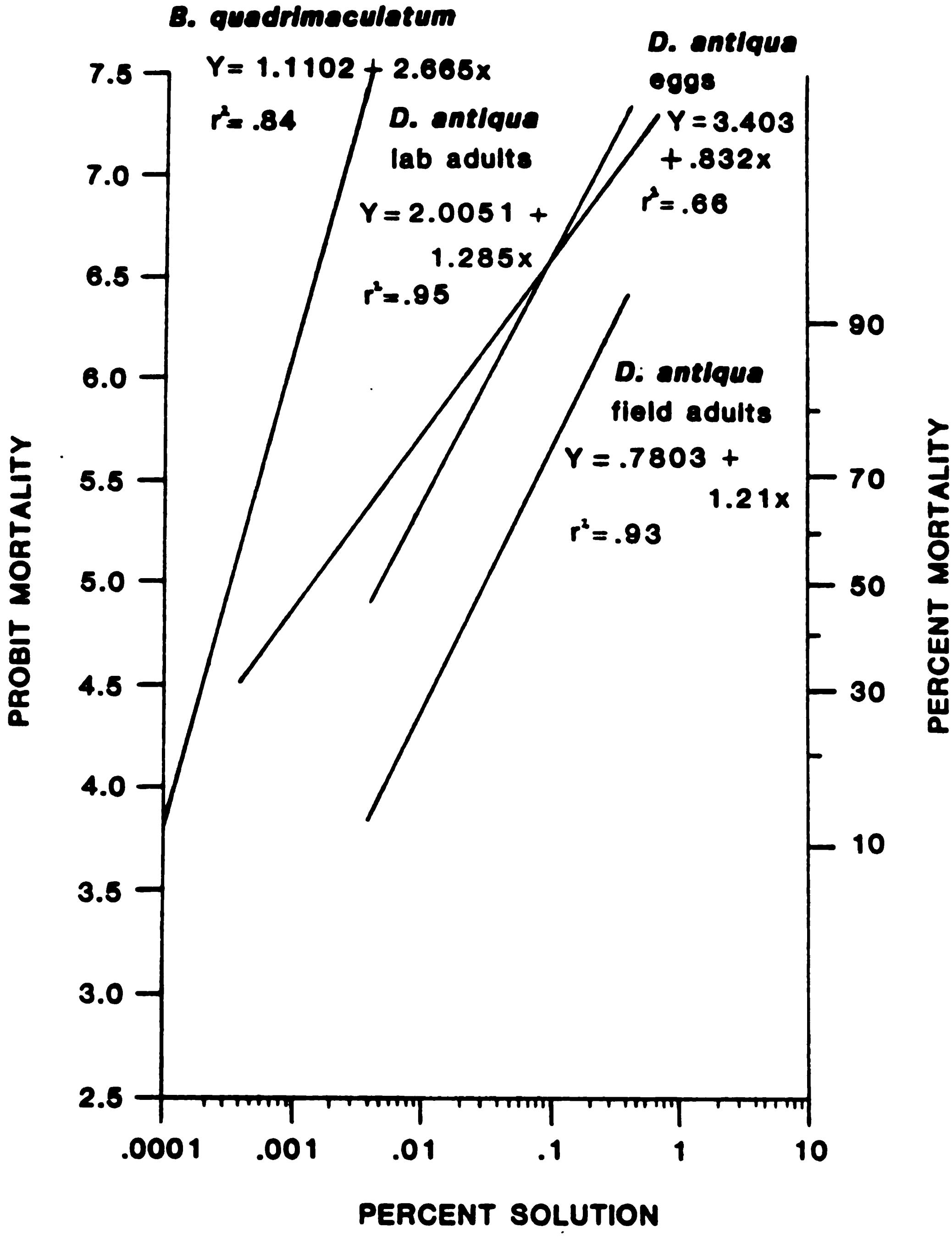

Figure 7. Log dose-probit mortality regressions for Bembidion quadrimaculatum, Delia antiqua eggs, D. antiqua field-collected adults and D. antiqua laboratory-reared adults exposed to naled.

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REFERENCES CITED

Abbott, W. S. 1925. A method of computing the effectiveness of an insecticide. J. Econ. Ent. 18:265-267.

Carruthers, R. I. 1981. The biology and ecology of Entomophthora muscae (Cohn) in the onion agroecosystem. Ph.D. Thesis. Michigan State University, East Lansing. 238 pp.

Critchley, B. R. 1972. A laboratory study of the effects of some soil-applied organophosphorus pesticides on Carabidae (Coleoptera). Bull. Ent. Res. 62:229-242.

Drew and Guyer. 1958. Test method for evaluating insecticides against the onion maggot. Proc. North Cent. Branch Entomol. Soc. Amer. 13:43-44.

Drummond, F. A. 1982. Post-harvest biology of the onion maggot, Hylemya antiqua (Meigen). M.S. Thesis. Michigan State University. 353 pp.

Freitag, R. 1979. Carabid beetles and pollution. Pages 507-521 in Carabid beetles: their evolution, natural history and classification. Proc. of the First Int. Symp. of Carabidology. Smithsonian Institution, Washington, D. C. August 21, 23 and 25, 1976. Dr. W. Junk bv Publishers, The Hague-Boston-London.

Grafius, E. J., F. W. Warner and M. Mitchell. 1983a. Onion maggot control, 1983. Insecticide and Acaricide Tests 8:155-158.

Grafius, E. J., F. W. Warner and M. Mitchell. 1983b. Thrips control in onions, 1983. Insecticide and Acaricide Tests 8:159-160.

Harris, C. R. and H. J. Svec. 1976. Onion maggot resistance to insecticides. J. Econ. Ent. 69(5):617-620.

Harris, C. R., H. J. Svec, J. H. Tolman, A. D. Tomlin and F. L. McEwen. 1981. A rational integration of methods to control onion maggot in southwestern Ontario. Proc. Br. Crop Protection Conf.--Pests and Diseases. 789-799.

Kendall, E. W., Jr. 1932. Notes on the onion maggot (Hylemya antiqua (Meig.)). Rep. Entomol. Soc. Ont. 62:82-84.

Matsumura, F. 1983. Personal communication. Department of Entomology, Michigan State Universty.

Mowat, D. J. and T. H. Coaker. 1967. The toxicity of some soil insecticides to carabid predators of the cabbage root fly (Erioischia brassicae (Bouche)). Ann. Appl. Biol. 59:349-354.

Thiele, H. U. 1977. Carabid beetles in their environments. Zoophysiology and Ecology 10. Springer-Verlag, Berlin, Heidelberg, New York. 369 pp.

Thomas, D. B., Jr. and E. L. Sleeper. 1977. The use of pitfall traps for estimating the abundance of arthropods with special reference to the Tenebrionidae (Coleoptera). Ann. Entomol. Soc. Amer. 70:242-248.

Tomlin, A. D. 1975. The toxicity of insecticides by contact and soil treatment to two species of ground beetles (Coleoptera: Carabidae). Can. Entomol. 107:529-532.

Warner, F. W. 1986. Bembidion quadrimaculatum L. predation on the eggs of the onion maggot (Delia antiqua (Meigen)). M.S. Thesis. Michigan State University.

Warner, F. W. and E. J. Grafius. 1981. Unpublished data. Department of Entomology, Michigan State University.

Whitfield, G. H. 1981. Spatial and temporal population analysis of the onion maggot, (Hylemya antiqua (Meig.)) in Michigan. Ph.D. Thesis. Michigan State Univeristy. 379 pp.

CONCLUSION

Summary

Bembidion quadrimaculatum L. is one of the most abundant carabids found in Michigan onion fields (Motyka and Edens 1984). These beetles are opportunistic feeders, but do show a preference for onion maggot eggs and first instar larvae. In the laboratory, B. quadrimaculatum adults consumed up to 25 Delia antiqua (Meigen) eggs per day.

B. quadrimaculatum adults do not apparently exploit the subterranean habitat. In a laboratory study, onion maggot larval numbers were reduced 70% when eggs were placed on the soil surface but only 17.5% when eggs were in the soil. These beetles do not appear to possess an effective mechanism for sensing prey, so searching is undoubtedly more rapid on than beneath the soil surface.

B. quadrimaculatum adults exhibit two periods of peak activity per year in Michigan. Overwintering adults become active in the spring; the second period of activity occurs in the fall (August-October). These activity peaks correspond roughly with spring and fall D. antiqua egg laying.

In a field cage study, B. quadrimaculatum adults reduced onion maggot larval numbers 57%. In this study, regardless of the number of beetles placed in each enclosure, maggot numbers were reduced. However, at best, only 43% of the variation in the numbers of surviving onion maggot larvae was explained by beetle numbers.

Insecticides are extremely toxic to B. quadrimaculatum. In the field, diazinon was more toxic than fenvalerate. The soil insecticides, fonofos and chlorpyrifos, reduced B. quadrimaculatum numbers in 1982. In the laboratory, diazinon was 485X, fenvalerate 492X and naled 65X more toxic to B. quadrimaculatum adults than to field-collected D. antiqua adults. It was concluded that, because these flies are difficult to kill, spray programs aimed at D. antiqua adults should be avoided. This unwarranted insecticide use can drastically reduce numbers of B. quadrimaculatum and other natural enemies of the pest (Carruthers 1981).

Augmenting naturally occurring
B. quadrimaculatum populations

Heavy insecticide pressure (soil insecticide at planting and 0-15 foliar applications during the growing season) is exerted upon the onion maggot by commercial onion growers. The majority of this insecticide use is unwarranted for onion maggot control because foliar sprays are not required to reduce damage caused by this pest (Warner and Grafius 1981, Whitfield 1981). This misuse of insecticide is unfortunate because while not reducing crop damage, it has all but obliterated many natural enemies of the maggot in commercial fields, including B. quadrimaculatum (Motyka and Edens 1984).

In order to attain and sustain a significant natural population of B. quadrimaculatum in commercial onion fields in Michigan, a drastic reduction in the use of pesticides is necessary. Presently, however, this does not appear to be acceptable to commercial onion growers. Therefore, the establishment of substantial B. quadrimaculatum and other beneficial insect populations capable of checking onion maggot outbreaks in onion fields is highly unlikely. The fact remains, that B. quadrimaculatum adults, and other beneficial organisms, are killed by concentrations of pesticides utilized by onion growers to control insects, weeds and fungal diseases (Table 1).

Table 1. Pesticides utilized by commercial onion growers known to be toxic (represented by *) to natural enemies of the onion maggot, Delia antiqua (Meigen), in Michigan.

	Aleochara[1] bilineata (Gyll.)	Aphaereta[2] pallipes (Say)	Bembidion quadrimaculatum L.	Coenosia[2] figrina (Fabricus)	Entomophthora[2] muscae (Cohn)
Insecticides			*		
chlorpyrifos 4EC			*		
diazinon 4EC			*		
fenvalerate 2.4EC		*			
fonofos 10G	*				
malathion		*		*	
naled			*		
Fungicides					
chlorothalonil		*			*
copper sulfate		*			*
maneb		*	*		*
Herbicides					
CDAA		*			
chloro-IPC		*			
glyphosate			*		
nitrofen		*			

[1]from Whitfield 1981.

[2]from Carruthers 1981.

What the future holds, however, for commercial onion growers is uncertain. Growers may be forced to look for alternative control measures due to the lack of effective insecticides (the onion maggot has eventually become resistant to virtually every insecticide used for its control) and to the economics associated with future insecticide use (e.g. increasingly high costs of fossil fuels). If this situation occurs, beneficial insects may hold the key for onion maggot control.

The invasion of onion fields by beneficial organisms will not occur overnight. Because these beneficials have been reduced to extremely low numbers by pesticides, recruitment must occur. Beneficial insects must disperse from adjacent habitats to onion fields to establish natural populations, or large numbers of insects can be released to accelerate this process. However, at this time, the rearing and release of large numbers of B. quadrimaculatum is highly improbable. These carabids are extremely difficult to culture due to the cannibalistic nature of the larvae. To rear large numbers of these insects, the larvae must be housed individually (Goulet 1976). This would not be an efficient use of resources and probably would not be economically feasible (cost of environmental chambers, labor, etc.). In addition, these beetles cannot be handled and released as easily as parasitoids.

B. quadrimaculatum adults rarely fly, so recruitment from neighboring habitats into onion fields may require a great deal of time, possibly 6 or 7 years (estimates used in this calculation; starting population = .1 B. quadrimaculatum adult/m^2, desired natural population = 6 adults/m^2, immigration from adjacent habitats = .2 adult/m^2, sex ratio 1:1, each female lays 16 eggs with 4 surviving to the adult stage, adult mortality = 50%). So, to aid in the recruitment of B. quadrimaculatum and other natural enemies into commercial onion fields, "nurseries" should be established adjacent to these fields. A nursery should be an area where beneficial insects are allowed to thrive. It could consist of a block of land (30 m x 30 m) where onions would be planted (maggots would surely infest the onions to ensure a food and host supply for the beneficials and the onions could possibly serve as a trap crop), weeds would be allowed (they would offer shelter and would serve as sites for flies infected by Entomophthora muscae (Cohn) (Carruthers 1981) to die) and most importantly these areas would be free of pesticides. In the fall, this block of land could be disked along with the neighboring onion fields and subsequently replanted in the spring. Carabid populations would not be disrupted because species that commonly inhabit cultivated fields are unaffected by cultivation practices or harvesting (Thiele 1977). Eventually this nursery area could serve as an index for the potential of biological control.

Bembidion quadrimaculatum and other carabids as biological control agents

B. quadrimaculatum adults (and possibly the larvae) can reduce onion maggot larval numbers in the field. However, B. quadrimaculatum is only one of over 50 species of Carabidae known to inhabit Michigan onion fields (Motyka and Edens 1984). Many of these carabids (e.g. Stenolophus comma and Anisodactylus sanctaecrucis) are known to feed on root maggot eggs and larvae (Wyman et al. 1976, Drummond 1982). Therefore, all of these species in combination may be capable of checking onion maggot populations.

Carabids are found in virtually all agricultural croplands (Allen 1979). They are an extremely successful group of insects (40,000 species described, Thiele 1977) largely due to the fact that they are almost uncontested in their ecological niche (their niche is partially overlapped by staphylinids and centipedes and shared by lycosid spiders, Thiele 1977). Because they are beneficial and quite frequently occur in large numbers in agricultural croplands (i.e. B. quadrimaculatum densities as high as 20/m^2 have been reported, Frank 1971a), it seems reasonable to suggest that they warrant attention when implementing integrated pest management programs. The impact carabids have on pest populations, especially root maggot populations, should not be overlooked.

APPENDIX

(Footnotes for Figure 1)

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(Footnotes for Figure 1)

Footnote 1:

Nye, P. H. et al. 1975. The possibility of predicting solute uptake and plant growth response form independently measured soil and plant characteristics. Plant and Soil 42:161-70.

Robinson, J. C. 1973. Studies on the performance and growth of various short-day onion varieties (*Allium cepa* L.) in the Rhodesian low veld in relation to date of sowing. Rhod. J. Agric. Res. 11:51-69.

Footnote 2:

Hancock, J. G. and J. W. Lorbeer. 1963. Pathogenesis of *Botrytis cinerea*, *B. squamosa* and *B. allii* on onion leaves. Phytopathology. 53:669-73.

Footnote 3:

Ellington, J. J. 1963. Field and laboratory observations on the life history of the onion maggot, *Hylemya antiqua* (Meigen). Ph.D. thesis, Cornell University. 124 pp.

Kendall, E. W. 1932. Notes on the onion maggot, *Hylemya antiqua* (Meigen). Entomol. Soc. Ontario Rep. 62:82-84.

Footnote 4:

Lewis, T. 1973. Thrips, their biology, ecology and economic importance. New York: Academic, 366 pp.

Footnote 5:

Martin, G. C. 1958. Root-knot nematodes (Meloidogyne spp.) in the federation of Rhodesia and Nyasaland. Nematologica 4:122-25.

USDA. 1960. Index of Plant Diseases in the United States, Agriculture Handbook, No. 165. Crops Research Division, Ag. Research Service, USDA. p. 365.

Footnote 6:

Sprague, R. 1950. Diseases of Cereals and Grasses of North America. Ronald Press, New York.

Footnote 7:

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua, under field conditions in southwestern Quebec. Ann. Soc. Entomol. Que. 17(1):29-47.

Footnote 8:

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua, under field conditions in southwestern Quebec. Ann. Soc. Entomol. Que. 17(1):29-47.

Footnote 9:

Stoffolono, J. G. 1969. Nematode parasites of the face fly and the onion maggot in France and Denmark. J. Econ. Entomol. 62:792-95.

Footnote 10:

Perron, J. P. and R. Crete. 1960. Premieres observations sur le champignon, Empusa muscae Cohn. (Phycomycetes: Entomophthora) parasitant la mouche de l'oignon, Hylemya antiqua (Meig.) (Dipteres: Anthomyiidae) dans le Quebec. Ann. Entomol. Soc. Quebec 5:52-56.

Footnote 11:

Perron, J.P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua, under field conditions in southwestern Quebec. Ann. Soc. Entomol. Que. 17(1):29-47.

Footnote 12:

Russell, H. M. 1912. An internal parasite of Thysanoptera. Tech. Ser. Bur. Ent. U.S. 23:25-52.

Footnote 13:

Charles, V. K. 1941. A preliminary checklist of the entomogenous fungi of North America. Tech. Bull. U.S. Dep. Agric. 21:707-85.

Footnote 14:

Cobb, N.A. 1917. The Mononchs, a genus of free-living predatory nematodes. Soil Science. 3:431-86.

Footnote 15:

Mankau, R. et al. 1975. The life cycle of an endoparasite in some tylenchid nematodes. Nematologica 21:89-94.

Footnote 16:

Connard, M. H. and P. W. Zimmerman. 1931. Origin of adventitious roots in cutting of *Portulaca oleracea*. Contrib. Boyce Thompson Inst. Plant Res. 3:331-46.

Zimmerman, C. A. 1969. The causes and characteristics of weediness in *Portulaca oleracea* L. Ph.D. Thesis, University of Michigan. 248 pp.

Footnote 17:

Shorthouse, J. D. and A. K. Watson. Plant galls and the biological control of weeds. Insect World Digest, pp. 8-11.

Footnote 18:

Sawyer, A. J. 1976. The effect on the cereal leaf beetle of planting oats with a companion crop. M.S. Thesis, Michigan State University. 145 pp.

Footnote 19:

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, *Hylemya antiqua*, under field conditions in southwestern Quebec. Ann. Soc. Entomol. Que. 17(1):29-47.

Footnote 20:

Webster, J. M. 1972. Nematodes and biological control, pp. 469-96. In: Webster (Ed.) Economic Nematology. Academic Press, N.Y.

Footnote 21:

Gorske, S. F. 1973. The bionomics of the purslane sawfly, Schizocerella pilicornis. M.S. Thesis, University of Illinois. 108 pp.

Footnote 22:

USDA. 1960. Index of plant diseases in the United States. Agriculture Handbook No. 165. Crops Res. Div., Agric. Res. Ser. 531 pp.

Footnote 23:

USDA. 1960. Index of plant diseases in the United States. Agriculture Handbook No. 165. Crops res. Div., Agric. Res. Ser. 531 pp.

Footnote 24:

USDA. 1960. Index of plant diseases in the United States. Agriculture Handbook No. 165. Crops Res. Div., Agric. Res. Ser. 531 pp.

Footnote 25:

Goeden, R. D. et al. 1974. Present states of projects on the biological control of weeds with insects and plant pathogens in the United States and Canada. Weed Science 22:490-95.

Footnote 26:

Breeland, S. G. 1958. Biological studies on the armyworm, Pseudaletia unipuncta (Haworth) in Tenessee. J. Tenn. Acad. Sci. 33:263-347.

Footnote 27:

Helgesen, R. G. and D. L. Haynes. 1972. Population dynamics of the cereal leaf beetle, Oulema melanopus (Coleoptera: Chrysomelidae): a model for age specific mortality. Can. Entomol. 104:797-814.

Tummala, R. L. et al. A discrete component approach to the management of the cereal leaf beetle ecosystem. Environ. Entomol. 4:175-86.

Footnote 28:

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua, under field conditions in southwestern Quebec. Ann Soc. Entomol. Que. 17(1):29-47.

Footnote 29:

Webster, F. M. and C. W. Mally. 1900. The purslane sawfly -- Schizocerus zabreskei. Can. Entomol. 32:51-55.

Footnote 30:

Gorske, S. F. 1973. The bionomics of the purslane sawfly, Schizorella pilicornia (Meig.). M.S. Thesis, University of Illinois. 108 pp.

Footnote 31:

Mankau, R., J. L. Imbiani. 1975. The life cycle of an endoparasite in some tylenchid nematodes. Nematologica 21:89-94.

Footnote 32:

Webster, J. M. 1972. Nematodes and biological control, pp. 469-496. In: J. M. Webster (ed.) Economic Nematology. Academic Press, N.Y.

Footnote 33:

Cobb, N.A. 1913. Notes on mononchus and tylenchulus. Washington Acad. Sci. 3:287-88.

Cobb, N. A. 1917. The mononchs, a genus of free-living predatory nematodes. Soil Science 3:431-486.

Footnote 34:

Raulin, F. W. 1975. A revision of the genus Archytas (Diptera Tachindae) for America north of Mexico. M.S. Thesis. Michigan State University. 80 pp.

Footnote 35:

Danks, H. V. 1975. Factors determining levels of parasitism by Winthemia rufopicta (Diptera: Tachinidae), with particular reference to Heliothis spp. (Lepidoptera: Noctuidae) as hosts. Can. Entomol. 107:555-684.

Danks, H. V. 1975. Seasonal cycle and biology of *Winthemia rufopicta* (Diptera: Tachinidae) as a parasite of *Heliothis* spp. (Lepidoptera: Noctuidae) on tobacco in North Carolina. Can. Entomol. 107:639-54.

Footnote 36:

Gage, S. H. and D. L. Haynes. 1975. Emergence under natural and manipulated conditions of *Tetrastichus julis*, an introduced larval parasite of the cereal leaf beetle, with reference to regional population management. Environ. Entomol. 4(3):425-34.

Footnote 37:

Maltby, H. I., F. W. Stehr, R. C. Anderson, G. E. Moorehead, L. C. Barton and J. D. Paschke. 1971. Establishment in the United States of *Anaphes flavipes* (Foerster), an egg parasite of the cereal leaf beetle, *Oulema melanopus* (L.) J. Econ. Entomol. 64:693-97.

Footnote 38:

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, *Hylemya antiqua* (Meig.), under field conditions in southwestern Quebec. Ann. Soc. Entomol. Que. 17(1):29-47.

Footnote 39:

Thompson, W. R. 1943. A catalogue of the parasites and predators of insect pests. Sect. I, Pt. 2. Belleville, Ontario, Canada. The Imperial Parasite Service. 99 pp.

Footnote 40:

USDA. 1960. Index of plant diseases in the United States. Agriculture Handbook No. 175. Crops Res. Div., Agric. Res. Ser., p. 280.

Footnote 41:

Gorlenko, M. V., I. V. Voronkevich and T. S. Maksimova. 1956. Mutual relations between the onion fly and onion syrphid and the bacteria that cause damp rots in plants. (in Russian) Zool. Zh. 35 pt. 1, pp. 16-20, 6 refs. Moscow, 1956. (With a summary in English, Suppl. p. 4).

Footnote 42:

Newhall, A. G. and B. G. Chitwood. 1940. Onion eelworm or bloat caused by the stem or bulb nematode, Ditylenchus dipsaci. Phytopathology 30:390-400.

Footnote 43:

USDA. 1960. Index of plant diseases in the United States. Agriculture Handbook No. 165. Crops Res. Div., Agric. Res. Ser., p. 365.

REFERENCES

REFERENCES CITED

Abbott, W. S. 1925. A method of computing the effectivenss of an insecticide. J. Econ. Ent. 18:265-267.

Allen, R. T. 1979. The occurrence and importance of ground beetles in agricultural and surrounding habitats. Pages 485-505 in Carabid beetles: their evolution, natural history and classification. Proc. of the First Int. Symp. of Carabidology, Smithsonian Institution, Washington, D. C. August 21, 23, and 25, 1976. Dr. W. Junk by Publishers, The Hague-Boston-London.

Andersen, A. 1982. Carabidae and Staphylinidae (Col.) in swede and cauliflower fields in south-eastern Norway. Fauna norv. Ser. B. 29:49-61.

Andersen, A., A. G. Hansen, N. Rydland and G. Oyre. 1983. Carabidae and Staphylinidae (Col.) as predators of eggs of the turnip root fly Delia floralis Fallen (Diptera, Anthomyiidae) in cage experiments. Z. ang. Ent. 95:499-506.

Andersen, A. and J. A. Sharman. 1983. Effect of chlorfenvinphos and isofenphos on Carabidae and Staphylinidae (Col.), and their predation of eggs of Delia floralis Fallen (Diptera, Anthomyiidae) in field experiments. Z. ang. Ent. 95:206-213.

Baker, A. D. 1927. The habits of the onion maggot flies (Hylemya antiqua Meigen). Rep. Entomol. Soc. Ont. 58:61-67.

Ball, G. E. 1960. Carabidae (Latreille, 1810). Pages 55-181 in R. H. Arnett. The beetles of the United States. The Catholic University of America Press, Washington, D.C.

Best, R. L. and C. C. Beegle. 1977. Food preferences of five species of carabids commonly found in Iowa cornfields. Environ. Entomol. 6(1):9-12.

Carruthers, R. I. 1979. Population sampling and spatial distribution of the immature stages of the onion maggot, Hylemya antiqua (Meigen). M.S. Thesis. Michigan State University. 197 pp.

Carruthers, R. I. 1981. The biology and ecology of Entomophthora muscae (Cohn) in the onion agroecosystem. Ph.D. Thesis. Michigan State University, East Lansing. 238 pp.

Chambers, B. C. 1984. The effects of agroecosystem structure on the population dynamics of Delia antiqua (Meigen). M.S. Thesis. Michigan State University.

Chapman, R. K. and C. J. Eckenrode. 1973. Effect of insecticide placement on predator numbers and cabbage maggot control. J. Econ. Ent. 66(5):1153-1158.

Coaker, T. H. 1965. Further experiments on the effect of beetle predators on the numbers of the cabbage root fly, Erioischia brassicae (Bouche), attacking brassicae crops. Ann. Appl. Biol. 56:7-20.

Coaker, T. H. and D. A. Williams. 1963. The importance of some Carabidae and Staphylinidae as predators of the cabbage root fly, Erioischia brassicae (Bouche). Entomol. Exp. Appl. 6:156-164.

Critchley, B. R. 1972. A laboratory study of the effects of some soil-applied organophosphorus pesticides on Carabidae (Coleoptera). Bull. Ent. Res. 62:229-242.

Davies, M. J. 1953. The contents of the crops of some British carabid beetles. Ent. Mon. Mag. 89:18-23.

Doane, C. C. 1953. The onion maggot in Wisconsin and its relation to rot in onions. Ph.D. Thesis. University of Wisconsin. 125 pp.

Drew and Guyer. 1958. Test method for evaluating insecticides against the onion maggot. Proc. North Cent. Branch Entomol. Soc. Amer. 13:43-44.

Drummond, F. A. 1982. Post-harvest biology of the onion maggot, Hylemya antiqua (Meigen). M.S. Thesis. Michigan State University. 353 pp.

Dudley, J. E. 1925. Cull onions as a trap crop. J. Econ. Ent. 18:639.

Durkis, T. J. and R. M. Reeves. 1982. Barriers increase efficiency of pitfall traps. Ent. News 93(1):9-12.

Eckenrode, C. J., E. V. Vea and K. W. Stome. 1975. Population trends of onion maggot correlated with air thermal unit accumulations. Environ. Entomol. 4(5):785-789.

Ellington, J. J. 1963. Field and laboratory observations on the life history of the onion maggot Hylemya antiqua (Meigen). Ph.D. Thesis. Cornell University. 124 pp.

Ellis, P. R. and C. J. Eckenrode. 1979. Factors influencing resistance in Allium sp. to onion maggot. Bull. Entomol. Soc. Amer. 25:151-153.

Esau, K. L. and D. C. Peters. 1975. Carabidae collected in pitfall traps in Iowa cornfields, fencerows and prairies. Environ. Entomol. 4(3):509-513.

Finlayson, D. G., J. R. MacKenzie and C. J. Campbell. 1980. Interactions of insecticides, a carabid predator, a staphylinid parasite, and cabbage maggots in cauliflower. Environ. Entomol. 9(6):789-794.

Fitch, A. 1867. Noxious, beneficial and other insects of New York. New York Agric. Soc. Rep. 11:31-38.

Frank, J. H. 1971a. Carabidae (Coleoptera) of an arable field in Central Alberta. Quaest. Entomol. 7(2):237-252.

Frank, J. H. 1971b. Carabidae (Coleoptera) as predators of the red-backed cutworm (Lepidoptera: Noctuidae) in Central Alberta. Can. Entomol. 103:1039-1044.

Freitag, R. 1979. Carabid beetles and pollution. Pages 507-521 in Carabid beetles: their evolution, natural history and classification. Proc. of the First Int. Symp. of Carabidology. Smithsonian Institution, Washington, D. C. August 21, 23 and 25, 1976. Dr. W. Junk by Publishers, The Hague-Boston-London.

Freitag, R., G. W. Ozburn and R. E. Leech. 1969. The effects of sumithion and phosphamidon on populations of five carabid beetles and the spider Trochosa terricola in northwestern Ontario and including a list of collected species of carabid beetles and spiders. Can. Entomol. 101:1328-1333.

Gostick, K. G., D. F. Powell and C. Slough. 1971. Dieldrin-resistant onion fly (Delia antiqua Meig.)) in England. Plant Pathol. 20:63-65.

Goulet, Henri. 1976. A method for rearing ground beetles (Coleoptera: Carabidae) Coleopterists Bull. 30(1):33-36.

Grafius, E. F. W. Warner and M. Mitchell. 1983a. Onion maggot control, 1983. Insecticide and Acaricide Tests 8:155-158.

Grafius, E. F. Warner and M. Mitchell. 1983b. Thrips control, 1983. Insecticide and Acaricide Tests 8:159-160.

Greenslade, P. J. M. 1964. Pitfall trapping as a method for studying populations of Carabidae (Coleoptera). J. Animal Ecol. 33:301-310.

Greenslade, P. J. M. 1973. Sampling ants with pitfall traps: digging-in effects. Insectes Soc. 20(4):343-353.

Groden, E. 1982. The interactions of root maggots and two parasitoids Aleochara bilineata (Gyll.) and Aphaereta pallipes (Say). M.S. Thesis. Michigan State University. 152 pp.

Harris, C. R. and H. J. Svec. 1976. Onion maggot resistance to insecticides. J. Econ. Ent. 69(5):617-620.

Harris, C. R., H. J. Svec, J. H. Tolman, A. D. Tomlin and F. L. McEwen. 1981. A rational integration of methods to control onion maggot in southwestern Ontario. Proc. Br. Crop Protection Conf. -- Pests and Diseases. 789-799.

Harris, M. 1982. Behavior of onion flies. M.S. Thesis. Michigan State University.

Haynes, D. L., R. L. Tummala and T. L. Ellis. 1980. Ecosystem management for pest control. BioScience 30(19):690-696.

Hsin, C., L. G. Sellers and P. A. Dahm. 1979. Seasonal activity of carabids and the toxicity of carbofuran and terbufos to Pterostichus chalcites. Environ. Entomol. 8(1):154-159.

Hughes, R. D. 1959. The natural mortality of Erioischia brassicae (Bouche) (Diptera, Anthomyiidae) during the egg stage of the first generation. J. Animal. Ecol. 28:343-357.

Humphrey, B. J. and P. A. Dahm. 1976. Chlorinated hydrocarbon insecticide residues in Carabidae and the toxicity of dieldrin to Pterostichus chalcites. Environ. Entomol. 5(4):729-734.

Johnson, N. E. and R. Scott Cameron. 1969. Phytophagous ground beetles. Ann. Entomol. Soc. Amer. 62(4):909-914.

Kendall, E. W., Jr. 1932. Notes on the onion maggot (Hylemya antiqua (Meig.)). Rep. Entomol. Soc. Ont. 62:82-84.

Kirk, V. M. 1971a. Ground beetles in cropland in South Dakota. Ann. Entomol. Soc. Amer. 64(1):238-241.

Kirk, V. M. 1971b. Biological studies of a ground beetle, Pterostichus lucublandus. Ann. Entomol. Soc. Amer. 64(3)540-544.

Kirk, V. M. 1972. Identification of ground beetle larvae found in cropland in South Dakota. Ann. Entomol. Soc. Amer. 65(6):1349-1356.

Kirk, V. M. 1975. Biology of Stenolophus (=Agnoderus) comma, a ground beetle of cropland. Ann. Entomol. Soc. Amer. 68(1):135-138.

Kirk, V. M. 1982. Carabids: minimal role in pest management of corn rootworms. Environ. Entomol. 11(1):5-8.

Lindroth, C. H. 1969. The ground beetles of Canada and Alaska-parts 1-6. Opusc. Entomol. Suppl. 20, 24, 29, 33, 34 and 35.

Loosjes, M. 1976. Ecology and genetic control of the onion fly, Hylemya antiqua (Meig.). Agric. Res. Rep. 857. Pudoc, Wageningen. 179 pp.

Los, L. M. and W. A. Allen. 1983. Abundance and diversity of adult Carabidae in insecticide-treated and untreated alfalfa fields. Environ. Entomol. 12(4):1068-1072.

Luff, M. L. 1975. Some features influencing the efficiency of pitfall traps. Oecologia 19:345-357.

Lund, R. D. and F. T. Turpin. 1977. Carabid damage to weed seeds found in Indiana cornfields. Envron. Entomol. 6(5):695-698.

Matsumura, F. 1983. Personal communication. Department of Entomology, Michigan State University.

Miles, M. 1953. Study of British anthomyiid flies. V. The onion fly, Delia antiqua. Bull. Ent. Res. 44:583:588.

Mitchell, B. 1963. Ecology of two carabid beetles Bembidion lampros (Herbst) and Trechus quadristriatus (Schrank). J. Animal Ecol. 32:377-392.

Motyka, G. and T. C. Edens. 1984. A comparison of heterogeneity and abundance of pests and beneficials across a spectrum of chemical and cultural controls. Prepared for submission to the E.P.A.

Mowat, D. J. and T. H. Coaker. 1967. The toxicity of some soil insecticides to carabid predators of the cabbage root fly (Erioischia brassicae (Bouche)). Ann. Appl. Biol. 59:349-354.

Pausch, R. D. and L. M. Pausch. 1980. Observations on the biology of the slender seedcorn beetle, Clivina impressifrons (Coleoptera: Carabidae). Great Lakes Entomol. 13(4):189-194.

Perron, J. P. 1972. Effects of some ecological factors on populations of the onion maggot, Hylemya antiqua (Meig.), under field conditions in Southwestern Quebec. Ann. Ent. Soc. Quebec 17:29-45.

Perron, J. P. and J. LaFrance. 1961. Notes on the life-history of the onion maggot, Hylemya antiqua (Meig.), under field conditions in Southwestern Quebec. Ann. Ent. Soc. Quebec 17:29-45.

Pimentel, D. and A. G. Wheeler. 1973. Species and diversity of arthropods in the alfalfa community. Environ. Entomol. 2:659-688.

Rivard, I. 1964a. Carabid beetles (Coleoptera: Carabidae) from agricultural lands near Belleville, Ontario. Can. Entomol. 96-517-520.

Rivard, I. 1964b. Observations on the breeding periods of some ground beetles (Coleoptera: Carabidae) in eastern Ontario. Can. J. Zool. 42:1081-1084.

Southwood, T. R. E. 1978. Ecological methods, 2nd ed. Chapman and Hall, London. 524 pp.

Thiele, H. U. 1977. Carabid beetles in their environments. Zoophysiology and Ecology 10. Springer-Verlag, Berlin, Heidelberg, New York. 369 pp.

Thomas, D. B., Jr. and E. L. Sleeper. 1977. The use of pitfall traps for estimating the abundance of arthropods with special reference to the Tenebrionidae (Coleoptera). Ann. Entomol. Soc. Amer. 70:242-248.

Tomlin, A. D. 1975. The toxicity of insecticides by contact and soil treatment to two species of ground beetles (Coleoptera: Carabidae). Can. Entomol. 107:529-532.

Tomlin, A. D. 1982. Personal communication. Research Centre, Agriculture Canada. London, Ontario.

Treherne, R. C. 1916. The cabbage maggot in British Columbia (Phorbia brassicae). The natural control by parasites and predaceous insects. Rep. Entomol. Soc. Ont. 46:140-145.

Warner, F. W. 1986. Bembidion quadrimaculatum L. predation on the eggs of the onion maggot (Delia antiqua (Meigen)). M.S. Thesis. Michigan State University.

Warner, F. W. and E. Grafius. 1981. Unpublished data. Department of Entomology, Michigan State University.

Whitfield, G. H. 1981. Spatial and temporal population analysis of the onion maggot, (Hylemya antiqua (Meig.)) in Michigan. Ph.D. Thesis. Michigan State University. 379 pp.

Wishart, G., J. F. Doane and G. E. Maybee. 1956. Notes on beetles as predators of eggs of Hylemya brassicae (Bouche) (Diptera: Anthomyiidae). Can Entomol. 88:634-639.

Workman, R. B., Jr. 1958. The biology of the onion maggot, Hylemya antiqua (Meigen), under field and greenhouse conditions. Ph.D. Thesis. Oregon State College, Corvallis. 82 pp.

Wright, D. W., R. D. Hughes and J. Worrall. 1960. The effect of certain predators on the numbers of cabbage root fly (Erioischia brassicae (Bouche)) and on the subsequent damage caused by the pest. Ann. App. Biol. 48(4):756-763.

Wyman, J. A., J. L. Libby and R. K. Chapman. 1976. The role of seedorn beetles in predation of cabbage maggot immature stages. Environ. Entomol. 5(2):260-263.