WESTERN CORN ROOTWORM DAMAGE ASSESSMENT IN VIRGINIA AND ADULT SAMPLING WITH COMMERCIAL YELLOW STICKY TRAPS

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ABSRACT

The risk of corn rootworm damage to continuously-grown corn was assessed in 32 fields from seven counties in Virginia in 1993 and 1994. Approximately 28% of the fields examined had economic root damage in corn left untreated with a soil insecticide. In addition, 19% of the fields overall had an economic loss in silage due to corn rootworm damage.

A second study evaluated the effectiveness of using adult corn rootworm counts on commercial Olson yellow sticky traps and ear-zone regions of corn plants to predict subsequent damage to corn. Regression models for each sampling method were used to calculate economic thresholds of 20 adults per trap per wk for the Olson trap and 0.3 adults per stalk for the ear-zone visual count method. Adult counts on Olson traps obtained in mid-Aug correctly predicted economic damage to corn 81% of the time, and resulted in only one serious error of failing to predict economic damage to corn. A sampling plan for the use of Olson traps is suggested.

A third study investigated a possible sexual dimorphism in the elytra coloration pattern of western corn rootworm, and compared the sex ratio of adults captured yellow sticky traps with those obtained by aspiration. Striped and solid variations in elytra pattern were found in both sexes of western corn rootworm; however, 98% of the adults that exhibited the solid elytra pattern were male. The sex ratio of adults varied over time; however, in all cases, sticky traps captured a significantly greater proportion of males compared with aspiration.

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CHAPTER 1

INTRODUCTION

THE WESTERN CORN ROOTWORM (WCR), *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae), is one of the most damaging pests of continuously-grown corn, *Zea mays* (L.), in the United States (Chiang 1978, Metcalf 1986). Total treatment expenses and crop losses from this pest are estimated at $1 billion annually (Metcalf 1986). Although adult WCR feed on corn pollen, silks and leaves, the most important damage to the crop is caused by the larval stage. Larvae chew back and tunnel into the root systems resulting in reduced water and nutrient flow in the plant (Kahler et al. 1985, Riedell 1990) and potential lodging of stalks which may lead to significant reductions in corn yield (Remison and Akinleye 1978, Sutter et al. 1990, Spike and Tollefson 1991). The WCR is a classic example of a man-made pest. Larvae feed specifically on the roots of corn and are almost exclusively limited to this plant as a host (Branson and Ortman 1970, Branson and Krysan 1981). Consequently, crop rotation has been a highly effective management tool for corn rootworms (Chiang 1973, Levine and Oloumi-Sadeghi 1991). However, after the introduction of soil insecticides following World War II, the acreage of continuous corn planted in this country rapidly increased. By the mid-1960's, WCR had evolved resistance to many of the cyclodiene insecticides used for control (Ball and Weekman 1962, 1963). As a result of the insecticide resistance and the established farming practice of planting corn after corn, WCR flourished in the Midwest and quickly spread across the United States (Metcalf 1986). The pest was first reported in Virginia in 1985, and since that time, damage in continuous corn fields has increased dramatically in the state (Youngman and Day 1993). The goal of the research described in this thesis was to advance the understanding of the western corn rootworm and contribute knowledge to the management of the pest in Virginia. The specific objectives of each study were as follows:

1) to assess the risk of western corn rootworm damage in commercial fields grown continuously in corn in Virginia by comparing root damage and silage yields in insecticide-treated and untreated sections of these fields.

2) to develop an economic injury level and evaluate the effectiveness of using counts of western corn rootworm adults captured on commercial Olson yellow sticky traps as a means of predicting subsequent damage to corn.

3) to determine if the difference in striped and solid elytra coloration patterns found in western corn rootworm adults is a sexually-dimorphic trait.

4) to compare the proportions of female western corn rootworm adults captured on two commercial yellow sticky traps with field proportions determined by aspiration.

LITERATURE REVIEW OF WESTERN CORN ROOTWORM

The WCR has been well studied and documented in the literature and extensive reviews of its biology and management can be found in Chiang (1973), Krysan and Miller (1986), and Levine and Oloumi-Sadeghi (1991). In addition, two bibliographies of corn rootworm research, by Irwin (1977) and Levine and Chan (1990), index much of the research on WCR conducted over the past few decades.

SYSTEMATICS and GEOGRAPHIC DISTRIBUTION

Western corn rootworm is most likely Neotropical in origin due to the great diversity of *Diabrotica* that can be found in the tropical regions (Krysan 1982). The catalogue of Wilcox (1965) listed 338 species of *Diabrotica* worldwide, including seven species which occur in the United States (Krysan 1986). Of the seven species found in this country, three are considered important agricultural pests and attack corn. In addition to WCR, these pests include: the northern corn rootworm (NCR), *D. barberi* Smith; southern corn rootworm, *D. undecimpunctata howardi* Barber; and a recently-described subspecies of WCR, the Mexican corn rootworm, *D. virgifera zeae* Krysan and Smith. The northern corn rootworm is an important pest of corn and is closely related to WCR in biology and host specificity. The geographic range of NCR extends across much of the United States; however, the insect seems to reach serious pest densities only in the northern Midwest states and Canada (Krysan 1986). The southern corn rootworm, also known as the spotted cucumber beetle, also feeds on corn, but has a host range of >250 plant species and is an economic pest of peanuts, potatoes, and other vegetable crops. It is not considered to be a major pest of corn because it overwinters in other crops and oviposits in the spring. Larval densities reach damaging levels too late as corn has often matured enough to tolerate their feeding. The Mexican corn rootworm, a subspecies of WCR, is primarily a pest of corn in Mexico and Central America (Krysan 1986). Reports of corn damage by this pest, however, appear to be increasing in the United States, particularly in parts of Texas and Oklahoma (G. L. Teetes, *personal communication*). Of the *Diabrotica*, WCR is the most damaging pest of corn in this country because of its voracious appetite, high reproductive capability, and its ability to outcompete other root-feeding insects, including NCR (Piedrahita et al. 1985).

Archaeological records indicate that *D. v. virgifera* probably immigrated to North America following the introduction of corn cropping during the past 1,000 years (Branson and Krysan 1981). The WCR was first discovered in Kansas feeding on blossoms of buffalo gourd, *Cucurbita foetidissima* HBK (LeConte 1868), and has been reported as a pest of corn since the early part of this century (Gillette 1912, Ainslie 1914). Until the 1940's, the distribution of this pest in the United States remained limited to a handful of states in the Midwest (Smith 1966, Chiang 1973). Following WWII, however, *D. v. virgifera* populations flourished and the geographic range expanded rapidly (Smith 1966, Krysan 1986). Reasons for the success and rapid expansion of WCR include: 1) the ability to survive subfreezing winters (Chiang 1973); 2) the switch from dryland to irrigated corn farming allowing conditions suitable for rapid population increases (Hill and Mayo 1980); 3) the heavy use of granular insecticides selecting for resistant strains and highly migratory strains of WCR (Krysan 1986); and 4) the tremendous increase in continuous corn acreage since WWII (Chiang 1978). By the 1980's, WCR increased its range to include all territory from the Rocky Mountains to the eastern seaboard of the United States (Krysan 1986). The species was first reported in southwestern Virginia in 1985, and has since spread to virtually all of the continuous corn growing regions of the state (Youngman and Day 1993).

LIFE HISTORY and BIOLOGY

Egg stage

Western corn rootworm is univoltine and overwinters in the egg stage below the soil surface (Chiang 1973). The insect usually completes its development in about one year, however recent studies have reported the presence of an extended two-year egg diapause in some populations of WCR in the Midwest (Levine et al. 1992a). However, extended diapause occurred in only about 0.2% of the WCR population.

Egg hatch depends on soil temperature (Wilde 1971) and may begin as early as May in Virginia. Eggs hatch with or without exposure to a cold diapause (Branson 1974). Extremely cold temperatures decrease egg survival and vigor, and temperatures below -15° C can cause 100% mortality (Branson 1974). Temperatures around 4 to 5° C are optimal for egg diapause (Chiang et al. 1972). Levine et al. (1992a) examined the thermal requirements for hatching in WCR, and determined that the developmental rate for first hatch increased linearly with increasing temperature, and that the threshold temperature (t) and thermal constant (K) for first hatch were $t = 12.7°C$ and $K = 209.7$ degree days, respectively.

Larval stage

Following egg hatch WCR larvae must locate a suitable host. Recent studies have shown that first instars must migrate through the soil and establish on corn roots within 72 h to avoid mortality (Bergman and Turpin 1986, Branson 1989). Field experiments have demonstrated that WCR neonates (3-4 mm in length) are capable of moving considerable distances through the soil in search of corn root systems (Suttle et al. 1967, Short and Luedtke 1970). A recent study reported lateral movements of WCR in soil >100 cm (Gustin and Schumacher 1989). However, it should be noted that the dispersal abilities of WCR larvae depend strongly on soil physical parameters such as moisture level, porosity, and compaction (Bergman et al. 1983, Strnad and Bergman 1987a, Gustin and Schumacher 1989, Ellsbury et al. 1994). The larvae are attracted to corn roots by carbon dioxide and kairomones given off by the host plant (Strnad et al. 1986). Once a suitable host is found, larvae begin feeding on root hairs and, as they mature, move into larger roots and eventually invade the root core (Sechriest 1969, Strnad and Bergman 1987b). The larval stage has three instars and completes development in about 3 wk (Chiang 1973). The developmental rate of WCR larvae is influenced by a number of factors including: intraspecific competition (Weiss et al. 1985, Elliott et al. 1989), interspecific competition (Woodson 1994), food quality and quantity (Branson and Ortman 1970, Oloumi-Sadeghi and Levine 1989), and temperature (Kuhlman et al. 1970). Studies have shown that a positive relationship exists between temperature and larval growth and development until an optimal temperature of approximately 25°C is reached (Kuhlman et al. 1970). Full-grown larvae are about 13 mm in length, and their bodies are slender and creamy-white in color, marked only by a dark-brown head capsule and plate on the upper surface of the last body segment (Krysan 1986).

Pupal stage

The pupal stage of WCR lasts about 7 to 10 days. Pupation occurs in earthen cells in the soil most often at depths between 0 to 5 cm (Sechreist 1969); however, pupae can be found at depths reaching 23 cm (Chiang 1973), which suggests that newly-emerged adults may be able to move a considerable distance in the soil. The pupal stage of WCR was first described by Sechreist (1969), and the sex of WCR pupae can readily be determined. Female pupae bear a pair of distinctive papillae on the venter near the apex of the abdomen, whereas males lack such papillae (Krysan 1986).

Adult stage

The adult WCR is a leaf-feeding beetle about 6 to 7 mm long and yellow and black in color. The marking patterns on the elytra may vary considerably (Krysan and Smith 1987). Elytral color forms range from predominately black with only the tips of the wing margins yellow to black in background with two prominent, longitudinal yellow stripes. Adult emergence is correlated with corn plant phenology, and usually occurs from late-June to July (Chiang 1973, Naranjo and Sawyer 1988). Male WCR tend to emerge before females (Naranjo and Sawyer 1988). The life span of adult WCR is generally 75 to 100 d (Hill 1975). In Virginia, adult populations usually peak in late-July, yet adults can be found in corn fields through September.

WCR adults primarily feed on the leaves, pollen, silks, and developing kernels of corn plants (Chiang 1973, Branson and Krysan 1981). Adults may disperse out of corn fields and feed on the pollen of various cucurbit plants; however, most often these insects remain in corn for the duration of their lives (Branson and Krysan 1981). In addition, there is strong evidence for dispersal of WCR adults among corn fields as well (Ball and Weekman 1962, 1963, Coats et al. 1986, Grant and Seevers 1989, Naranjo 1991). Females may disperse out of their emergence corn fields in search of still-succulent corn, particularly in late season after food quality has deteriorated (Hill and Mayo 1980, Coats et al. 1986). As a result, late-planted corn fields, as well as first-year corn fields, often serve as attractive sites for WCR immigrants (Naranjo 1991).

Field studies involving spatial analysis of WCR adults have indicated that they are distributed in density-dependent aggregations (Steffey and Tollefson 1982, Midgarden et al. 1993). Geostatistic analyses based on relative position of sticky traps in corn fields, revealed that WCR adults were nonrandomly distributed at least half the time at all population densities; however, the presence and type of spatial pattern was density-independent (Midgarden et al. 1993). This information is important for the development of sampling programs, particularly for calculation of sample size needed. Also of importance to sampling is information on activity period of western corn rootworm. Witkowski et al. (1975) indicated that the diel activity pattern of WCR in corn is bimodal, with peaks just after sunrise and just before sunset. Temperature and wind may affect daily-flight activity as well (Van Woerkom et al. 1980, 1983).

Mating

Mating in WCR occurs shortly after female emergence (Ball 1957) with females often still in the teneral state (Lew and Ball 1979). Diel patterns in mating activity correlate well with the bimodal flight activity pattern of WCR, with peaks in the early morning and evening (Witkowski et al. 1975). Corn rootworm females attract males by releasing a sex pheromone (Guss 1976). The pheromone of WCR was isolated from virgin females and identified as 8-methyl-2-decyl-propanoate by direct analysis (Guss et al. 1982). Once attracted to a receptive female, males engage in a ritual of courtship and mounting behaviors (Lew and Ball 1979). Various tactile stimuli, including antennal palpitation and stroking activities involving the mesothoracic legs are performed by the male during mating. The average time duration for copulation is 3 to 4 hours, during which time the female may move about, feed, and even groom herself (Lew and Ball 1979). Female WCR only mate once, whereas males may mate several times (Hill 1975, Branson et al. 1977).

Oviposition

Egg laying usually commences in mid to late summer and continues until the first frost of the year. The tiny, white WCR eggs are almost exclusively laid in corn fields; however, a few exceptions have been reported of eggs having been laid in soybeans (Shaw et al. 1978). Female WCR have a mean fecundity of approximately 1000 eggs

(Hill 1975) and can lay viable eggs up to 60 days after mating (Branson and Johnson 1973). Eggs are laid in clutches of 10 to 15 over a mean reproductive period of 76.4 days (Hill 1975). The earliest egg clutches are usually the largest, thus, approximately 80% of eggs are usually laid by the eighth clutch (Hill 1975).

Numerous factors affect oviposition in WCR. No oviposition occurs below a temperature of 10°C, and the optimum temperature for oviposition is 16.7°C (Ball 1957). Eggs are laid in the soil, and are found most often in the top 16 cm (Ball 1957, Pruess et al. 1968). The spatial distribution of eggs is dependent upon soil moisture, as well. Weiss et al. (1983) reported that approximately 80% of rootworm eggs were found in the upper 10 cm of soil in irrigated fields; however, only 45% of eggs were found at this level under dryland conditions. Most eggs are found at the base of plants in dryland fields, and between rows in irrigated fields (Patel and Apple 1967). In hilly fields, the slope is most favored for oviposition and the top of the hill is least favored (Chiang 1973). Ovipositing beetles will not make their own burrows (Reusink 1986), and thus, are attracted to soil cracks, earthworm burrows, grass clumps, and the bases of stalks for their egg laying (Kirk et al. 1968, Foster et al. 1979, Kirk 1979, 1981a, 1981b). Odors also play a major role in choice of oviposition site. In a laboratory experiment, Lance (1992) showed that WCR females laid significantly more eggs on towlettes treated with homogenates of WCR female abdomens than on towlettes treated with distilled water alone. Females also chose dishes with odors of excised maize roots or elevated levels of carbon dioxide over control dishes treated with distilled water alone.

DAMAGE

Both the adult stage and larval stage of WCR can cause damage to corn. Adult WCR can interrupt corn pollination by feeding on silks and clipping them back to ear tips, which can lead to decreased fertilization and a reduction in grain yield (Ainslie 1914, Culy et al. 1992). However, Capinera et al. (1986) determined that corn could sustain a considerable amount of adult feeding (20 beetles per ear) without a significant reduction in grain yield. The larval stage of WCR, on the other hand, can cause severe damage to corn. Rootworm larvae chew back small roots and eventually burrow into root cores. Root feeding can lead to a decrease in water and nutrient uptake by the plant which may induce water stress (Riedell 1990). Root feeding also weakens and destabilizes the support system of the plant, often resulting in stalk lodging during heavy winds or rain. Extensive lodging makes harvesting difficult and can lead to significant reductions in yield (Sutter et al. 1990). Reed et al. (1991) determined an economic threshold for WCR larval density to be two larvae per stalk using the larval sampling method of Bergman et al. (1981). The relationship between larval feeding and yield loss in corn, however, is very complex, and a number of environmental and agronomic parameters can affect the plant response to root injury making it difficult to quantify economic damage levels (Chiang et al. 1980, Foster et al. 1986, Mayo 1986, Spike and Tollefson 1989a, 1989b, 1991).

In addition to direct-feeding damage, corn rootworms can potentially injure crops by transmitting plant diseases. Adult WCR have been shown to vector the cowpea mosaic virus (Jansen and Staples 1971) and the squash mosaic virus (Lastra 1968). However, both cowpeas and squash are minor hosts for WCR. In addition, Nault et al. (1978) and Uyemoto (1983) demonstrated that WCR larvae can vector maize chlorotic mottle virus (MCMV) by acquiring infected residues from corn roots. Although the efficiency of transmission is very low, the fact that infected residue within the insect can serve as a virus source has important implications for managing the MCMV disease (Gergerich et al. 1986). Corn rootworm adults also can cause damage to corn plants by vectoring or providing sites of entry into corn ears for secondary fungal infections, which can cause corn rot. Gilbertson et al. (1986) showed a positive correlation between number of corn rootworm adults feeding on corn ears and level of *Fusarium moniliforme* Sheldon and *F. subglutinans* (Wr. and Reink) contamination in kernels of corn.

PEST MANAGEMENT

Cultural control

Crop rotation, first proposed over a century ago by Forbes (1882) for the control of NCR and by Gillette (1912) for the control of WCR, is still the most effective management practice for corn rootworms. In recent years, however, there has been a casual but persistent pattern of observations of corn rootworm damage in fields where corn is rotated annually with a nonhost crop such as soybeans (Steffey et al. 1992). These observations can be explained in part, by the existence of prolonged diapause in the eggs (Levine et al. 1992a). Prolonged (two-year) egg diapause was first detected in NCR eggs from Minnesota some 30 years ago by Chiang (1965). Subsequently, Krysan et al. (1984, 1986) detected prolonged egg diapause in nearly half of the NCR eggs examined from adults collected from fields where corn was rotated. More recent studies have discovered the existence of multi-year diapause in NCR eggs (Levine et al. 1992b). The current NCR egg diapause ranges from 1 to 4 years. Prolonged egg diapause also has been detected in WCR. Levine et al. (1992a) reported the first detection of extended diapause in *D. v. virgifera* eggs from study sites in Illinois and Ontario, Canada. Approximately 0.14% of the eggs from Illinois and 0.21% of the eggs from Ontario hatched only after passing through two simulated winters in the laboratory. Although numerous studies have shown the existence of prolonged diapause in corn rootworms, recent surveys have determined that prolonged diapause rarely causes subsequent economic damage in corn that has been rotated (Steffey et al. 1992). Moreover, the recommendation in the Midwest is still for growers not to apply soil insecticides to prevent corn rootworm injury in rotated corn (Steffey et al. 1992).

In addition to crop rotation, other cultural methods for the control of rootworms have been investigated. Hill and Mayo (1974) examined the possibility of planting a late patch of "trap corn" to attract ovipositing females, and thus, reduce the damage in the fields used for harvest. As a control measure it has been somewhat effective, but not adequate to prevent significant damage in fields with high infestations of corn rootworms. The effect of tillage practices also have been examined, but in general, have shown little success in controlling high rootworm populations (Gray & Tollefson 1987, 1988). Moreover, it has been shown that beneficial arthropods, such as predators, parasites, and decomposers of plant matter, are more numerous in corn fields with less tillage (Stinner et al. 1988, Clark et al. 1993). The effect of planting date on corn rootworm control also has been investigated (Musick et al. 1980, Bergman and Turpin 1984). Corn planting date can severely affect the larval population density within a field. WCR eggs hatch after a certain number of degree days regardless of the corn phenology, and newly-hatched larvae can survive for only 72 hours before finding food (Branson 1989). Thus, corn planted after most larvae have hatched and subsequently starved, sustains less damage than if planted earlier (Bergman and Turpin 1986). Musick et al. (1980) found that late planting reduced damage, but did not eliminate it. Moreover, it should be noted that use of late planting as a control measure could lead to natural selection for late-emerging eggs. The benefits of fertilizer and manure applications also have been investigated. Hill et al. (1948) found that increased nitrogen levels of 45-90 kg N/ha resulted in a reduction in rootworm damage. Spike and Tollefson (1988) determined that nitrogen applications enhanced root regeneration and decreased plant lodging by 44% in plants injured by WCR. Conversely, Foster et al. (1986) observed that rootworm damage ratings were positively correlated with increased nitrogen applications. Chiang (1970) and Allee (1992) demonstrated the advantages of applying manure to corn fields as a source of fertilizer. Chiang (1970) showed that manure applications caused an increase in predatory mite numbers. Predation by these mites was shown to decrease WCR larval populations by an average of 63% (Chiang 1970). The overall effectiveness of manure applications as a cultural control method for corn rootworms, however, has not been determined. Soil moisture (Chiang et al. 1980) and the compensatory root-regrowth capabilities of the corn plant (Spike and Tollefson 1988, 1989b) also affect the amount of damage resulting from rootworm feeding, hence, selection of appropriate corn cultivars may also help in decreasing damage to the crop.

Biological control

Numerous studies have evaluated the potential of biological organisms for the control of corn rootworms, but no agent or method of biocontrol has been found to be completely effective and/or applicable for corn rootworm pest management. Relative to other important insect pests of corn such as armyworms, corn earworms, and corn borers, corn rootworms have few natural enemies (Levine and Oloumi-Sadeghi 1991). Corn rootworm eggs, larvae, and adults are fed upon by numerous predators such as mites (Chiang 1970), ants (Ballard and Mayo 1979, Kirk 1981c), carabid beetles (Kirk 1982), and birds (Bollinger and Caslick 1985), but, in general, predators play a minimal role in reducing corn rootworm populations (Kirk 1982).

The potential of entomopathogens for corn rootworm control has been investigated. Sutter (1969) showed that WCR was not susceptible to *Bacillus thuringiensis* Berliner or *B. popillae* Dutky, the bacteria most commonly used in biological control of insects. Day (1985) found that the fungus *Beauveria bassiana* Balsamo caused some mortality in corn rootworms, but not enough to effectively control pest populations. The recent discovery of an entomophthoralean fungus (Zygomycetes: Entomophthorales) infecting adult NCR may show promise for future corn rootworm biological control programs (Naranjo and Steinkraus 1988). The effect of parasitic nematodes also has been investigated (Munson and Helms 1970, Poinar et al. 1983, Jackson and Brooks 1989, Thurston and Yule 1990). The soil-inhabiting entomogeneous nematode, *Steinernema feltiae* Filipjev (=*Neoaplectana carpocapsae*), has a wide host range including larvae of *Diabrotica*, and has been approved by the EPA for general use as a biological control agent. The nematode has shown variable results at controlling corn rootworms. Poinar et al. (1983) field-tested *S. feltiae* in Nebraska and found significantly fewer corn rootworms in the nematode-treated area than in the control or in the area treated with chlopyrifos granular insecticide. Similar studies in Illinois, however, showed that *S. feltiae* was ineffective against corn rootworm larvae (Levine and Oloumi-Sadeghi 1991). Application techniques, edaphic factors, and the choice of strain of *S. feltiae* can influence the effectiveness of the nematode as a soil-insect control agent (Jackson and Brooks 1989, Levine and Oloumi-Sadeghi 1991). Other benefits of using nematodes for corn rootworm control include non-damaging effects to beneficial organisms and prolonged activity in the soil, which make it preferable to insecticides. Futher investigation and consideration of this control method is warranted.

Chemical control

Soil insecticides applied at planting have been the primary control measure for corn rootworms since their introduction more than four decades ago. The widespread use of insecticides for the control of corn rootworms has propelled the *Diabrotica* into a status as one of the most expensive insect pest groups which occur in North America. Control costs and crop losses attributed to these pests can exceed $1 billion annually (Metcalf 1986). Approximately 16 to 18 million kg of insecticide are applied annually to control corn rootworms over some 14 million ha of corn in the United States (Sutter et al. 1981).

Cyclodiene insecticides were introduced to control corn rootworms in the late 1940s. Hill et al. (1948) and Muma et al. (1949) demonstrated that soil applications of benzene hexachloride (=hexachloro cyclohexane) greatly reduced corn rootworm populations, and almost eliminated corn root injury. A variety of other types of cyclodiene compounds were found to be effective in the subsequent years, including aldrin, chlordane, dieldrin, and heptachlor (Cox and Lilly 1953, Burkhardt 1954, Lilly 1954). However, corn rootworm resistance to the cyclodienes was found in many populations as early as 1959 (Weekman 1961, Ball and Weekman 1962, Bigger 1963). Insecticide resistance, as well as EPA cancellation of registrations for aldrin, dieldrin, chlordane, and heptachlor in the 1970s led to a need for alternative insecticidal compounds for the control of rootworms. Carbamates, organophosphates, and pyrethroid insecticides, although more expensive than chlorinated hydrocarbons, have provided farmers with an effective alternative control measure with considerably less residual activity in the environment (Ball 1968, Munson and Hill 1970, Apple 1971). Most of the compounds developed and marketed for the control of corn rootworms have been granular formulations, which have extended the residual activity of the active ingredients and provided increased safety to human applicators. Some of the most commonly used soil insecticides in today's market for the control of corn rootworms include the following: chlorpyrifos; terbufos; tefluthrin; fonofos; and phorate (Levine and Oloumi-Sadeghi 1991).

The most cost-efficient method for the application of the soil insecticides is to apply the chemicals in-furrow, or in a band over the row at planting. The causes for inconsistent root protection by soil insecticides are numerous and depend upon the interactions of many factors including: larval density; soil moisture (Sutter et al. 1989); planting date (Mayo 1980, Gray et al. 1992); chemical toxicity (Ball and Su 1979, Smith 1981, Sutter 1982); and chemical properties of the insecticide, such as degradation (Felsot 1989) and water solubility (Harris 1972, Sutter et al. 1991). Some operational strategies to help ensure effectiveness of the insecticides include proper application rates (Ball and Su 1979, Smith 1981), accurate calibration of equipment, proper placement and incorporation of insecticide, and rotation of chemicals (Levine and Oloumi-Sadeghi 1991). Alternation of insecticides from one year to the next has been widely recommended, especially as a strategy to delay the development of insecticide resistance (Felsot 1989). Other strategies include reducing soil insecticide application rates (Gray et al. 1992), and the use of semiochemicals to improve the targeting of insecticides to soil-borne larvae (Levine and Oloumi-Sadeghi 1991). Corn seedling volatiles, particularly 6-methoxy-2-benzoxazolinone, have been found to be important in orienting WCR larvae to roots. In a recent study, these volatiles also attracted WCR larvae to soil insecticides and significantly increased larval mortality (Hibbard et al. 1995).

Controlling corn rootworm adult populations with foliar insecticides also has been evaluated (Luckmann 1978). Most studies have concluded that adult control could be used to minimize subsequent larval damage, but the level of control was no better than that achieved from use of soil-applied insecticides (Pruess et al. 1974, Levine and Oloumi-Sadeghi 1991, Steffey and Gray 1993).

SAMPLING METHODS

Research interests in population biology and integrated pest management programs have led to the development of numerous methods of sampling all stages of corn rootworms (Chiang 1973). Several techniques for sampling corn rootworm eggs have been investigated (Patel and Apple 1967, Chiang et al. 1969, Howe and Shaw 1972), but to date no single technique has been universally accepted as best (Reusink 1986). All of the egg sampling methods include a technique for removing soil from the field and a technique for separating eggs from the soil. Foster et al. (1979) evaluated five techniques for removing soil from the field with regard to accuracy and time efficiency, and concluded that the method of Patel and Apple (1967), using a 5.4-cm diameter soil auger to dig a core sample 10 cm deep, was the most time efficient; however, the frame method of Foster et al. (1979), using a 10- x 100-cm rectangular frame placed 10-cm deep perpendicularly to the row, was the most accurate. More recently, Reusink and Shaw (1983) developed a gasoline-powered trencher technique to improve the time efficiency of the frame method. Of the techniques for separating the eggs from the soil (Chandler et al. 1966, Lawson and Weekman 1966, Matteson 1966, Montgomery et al. 1979), probably the fastest and most efficient method uses a mechanized washing and sieving technique (Shaw et al. 1976, Reusink 1986). Some advantages of sampling the egg stage over other life stages are that: 1) eggs are stationary; 2) eggs are available in the field for extended periods of time (Chiang 1973); and 3) the egg stage immediately precedes the larval stage, which allows sampling before any root damage can occur (Foster et al. 1979). Some disadvantages of egg sampling include the following: 1) eggs are small and difficult to count; 2) eggs are often clumped in distribution with great variation (Patel and Apple 1967, Chiang 1973); and 3) it is very laborious and time consuming to dig, transport and sift through large volumes of soil (Reusink 1986).

Sampling methods for the larval stage of corn rootworms also have been investigated. Chiang (1973) described a method that involved digging up the root system with its surrounding soil and driving the larvae out of the soil by air drying the roots. Other methods have involved visual searching of soil, recovering larvae by use of a Tullgren funnel, and washing the roots and sifting soil through a screen. Bergman et al. (1981) evaluated the various methods of larval sampling and concluded that the washing-sieving-flotation method is the most effective technique for recovering larvae from soil samples. Reed et al. (1991) determined an economic threshold for WCR larval density to be two larvae per stalk using this larval sampling method. Relatively little effort has been made to develop and improve upon larval sampling methods in recent years probably due, in part, to the difficulties in working with subterranean organisms (Fisher and Bergman 1986). In addition, there is no assurance with larval sampling that all eggs have hatched, or that all larvae present in a sample have been counted due to the variation in size of the different instars (Chiang 1973).

Because of the drawbacks associated with sampling immatures, much of the recent development of sampling techniques for corn rootworm pest management has focused on the adult stage. Visual field counts of corn rootworm adults on plants have been used to accurately identify fields at risk to corn rootworm damage (Chiang and Flaskerd 1965, Lovett 1975, Steffey et al. 1982, Stamm et al. 1985, Tollefson 1986). Steffey et al. (1982) found that whole-plant counts, which involve counting all the beetles on a corn plant, are one of the most accurate and practical methods for sampling corn rootworm adults. Current recommendations are for treatment with a soil insecticide at planting or crop rotation in fields that have a mean density greater than 1.0 beetle per plant during the previous scouting season (Foster et al. 1982). Stamm et al. (1985) determined that lowering the economic injury level to 0.75 or 0.90 beetles per plant increases the prediction accuracy. In addition to whole-plant counts, ear-zone counts also have been investigated as tools for sampling adult corn rootworms (Stamm et al. 1985, Weiss and Mayo 1985). The ear-zone is defined as the inclusive area from the upper surface of the first leaf below the ear to the lower surface of the first leaf above the ear (Tollefson 1986). Ear-zone counts have been significantly correlated with whole-plant counts (Stamm et al. 1985, Weiss and Mayo 1985) and may be a better alternative to whole-plant counts because of the reduction in time involved in scouting fields. In addition, Foster et al. (1982) developed a sequential sampling plan for plant-count methods that can further decrease the overall time involved in sampling; however, to maintain accuracy and efficiency, trained personnel (scouts) were required to take the plant counts. Some disadvantages of plant-count methods as a means of scouting WCR are: 1) the cost and time involved in training scouts; 2) the high probability of sampling error due to variability in climate and time of day of field sampling; and 3) human error factors involved in counting mobile organisms.

As an alternative to plant-count sampling, the potential for sticky-trap sampling of corn rootworm adults was investigated (Tollefson et al. 1975). Counts of corn rootworm adults captured on yellow sticky traps were shown to be as reliable as whole-plant counts in predicting larval damage in corn fields the following season (Hein and Tollefson 1985). The commercial Pherocon AM yellow sticky trap (Trécé, Salinas, CA) was shown to be an effective tool for sampling adult WCR and became the scouting tool of choice for corn rootworm IPM programs in the Midwest because of its commercial availability and ease of handling. (Hein and Tollefson 1984, 1985). Methods for field implementation of the sticky traps can be found in Hein and Tollefson (1985) and Tollefson (1986). Karr and Tollefson (1987) showed that Pherocon AM traps could be left out in the field for up to 10 days without a significant loss in catch efficiency. An economic threshold of six beetles per trap per day, or 40 beetles per trap per week was calculated by Hein and Tollefson (1985). Godfrey and Turpin (1983) showed that the economic threshold should be lowered for first-year cornfields due to increased number of females that migrate to new fields.

Three major advantages of using sticky-trap sampling over plant-count sampling are: 1) that trap catch occurs over an extended period of time and thus is less subject to short-term climate fluctuations (Karr and Tollefson 1987); 2) less chance of human error in counting the beetles; and 3) less time is required to train individuals to use the traps than to perform plant counts (Hein and Tollefson 1985). Some disadvantages of sticky-trap sampling are: 1) that scouts must visit fields at least twice, often more, depending on the beetle populations in the fields; 2) sticky traps are messy to handle (Levine and Oloumi-Sadeghi 1991); and 3) the cost of currently-recommended traps (i.e., Pherocon AM traps) relative to the cost of applying a granular insecticide at planting becomes prohibitive in small fields, especially if traps need to be used more than twice. Although sticky-trap sampling is not without its drawbacks, the advantages over plant-count methods make it a suitable alternative for use in a corn rootworm scouting program.

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CHAPTER 2

RISK OF WESTERN CORN ROOTWORM DAMAGE TO CONTINUOUS CORN IN VIRGINIA

ABSTRACT

Information on the risk of western corn rootworm damage to continuously-grown corn is lacking in Virginia, as well as other mid-Atlantic states. A two-year study was completed comparing root damage and silage yields in insecticide-treated and untreated areas of 32 continuous corn fields in Virginia. Approximately 28% of the fields examined had serious root damage exceeding a rating of 3.5 (1-6 scale) in sections left untreated with a granular insecticide. In addition, 19% of the fields overall had an economic loss in silage due to corn rootworm damage. Because much of the continuous corn acreage in Virginia is treated preventively with soil insecticides for corn rootworms, my results suggest that a large percentage of this insecticide use is unnecessary.

INTRODUCTION

THE WESTERN CORN ROOTWORM, *Diabrotica virgifera virgifera* LeConte, is one of the most important pests of continuous corn, *Zea mays* (L.), in the United States (Chiang 1978, Metcalf 1986). Larvae feed voraciously on the root systems of corn resulting in reduced water and nutrient flow in the plant (Kahler et al. 1985, Riedell 1990) and lodging of stalks which may lead to significant reductions in yield (Remison & Akinleye 1978, Sutter et al. 1990, Spike & Tollefson 1991). Reviews of corn rootworm biology, ecology, and management can be found in Chiang (1973), Krysan & Miller (1986), and Levine & Oloumi-Sadeghi (1991).

The western corn rootworm is most likely neotropical in origin (Krysan 1982). Researchers speculate that *D. virgifera virgifera* became specialized on corn in the tropics and followed the diffusion of corn into temperate North America about 1,000 yr ago (Branson & Krysan 1981). The insect has been reported as a pest of corn in the United States since the early part of this century (Gillette 1912, Ainslie 1914). Until the 1940's, however, the distribution of this pest in the United States remained limited to a handful of states in the Midwest (Smith 1966, Chiang 1973). With dramatic increases in continuous corn acreage in the United States following WWII, the geographic range of *D. virgifera virgifera* expanded rapidly, and by 1983, it reached the eastern seaboard (Krysan 1986). The species was first reported in southwestern Virginia in 1985, and has since spread throughout virtually all of the continuous corn growing regions of the state (Youngman & Day 1993).

Several studies have investigated the risk of damage by western corn rootworm on a geographic basis. Research from 1972 to 1974 showed that less than 4% of the corn acreage in Indiana suffered economic loss due to corn rootworm (Turpin & Thieme 1978). Similarly, Luckmann (1978) reported 11 to 19% of the corn acreage to be at risk in Illinois. Stamm et al. (1985), in an extensive study in Nebraska in 1981 and 1982, reported that less than 10% of the total corn acreage was at risk to serious corn rootworm damage. More recent research involving 58 corn fields in Illinois has led researchers to suggest that approximately 25% of the fields in the Midwest are at risk to economically-damaging levels of corn rootworms each year (Gray et al. 1993). Information of this nature for Mid-Atlantic states such as Virginia is lacking. The objective of this study was to assess the risk of western corn rootworm damage in commercial fields grown continuously in corn in Virginia by comparing root damage and silage yields in insecticide-treated and untreated sections of these fields.

MATERIALS & METHODS

In 1993 and 1994 a total of 32 commercial corn fields from seven counties in Virginia were investigated. Field size ranged from 2 to 30 ha, and soil types ranged from a fine sandy loam (10.5% clay) to silt loam (20.0% clay). All fields had been under continuous corn production and treated with a soil insecticide for at least four yr prior to the study. Preexisting population densities of western corn rootworm, or any other insect pest were not known for any of the fields. During each study yr, corn fields were planted no-till during the first 2 wk of May and treated with a soil insecticide at planting, except for a rectangular strip (4 to 8 rows by 70 m) near the center of each field, which was left untreated. In July of each yr, corn rootworm larval feeding damage was assessed on 20 arbitrarily-chosen plants dug from the center two rows in the treated and untreated sections of each field. Root systems were removed from the field, washed free of soil and evaluated using the standard 1-6 root-damage rating system developed by Peters and Eiben (described by Hills & Peters 1971). The categories of this rating system are: (1) no apparent feeding damage; (2) feeding scars evident, but no roots completely chewed off; (3) several roots chewed off, but never an entire node of roots destroyed; (4) one node of roots completely destroyed; (5) two nodes of roots completely destroyed; and (6) three or more nodes destroyed.

Corn silage yields were determined on a per field basis using a harvest protocol similar to that of Laub & Luna (1991). Two plots (2 rows x 10 m) in both the treated and untreated sections were hand-harvested using a machete and weighed in the field using a tripod and scale. Stand counts also were made in each plot. Ten stalks from each plot were chopped for silage using a Tomahawk® 8HP Chipper/Shredder (Troy-Bilt Manufacturing Co., Troy, N.Y). A 1 kg subsample of silage was removed and dried at 70°C for 48 h to determine percent dry matter. Silage wts were adjusted to 65% moisture

(Davis 1994) and reported in metric tons/ha (1 MT/ha = 0.455 tons/acre). Silage subsamples were taken to the Virginia Tech Forage Testing Laboratory, Blacksburg, Virginia for quality analysis, including % crude protein (CP) and % acid detergent fiber (ADF). Crude protein was determined by measuring the total nitrogen contained in the silage. In most forages, nitrogen is 16% of the weight of proteins. Thus, % CP was calculated as 6.25 times the %N in the sample. Acid detergent fiber fraction is a measure of the cellulose and other compounds in feed that are only partially utilized by the animal.

Analysis of variance (ANOVA) was used to compare mean root damage ratings, stand counts, silage yield, % CP, and % ADF in insecticide-treated and untreated sections of all fields. Mean silage yield losses and silage quality parameters in untreated corn were compared for various root damage rating groupings. Based on these comparisons, an economic root damage level for silage corn in Virginia was suggested.

RESULTS & DISCUSSION

Mean root damage ratings, stand counts, silage yields and silage quality assays for insecticide-treated and untreated sections of all corn fields are reported in Table 2.1. Overall mean root damage rating in the untreated corn (3.37) was significantly higher than in the insecticide-treated corn (2.63) (F = 24.30; df = 1, 31; $P < 0.0001$). Insecticide-treated corn did not differ significantly from untreated corn in mean stand counts (F = 0.27; df = 1, 31; P = 0.60), silage yield (F = 0.98; df = 1, 31; P = 0.33), % crude protein (CP) (F = 1.36; df = 1, 31; P = 0.25), and % acid detergent fiber (ADF) (F = 0.05; df = 1, 31; P = 0.83).

Table 2.1. Mean root damage, stand count, yield and silage quality assessment of granular insecticide-treated and untreated sections of continuous corn fields in Virginia.

Fields ($n = 33$)	Root rating[a] (1-6 scale)	Stand count (per 20 row m)	Silage yield[b] (MT/ha)	Silage quality	
				% Crude protein[c]	% Acid detergent fiber[d]
Treated	2.63**	92.28	46.29	6.64	29.89
Untreated	3.37	89.81	43.81	6.87	30.11

[a] Root damage rating based on the Peters & Eiben 1-6 scale (Hills & Peters 1971).
[b] Silage yield weights were adjusted to 65% moisture (1 MT/ha = 0.455 tons/acre).
[c] Percent crude protein was calculated as 6.25 times the %N in a sample of silage.
[d] Percent acid detergent fiber is a measure of the cellulose fraction in a sample of silage.
**Means within a column are significantly different ($P \leq 0.05$; ANOVA).

There is some discrepancy among researchers concerning exactly which root damage rating level corresponds to a yield loss in corn equivalent to the cost of applying an insecticide. Root damage ratings of 2.5-3.0 have been accepted by many researchers in the corn belt as the economic injury level (Turpin et al. 1978, Branson et al. 1980, Mayo 1986). Others, however, feel that a root damage rating of 3.0 is too low and that a rating of 4.0 must be reached before economic yield loss occurs in corn (Sutter et al. 1990, Gray et al. 1993). Of the 32 continuous corn fields evaluated in my study, 16 (50.0%) had root damage in the untreated corn that exceeded 3.0 on the root-rating scale, 9 (28.1%) exceeded 3.5, and 5 (15.6%) exceeded 4.0. In the insecticide-treated corn, most (88.5%) fields had root ratings ≤ 3.04; however, 4 (12.5%) fields had root ratings which ranged from 3.05 to 3.2.

Economic loss in silage yield for Virginia corn was calculated to be 4.9 MT/ha (at 65% moisture) based on a crop value of $22.00/MT and a treatment cost of $37.00/ha. Seven (21.9%) fields overall suffered economic loss in silage yield from not treating with an insecticide (Table 2.2). Of these 7 fields, 5 (15.6% overall) had serious corn rootworm feeding damage to the roots (ratings ≥ 3.8) which likely explained the loss of silage in the untreated corn. In the other 2 fields, root damage in the untreated corn was relatively low (root ratings = 2.95 and 3.20) and not substantially different from that in the insecticide-treated corn (root ratings = 2.60 and 2.90, respectively). In addition, stand counts were similar in the treated and untreated corn. The specific cause for economic loss of silage in these fields probably was not related to corn rootworm feeding damage.

Comparisons of silage yield losses for untreated sections of fields according to root damage ratings are shown in Table 2.3. Fields with root ratings >2.50-3.0 in the untreated corn had a mean silage yield loss = 0.39 MT/ha, representing a 1.6% reduction in yield. Similarly, fields with root ratings >3.0-3.5 had a mean silage yield loss = 1.19

Table 2.2. Fields with economic loss in silage yield in corn left untreated with a soil insecticide (n = 7).

Root rating[a]		Stand count		Silage yield[b]		% yield reduction[c]
Treated	Untreated	Treated	Untreated	Treated	Untreated	
3.15	5.35	96	79	33.83	20.36	66.2
3.10	5.00	89	90	37.98	30.99	22.6
2.70	4.90	156	160	65.47	51.51	27.1
2.45	3.95	94	90	49.16	36.60	34.3
2.90	3.80	94	72	60.13	47.20	27.4
2.90	3.20	94	92	38.94	31.24	24.6
2.60	2.95	56	51	39.13	32.23	21.4

[a] Root damage rating based on the Peters & Eiben 1-6 scale (Hills & Peters 1971).
[b] Silage wts adjusted to 65% moisture (1 MT/ha = 0.455 tons/acre).
[c] Percent yield reduction = silage yield loss/silage yield in untreated corn.

Table 2.3. Mean silage yield loss in untreated sections of corn fields according to root damage rating.

Root rating[a]	No. of Fields (n)	Mean silage yield loss[b] (MT/ha) ± SEM	Mean % yield reduction[c] ± SEM
2.0-2.5	2	3.44 ± 0.16	8.44 ± 1.51
>2.5-3.0	14	0.39 ± 1.14	1.63 ± 2.69
>3.0-3.5	7	1.19 ± 1.43	2.58 ± 4.46
>3.5-4.0	4	4.94 ± 4.67*	12.75 ± 10.81
>4.0-4.5	1	0.62 ± 0.00	1.45 ± 0.00
>4.5-5.0	2	10.48 ± 3.50*	24.83 ± 2.28
>5.0	2	8.65 ± 4.84*	36.96 ± 29.29

[a] Root damage rating based on the Peters & Eiben 1-6 scale (Hills & Peters 1971).

[b] Silage wts adjusted to 65% moisture (1 MT/ha = 0.455 tons/acre).

[c] Percent yield reduction = silage yield loss/silage yield in untreated corn.

*Denotes silage loss above the economic level of 4.9 MT/ha based on a crop value of $22.00/MT and treatment cost of $37.00/ha.

MT/ha, representing a 2.6% reduction in yield. However, fields >3.5-4.0 had a mean silage loss of 4.94 MT/ha, which exceeded the economic level and represented a 12.8% reduction in yield. In addition, all fields with root ratings >4.5 experienced a mean silage yield loss that exceeded the economic level. One field with a root rating = 4.30 in the untreated corn had a mean silage loss of only 0.62 MT/ha. Although I cannot account for the low yield loss in this field, it may be that nearly optimal growing conditions negated the deleterious effects of rootworm feeding damage in this field.

Corn silage quality parameters for untreated sections of fields according to root damage ratings are shown in Table 2.4. Western corn rootworm damage did not appear to seriously affect the quality of corn silage in my study. Silage % CP and % ADF were very similar for all root damage ratings. Davis (1994) also found that corn rootworm feeding damage did not seriously affect corn silage quality, and suggested that environmental factors such as seasonal climate and crop maturity at harvest have a much greater effect on silage quality than rootworm feeding.

Conclusion:

Knowledge of the risk of damage by a particular pest in a given geographic area is a critical part of the decision-making process in pest management programs. This is particularly true for pests such as western corn rootworm, where growers often rely on preventive measures of control. Recent studies suggest that approximately 25% of the fields grown continuously in corn in the Midwest are at risk to serious western corn rootworm damage each yr. My study indicates that, although the western corn rootworm has only recently expanded its range to states on the eastern seaboard (Krysan 1986), the risk of damage in these states appears to be similar to that in the Midwest. Just over 28%

Table 2.4. Mean percentages for crude protein (CP) and acid detergent fiber (ADF) in silage samples from untreated sections of corn fields according to root damage rating.

Root rating[a]	No. of Fields (*n*)	Mean silage % CP[b] ± SEM	Mean silage % ADF[c] ± SEM
2.0-2.5	2	6.12 ± 0.50	29.50 ± 1.71
>2.5-3.0	14	6.81 ± 0.13	30.31 ± 1.18
>3.0-3.5	7	7.15 ± 0.33	30.03 ± 2.07
>3.5-4.0	4	6.76 ± 0.43	28.43 ± 2.47
>4.0-4.5	1	7.21 ± 0.00	29.20 ± 0.00
>4.5-5.0	2	6.94 ± 1.32	30.70 ± 2.71
>5.0	2	7.07 ± 0.59	32.80 ± 5.42

[a] Root damage rating based on the Peters & Eiben 1-6 scale (Hills & Peters 1971).
[b] Percent crude protein was calculated as 6.25 times the %N in a sample of silage.
[c] Percent acid detergent fiber is a measure of the cellulose fraction in a sample of silage.

of the continuous corn fields investigated had serious root damage exceeding a rating of 3.5 in corn left untreated with a granular insecticide. In addition, 19% of the fields overall suffered economic loss in silage yield due to corn rootworm feeding damage. Studies show that approximately 90% of fields grown continuously in corn in the Midwest are treated preventively each year with a soil insecticide for corn rootworm (Luckmann 1978, Turpin & Thieme 1978, Stamm et al. 1985, Gray et al. 1993). A recent survey has revealed similar trends for Virginia (R.R.Y., unpublished data). Results of my study suggest that a large percentage of this insecticide use is unnecessary.

The relationship between root-damage rating and yield loss in corn is very complex. A number of environmental and agronomic parameters can affect the plant response to root injury making it very difficult to quantify economic damage levels (Chiang et al. 1980, Foster et al. 1986, Mayo 1986, Spike & Tollefson 1989a, 1989b, 1991). Initial studies on this relationship suggest that the potential for economic loss in yield exists in a field if root ratings exceed 2.5-3.0 on the Peters & Eiben 1-6 scale (Branson et al. 1980, Mayo 1986). More recent studies suggest that an economic injury index of 3.0 is too low and that a root rating of 4.0 or 5.0 might be more realistic (Sutter et al. 1990, Gray et al. 1993). These studies were conducted on corn grown for grain. Corn grown for silage, however, suffers greater dollar losses from rootworm injury than corn grown for grain, thus, economic injury levels should be lower for silage corn than for grain corn (Davis 1994). Results of my study showed that fields with root ratings at or below a level of 3.5 in the untreated corn had a mean silage yield reduction of only 1 to 3%. Fields with root damage ratings >3.5-4.0, however, had a mean silage yield reduction of 12.8% which exceeded the economic level for silage loss in corn. Thus, for Virginia silage corn at least, 3.5 appears to be the root damage level that induces a yield loss equivalent to or greater than the cost of applying an insecticide. It is important to realize, however, that no root rating can correctly predict economic damage all of the time. A number of factors including soil moisture, nitrogen level, plant density, root regrowth and lodging potential can affect the relationship between root damage and yield loss in corn (Turpin et al. 1978, Chiang et al. 1980, Spike & Tollefson 1989a, 1989b, 1991).

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CHAPTER 3

DEVELOPMENT OF ECONOMIC THRESHOLDS FOR OLSON YELLOW STICKY TRAPS AND EAR-ZONE VISUAL COUNTS FOR SAMPLING WESTERN CORN ROOTWORM ADULTS

ABSTRACT

A two-yr field study was conducted in Virginia in 1992-94 to evaluate the effectiveness of using adult corn rootworm counts on commercial Olson yellow sticky traps and ear-zone regions of corn plants to predict subsequent damage to field corn. Western corn rootworm, *Diabrotica virgifera virgifera* LeConte adults accounted for >97% of the total corn rootworms sampled. Adult population estimates obtained at calendar wk 33 (mid-Aug) had the highest correlations with subsequent root damage among all sampling intervals from Jul through Aug for both the Olson trap ($r = 0.74$), and the ear-zone visual counts ($r = 0.64$). Linear regression models for Olson trap catch and ear-zone counts explained 65 and 41% of the variability in root ratings, respectively, and were used to calculate western corn rootworm economic thresholds for each sampling method. Various edaphic and agronomic variables, including planting date, years in continuous corn, % sand in soil, and monthly precipitation levels were used to help improve the models of adult counts as a predictor of subsequent damage. Sampling plans and economic thresholds of 20 western corn rootworm adults per trap per wk for the Olson trap and 0.3 adults per stalk for the ear-zone visual counts were suggested. Olson traps correctly predicted economic damage (root rating >3.5) to corn 81% of the time, and resulted in only one serious error of failing to predict economic damage in a field which had a root rating of 3.7 in corn planted the following season. Ear-zone counts correctly

predicted economic damage to corn ≈ 77% of the time, but resulted in 4 (9%) serious errors of failing to predict economic damage to corn.

INTRODUCTION

The western and northern corn rootworms, *Diabrotica virgifera virgifera* LeConte and *D. barberi* Smith & Lawrence (Coleoptera: Chrysomelidae), respectively are the most economically-important insect pests of corn grown continuously in the United States (Levine & Oloumi-Sadeghi 1991). Insecticide applications and crop losses associated with rootworm feeding damage cost producers over $1 billion each year (Metcalf 1986). Extensive research has been conducted on pest management strategies for these insects, including the development and optimization of sampling methods for decision-making regarding the use of control measures. Initial sampling research focused on the use of egg and larval population estimates to predict fields at risk to corn rootworm damage (Patel & Apple 1967, Chiang et al. 1969, Howe & Shaw 1972, Bergman et al. 1981). However, because the immature life stages of corn rootworms are soil-borne, egg and larval sampling methods were determined to be too labor intensive and time consuming for feasible use in pest management scouting programs (Foster et al. 1979, Bergman et al. 1981).

Consequently, the development of pest management sampling programs for corn rootworms has centered around the use of adult population estimates to determine the potential for larval damage the following year (Levine & Oloumi-Sadeghi 1991). Whole-plant visual counts (Chiang & Flaskerd 1965, Pruess et al. 1974) have been shown to be one of the most practical methods for sampling corn rootworm adults (Steffey et al. 1982). Foster et al. (1982) suggested an economic injury level of 1.0 corn rootworm adult per plant; however, Stamm et al. (1985) determined that lowering the economic injury level to 0.75 or 0.90 adult per plant increased the prediction accuracy of the sampling method. Furthermore, Weiss & Mayo (1985) suggested that counting corn rootworm adults in only the ear-zone region of corn plants may be a better alternative to whole-plant counts because of the reduction in time involved in scouting fields.

More recently, adult corn rootworm catches on yellow sticky traps was shown to be as reliable as visual plant counts at predicting subsequent root-feeding damage to corn (Hein & Tollefson 1984, 1985a). Sticky trap sampling offers two major advantages over visual plant count methods: 1) because trap catch occurs over an extended period of time, short-term fluctuations in climate are less of a problem (Karr & Tollefson 1987), and 2) there is less human error and inter-sampler variability associated with counting immobile insects on a sticky surface versus counting active insects on plants (Tollefson 1986). The Pherocon AM yellow sticky trap (Trécé, Salinas, CA) was suggested as a practical method for corn rootworm scouting programs because of its ease of use and commercial availability (Hein & Tollefson 1985a, Karr & Tollefson 1987). However, the trap has not been widely accepted by farmers and crop consultants for use in IPM scouting programs, in part, because of its relatively high cost (approximately $1.00 per trap).

Field studies conducted in Virginia (R.R.Y & T.P.K, unpublished data) have shown that a more compact yellow sticky trap, manufactured by Olson Products Inc. (Medina, OH), is more efficient at capturing corn rootworm adults and costs approximately one-fifth as much as the Pherocon AM trap. The Olson trap may prove to be a better alternative to the Pherocon AM trap for sampling corn rootworm adults. The objective of this study was to develop an economic threshold and evaluate the effectiveness of using counts of corn rootworm adults captured on Olson yellow sticky traps as a means of predicting subsequent damage to corn planted the following season.

MATERIALS & METHODS

A total of 43 corn fields in eight counties of Virginia were sampled at weekly intervals for corn rootworm adults from Jul through Aug 1992 and 1993. Field size ranged from 2 to 10 ha, and soil texture ranged from a fine sandy loam to clay loam. Most fields were under commercial silage production and were planted no-till. All fields were maintained using standard agronomic practices, and included the application of a soil insecticide at planting for rootworm control.

Unbaited yellow sticky traps were obtained from Olson Products Inc. (Medina, Ohio). The Olson trap consisted of a 10.2 x 15.2 cm rectangular polystyrene panel which was coated on both sides with Stiky Stuff adhesive (Olson Products Inc., Medina, Ohio). Silicone-coated release paper was used to protect the adhesive sides of the trap which allowed one side to be used at a time, in effect doubling the life of the trap. Ten traps per field were fastened to cornstalks at a height of 1.0 to 1.7 m (Witkowski et al. 1975). Due to the aggregated spatial distribution of corn rootworm adults (Steffey & Tollefson 1982), traps were placed >50 m apart along corn rows to obtain population estimates that were spatially independent (Midgarden et al. 1993). Counts of western and northern corn rootworm adults captured on the traps were recorded weekly from the first wk in Jul through the last wk of Aug. In addition to sticky trap sampling, ear-zone visual counts of corn rootworm adults were made in each field. The ear-zone region refers to the inclusive area from the upper surface of the first leaf below the ear to the lower surface of the first leaf above the ear (Weiss & Mayo 1985). Ear-zone counts were made on 50, arbitrarily-chosen stalks in each field per sample wk. Overall growth stage of the corn was recorded at sampling using the method of Ritchie & Hanway (1982).

The following season, control strips (≈4 rows x 100 m) without soil insecticides were planted near the center of each corn field. In early July, roots from 20 arbitrarily-selected plants were dug from each of the untreated sections. The roots were washed free of soil and rated for corn rootworm larval feeding damage using the standard 1-6 root-damage rating system developed by Peters and Eiben (described by Hills & Peters 1971). The categories of this rating system are: (1) no apparent feeding damage; (2) feeding scars evident, but no roots completely chewed off; (3) several roots chewed off, but never an entire node of roots destroyed; (4) one node of roots completely destroyed; (5) two nodes of roots destroyed; and (6) three or more nodes destroyed.

Various edaphic and agronomic variables were recorded for each field. Soil texture, slope and drainage were determined from county soil survey maps (United States Department of Agriculture, Soil Conservation Service). Soil texture was measured as % clay and % sand fraction in the upper 20 cm of soil. Drainage was measured on a 1-7 scale where 1 represents very poorly-drained soil and 7, excessively-drained soil. Monthly precipitation data for each field were gathered from the nearest National Oceanic and Atmospheric Administration weather station. Planting dates, plant density, and field cropping history were obtained from grower-cooperators.

Field means of adult corn rootworm trap catch and ear-zone counts for each of the following sampling intervals were correlated with subsequent mean root damage ratings, peak weekly adult counts, individual counts at calendar wks 28 through 34, counts at corn pollination, and total counts summed over the 7-wk sampling period. Regression equations were used to describe relationships between each of the population estimates and subsequent root ratings. Multiple regression procedures, which took into account the various edaphic and agronomic variables, were used to improve the model of corn rootworm adult counts as a predictor of subsequent damage for both ear-zone counts and Olson trap catch. Optimal number of Olson sticky traps needed per field for accurate corn rootworm sampling was determined from Taylor's Power Law regression of trap catch data (Taylor 1961).

RESULTS & DISCUSSION

Seasonal catch of corn rootworm adults on sticky traps peaked from Jul wk 3 to Aug wk 1 in both sample years for most (≈90%) fields. Western corn rootworm, *D. v. virgifera* LeConte adults accounted for >97% of the total corn rootworms for any given sample. Similar results were obtained by Midgarden et al. (1993) for Virginia. Thus, *D. v. virgifera* appears to be the dominant corn rootworm species in Virginia corn fields. Also, because northern and western corn rootworms are not considered equal units when calculating economic injury levels for corn (Hein & Tollefson 1985a), only counts of western corn rootworm adults were analyzed. Correlation coefficients (*r*) for the relationship between western corn rootworm population estimates at various sampling intervals and subsequent root damage are shown in Table 3.1. Population estimates at all sampling intervals were significantly correlated ($P < 0.05$) with root ratings. Western corn rootworm adult counts obtained at calendar wk 33 (Aug wk 3) had the highest correlation with subsequent root damage among the individual sampling intervals for both Olson sticky traps ($r = 0.74$) and ear-zone visual counts ($r = 0.64$). For most fields, calendar wk 33 corresponded with corn growth stage 6 (Ritchie & Hanway 1982), in which silks were brown and kernels were in the blister stage of development. Although timing of crop phenology varied among fields, all fields had at least reached pollination by wk 33. The only adult estimate correlations with subsequent damage that were comparable to those obtained from wk 33 were produced from total western corn rootworm counts summed over the 7-wk sample period. However, because the increased time and effort required in obtaining these estimates would not lead to better correlations with damage, the sample counts of western corn rootworm adults obtained at wk 33 were chosen for further analyses and model building.

Olson sticky trap. Simple linear regression of Olson trap catch at wk 33 on subsequent root damage resulted in a coefficient of determination ($r^2 = 0.55$). Log transformation of the data improved the relationship between trap catch and subsequent root injury ($r^2 = 0.65$) (Fig. 3.1). The model of adult western corn rootworm counts as a predictor of root damage was improved by taking into account various edaphic and agronomic variables which have been shown in previous studies (Turpin et al. 1978, Foster et al. 1986) to affect corn rootworm biology and/or plant response to feeding damage. The variables chosen for consideration were planting date, plant density, years in continuous corn, soil drainage, % slope, % clay, % sand and precipitation for Apr, May, June, and Aug. Step-down multiple regression showed that years in continuous corn and western corn rootworm trap catch at wk 33 contributed the most to the model, which accounted for 71% of the variability in root damage ratings. Removing all variables from the model except trap catch at wk 33, years in continuous corn, planting date, % sand, and precipitation in April and June did not substantially reduce the coefficient of determination of the model ($r^2 = 0.69$) Table 3.2. Parameters such as planting date, plant density, precipitation, and soil type may not have contributed as much to the model as might be expected (Turpin et al. 1978, Musick et al. 1980, Weiss & Mayo 1985) due to lack of variability in the parameter measures among the 43 fields sampled. Soil type and rainfall data were generally similar for most of the fields sampled in the two yrs of the study. In addition, with the exception of two fields, corn was planted within a

Table 3.1. Correlation coefficients (*r*) for relationships between western corn rootworm adult density estimates and subsequent root damage[1] (*n* = 43 fields).

	Correlation coefficient (*r*)	
Sampling period	Olson yellow sticky trap	Ear-zone visual count
Counts at wk 28	0.18	0.15
Counts at wk 29	0.27	0.29
Counts at wk 30	0.40	0.54
Counts at wk 31	0.57	0.47
Counts at wk 32	0.65	0.60
Counts at wk 33	0.74	0.64
Counts at wk 34	0.55	0.44
Peak count	0.56	0.56
Total counts for 7-wks	0.67	0.68
Counts at corn pollination	0.52	0.53

[1] Based on 1-6 root rating scale (Hills & Peters 1971).

relatively narrow range of plant density (52 to 65,000 plants per ha) thus, potentially masking the full influence of this variable.

Ear-zone visual counts. Simple linear regression of ear-zone counts of western corn rootworm adults at wk 33 on root damage resulted in a $r^2 = 0.41$ (Fig. 3.2). Step-down multiple regression showed that years in continuous corn, planting date, soil drainage, and counts at wk 33 contributed the most to the model, which accounted for 69% of the variability in subsequent root ratings. Removing all variables from the model except ear-zone counts, years in continuous corn, planting date, soil drainage, and precipitation in May did not significantly reduce the coefficient of determination of the model ($r^2 = 0.66$) Table 3.3.

Sampling plan for Olson sticky traps:

Determination of sample size. The number of Olson sticky traps needed per field for sampling western corn rootworm adults was estimated from the following equation (1):

(Adopted from Taylor 1961)

$$N = \left(\frac{100}{c}\right)^2 t^2 a m^{b-2} \qquad (1)$$

where N is sample size, t is the appropriate value of the t distribution at a probability level of 0.05, m is the average western corn rootworm adult catch per trap, c is the accuracy level, and a and b are obtained from linear regression of log variance on log mean of trap catch within fields. Regression of log variance on log mean of trap catch data resulted in the following equation, $y = 0.123 + 1.478x$; $r^2 = 0.89$. Approximately 12 traps were needed per field to be 95% sure that the mean sample estimate of adult western corn rootworms was within 25% of the true value. Size of the field also should be considered when determining the number of traps needed for sampling. In order to obtain a

Table 3.2. Components of the final regression model for subsequent root damage[1] to corn using adult western corn rootworm counts on Olson yellow sticky traps at calendar wk 33 as the principal variable (n = 43 fields; r^2 = 0.69).

Variable	Coefficient	Std. Error	P - Value
Intercept	2.812	1.282	0.0347
Olson trap catch at wk 33	0.015	0.002	0.0001
June precipitation	0.328	0.127	0.0138
April precipitation	0.215	0.115	0.0698
Soil % sand	-0.005	0.004	0.1529
Years in continuous corn	0.095	0.042	0.0301
Planting date	-0.012	0.008	0.1097

[1] Based on 1-6 root rating scale (Hills & Peters 1971).

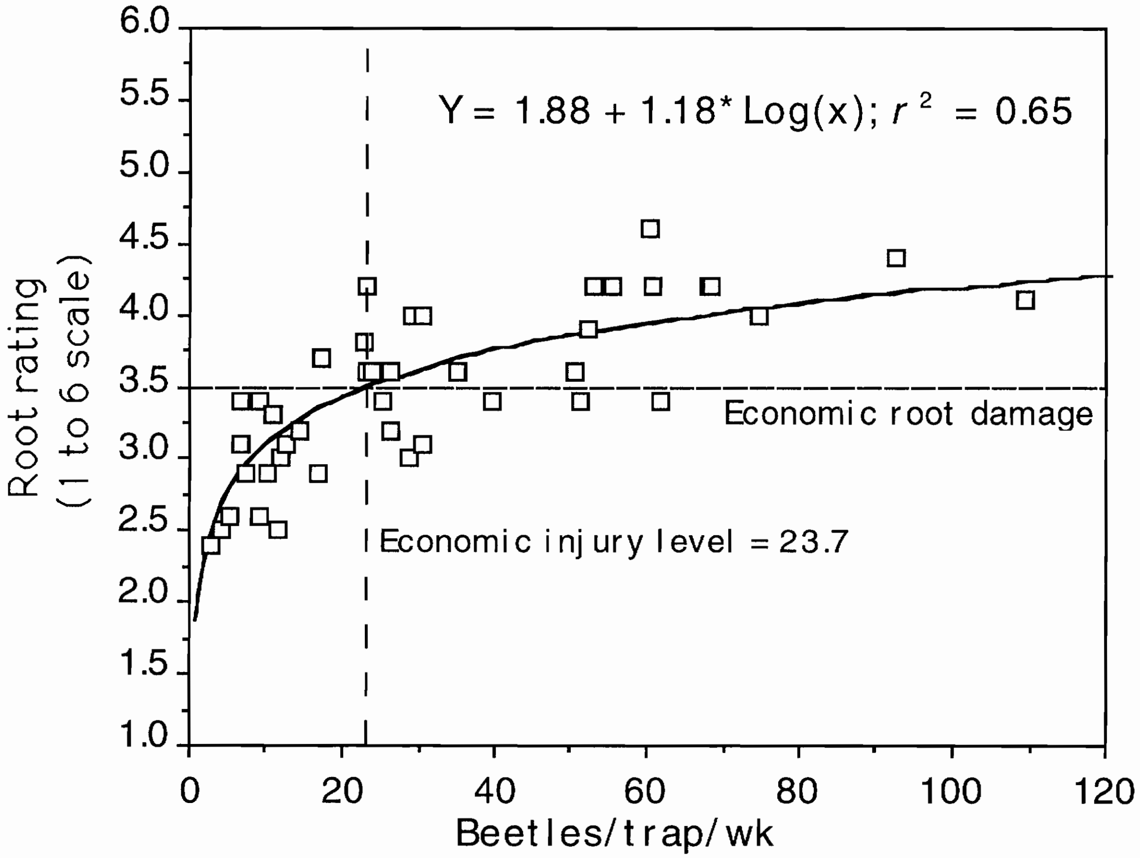

Fig. 3.1. Relationship between mean catch of western corn rootworm adults on Olson sticky traps at calendar wk 33 and subsequent root feeding damage (*n* = 43 fields).

Table 3.3. Components of the final regression model for subsequent root damage[1] to corn using adult western corn rootworm ear-zone counts at calendar wk 33 as the principal variable (n = 43 fields; r^2= 0.66).

Variable	Coefficient	Std. Error	*P* - Value
Intercept	5.621	0.948	0.0001
Ear-zone counts at calendar wk 33	1.035	0.161	0.0001
Years in continuous corn	0.170	0.043	0.0004
Planting date	-0.022	0.006	0.0014
Drainage	-0.146	0.078	0.0683
May precipitation	0.098	0.081	0.2361

[1] Based on 1-6 root rating scale (Hills & Peters 1971).

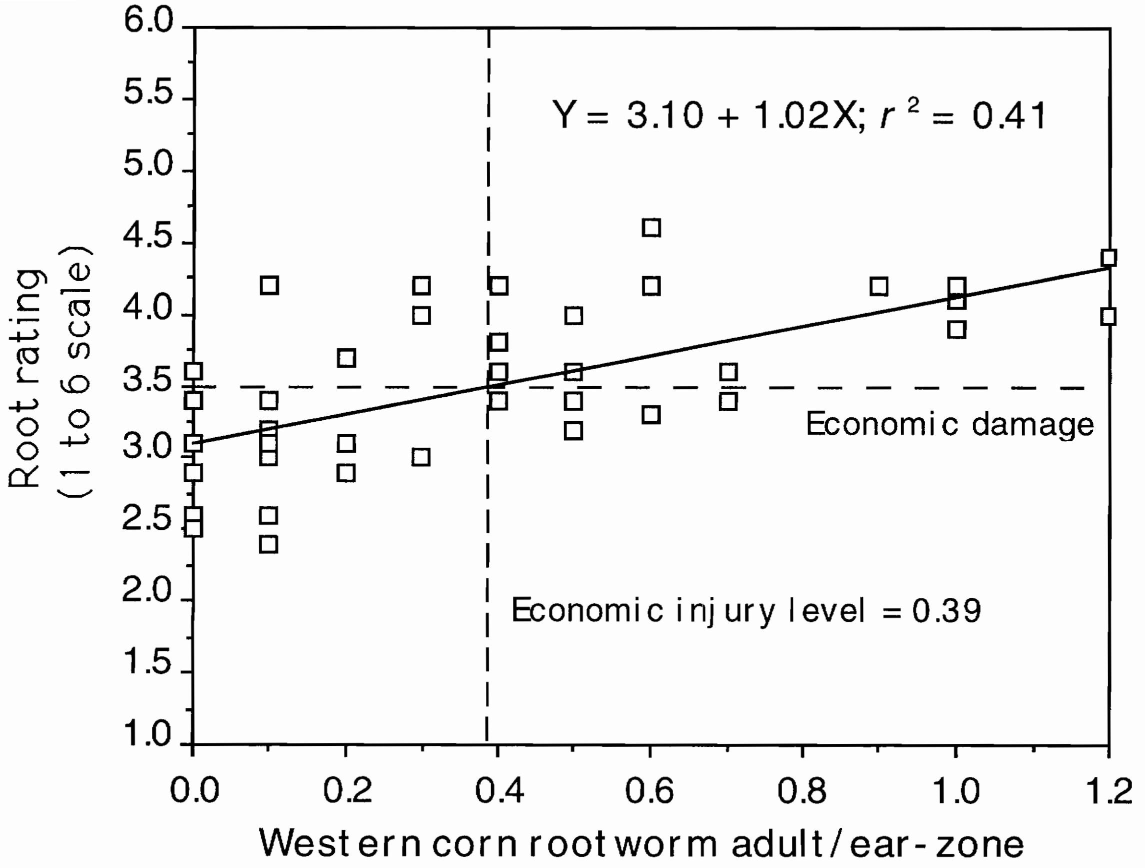

Fig. 3.2. Relationship between mean ear-zone visual counts of western corn rootworm adults at calendar wk 33 and subsequent root feeding damage (*n* = 43 fields).

representative sample of the true population, enough traps should be arranged systematically to cover all areas of the field (Tollefson 1986). However, due to the aggregated spatial dispersion of corn rootworm adults, traps must be placed greater than 30 m apart in order to obtain spatially-independent samples (Midgarden et al. 1993). As a result, fewer than 12 traps may be needed for sampling small fields of approximately 3 ha in size or less. Based on our experience in Virginia, we suggest that 1 sticky trap per 0.6 ha of corn be used for reliable sampling of corn rootworm adults. Too much emphasis, however, should not be placed on exact determinations of sample size because population densities and variance within a field are constantly changing (Southwood 1978). Steffey et al. (1982) addresses, in much more detail, the precision and cost benefits of varying the sample size for adult corn rootworm density estimates.

Calculating an economic threshold. Recent studies suggest that a root damage rating of 4.0 (= one complete node of roots destroyed) must be reached before yield losses would be minimized by insecticides (Sutter et al. 1990, Gray et al. 1993). These studies were based on corn grown for grain. Corn grown for silage, however, suffers greater dollar losses from root damage than corn grown for grain; thus, economic injury levels should be lower for silage corn than for grain corn (Davis 1994). In Virginia, much of the continuous corn acreage at risk to corn rootworm damage is grown for silage (Youngman & Day 1993). Consequently, we used a root damage rating of 3.5 to represent economic damage. A root rating of 3.5 is also currently used by industry for evaluating the performance of soil insecticides (DowElanco 1994).

Applying an economic damage value of 3.5 to the regression equation for Olson sticky trap catch (Fig. 3.1) resulted in a calculated economic injury level of 23.7 western corn rootworm adults per trap per wk, or 3.4 adults per trap per d. Because economic thresholds should be conservative, we suggest a threshold of 20 adults per Olson trap per wk. A system of grouping fields into categories based on mean western corn rootworm adult trap catch was used to compile root damage rating data and evaluate success of the prediction method (Table 3.4). Mean root ratings increased accordingly with trap catch categories. Fields with trap catch ≤ 10.0 adults per trap per wk (*n* = 8) had a mean root damage rating of 2.86 with no fields that exceeded a rating of 3.5. Fields with >10.0 to 20.0 adults per trap per wk (*n* = 8) had a mean root rating of 3.08; however, one field in this grouping (trap catch = 17.3) had a root rating of 3.7 and represented a prediction error according to the threshold of 20 adults per trap per wk. All trap catch groupings of fields with > 20.0 adults per trap had mean root ratings exceeding 3.5; however, seven individual fields did not exceed 3.5 and thus, represented conservative prediction errors. In summary, using an economic threshold of 20 western corn rootworm adults per trap per wk with the Olson sticky trap correctly predicted subsequent feeding injury by western corn rootworm in 35 of the 43 fields (81.4%). Of the incorrect predictions, only one (2.3%) was of the more serious error of failing to predict a corn field that would suffer moderate economic root damage.

Performance of ear-zone counts. Applying a damage threshold of 3.5 to the regression equation for ear-zone visual counts of western corn rootworm adults at wk 33 (Fig. 3.2) resulted in a calculated economic threshold of 0.39 adult per ear-zone. An action threshold of 0.5 adult per ear-zone was suggested by Stamm et al. (1985). As was done for the Olson trap data, fields were grouped into categories based on ear-zone counts in order to compile root damage rating data and evaluate success of the prediction method (Table 3.5). Fields with ear-zone counts in the categories of 0.0 to 0.1 (*n* = 16) and > 0.1 to 0.40 adult per plant (*n* = 11) had mean root ratings of 3.09 and 3.53, respectively. Nine fields within these two categories had root damage that exceeded a rating of 3.5, and thus, represented serious prediction errors according to the suggested economic threshold of 0.5 adult per ear-zone. Ear-zone count groupings of > 0.4 to 0.7 and > 0.7 to 1.2 had mean root ratings of 3.69 and 4.13, respectively; however, four fields had mean root ratings below the economic damage level of 3.5. Thus, use of an economic threshold of 0.5 western corn rootworm adult per ear-zone resulted in an overall prediction accuracy of 69.8% with 9 serious errors (Table 3.6). We feel that an economic threshold of 0.50 adult per ear-zone is too high. Use of 0.3 as the threshold for ear-zone counts improved the prediction accuracy to 74.4% and reduced the number of serious errors from 9 (20.9%) to 4 (9.3%) fields (Table 3.6).

Conclusion. A number of factors can influence the seasonal abundance and activity of corn rootworm adults in corn fields (Hill & Mayo 1980, Godfrey & Turpin 1983, VanWoerkom et al. 1983, Weiss & Mayo 1985, Naranjo & Sawyer 1988; Bergman & Turpin 1986, Fisher et al. 1991). However, the decision of when to sample for these insects often is based on calendar date alone. Hein & Tollefson (1985b) determined that most corn rootworm oviposition occurs in the last 3 wk of August. In addition, most studies on adult corn rootworm sampling have shown that the most effective period to sample in the corn belt is mid- to late Aug (Hein & Tollefson 1984, 1985a; Weiss & Mayo 1985; Levine & Gray 1994). Our study showed similar results for Virginia. The most reliable predictors of subsequent rootworm feeding damage to corn were produced from adult estimates determined at calendar wk 33 (Aug wk 3) for both Olson sticky traps and ear-zone counts. Thus, we agree with Levine & Gray (1994) in that the sampling period for adult corn rootworms need not cover a long period of time, and that sampling from late Jul to late Aug should be sufficient for reliable predictions of subsequent damage. There are exceptions, however, such as corn planted very late,

Table 3.4. Reliability of the Olson sticky trap at predicting western corn rootworm damage in corn planted the following yr using an economic threshold of 20 adults per trap per wk, (*n* = 43 fields).

Mean western corn rootworm adults/trap/wk[a]	Mean root damage[b]	Frequency of correct predictions (%)[c]
	Control measure not recommended	
0 - 10.0	2.86 (8)	100
>10.0 - 20.0	3.08 (8)	88
	Control measure recommended	
>20.0 - 30.0	3.60 (10)	70
>30.0 - 60.0	3.71 (9)	67
>60.0	4.10 (8)	88

[a] Sampled at calendar wk 33 (Aug wk 3).

[b] Based on 1-6 root rating scale (Hills & Peters 1971); number in parentheses represents number of fields.

[c] A correct prediction for fields with < 20 adults/trap/wk occurred when root damage ratings were < 3.5; for fields with ≥ 20 adults/trap/wk, a correct prediction occurred when root ratings were ≥ 3.5 (economic damage).

Table 3.5. Reliability of the ear-zone visual count method at predicting western corn rootworm damage in corn planted the following yr using an economic threshold of 0.5 adult per ear zone[a], (n = fields).

Mean western corn rootworm adults per ear-zone region[b]	Mean root damage[c]	Frequency of correct predictions (%)[d]
	Control measure not recommended	
0 - 0.10	3.09 (16)	81
>0.10- 0.40	3.53 (11)	45
	Control measure recommended	
>0.40 - 0.70	3.69 (10)	60
>0.70 - 1.20	4.13 (6)	100

[a] The ear-zone region refers to the inclusive area from the upper surface of the first leaf below the ear to the lower surface of the first leaf above the ear; an action threshold of 0.5 western corn rootworm adult per ear zone was suggested by Stamm et al. (1985).

[b] Sampled at calendar wk 33 (Aug wk 3).

[c] Based on 1-6 root rating scale (Hills & Peters 1971); number in parentheses represents number of fields.

[d] A correct prediction for fields with < 0.5 adult per ear zone occurred when root damage ratings were < 3.5; for fields with ≥ 0.5 adult per ear zone, a correct prediction occurred when root ratings were ≥ 3.5 (economic damage).

Table 3.6. Performance of sampling methods at predicting western corn rootworm damage in corn planted the following yr, (n = 43 fields).

Sampling method[a]	Economic threshold	Correct decisions	Serious errors[b]
Olson yellow sticky trap	20 beetles/trap/wk	35 (81%)	1 (02%)
Ear-zone counts	0.5 beetle/stalk	30 (70%)	9 (21%)
Ear-zone counts	0.3 beetle/stalk	32 (74%)	4 (09%)

[a] Based on counts of western corn rootworm adults obtained at calendar wk 33 (Aug wk 3).

[b] Serious errors refer to fields determined to be below the economic threshold, but later suffered economic damage (root ratings ≥ 3.5).

which would likely require a later sampling date due to the potential for late-season immigration of females (Naranjo 1991).

The currently-used methods for sampling corn rootworm adults include whole-plant visual counts and unbaited Pherocon AM sticky traps (Tollefson 1986). Corn rootworm adult estimates obtained from these methods, however, account for less than 30% of the variability in subsequent root injury to corn (Hein & Tollefson 1985a). Foster et al. (1986) and Levine & Gray (1994) suggested the need for a better sampling method for corn rootworm adults. Results of our study show that commercial Olson yellow sticky traps (10.2 x 15.2 cm) can be an effective tool for sampling western corn rootworm adults in field corn. Adult counts on traps obtained at calendar wk 33 explained 65% of the variability in subsequent root damage ratings ($r^2 = 0.65$). Use of an economic threshold of 20 adults per trap per wk correctly predicted economic damage (root rating >3.5) to corn 81% of the time, and resulted in only one serious error of failing to predict economic damage in a field which had root ratings exceeding 3.5 in corn planted the following season. For the most reliable estimates of adult corn rootworm densities, ≥12 traps should be placed at least 30 m apart (Midgarden et al. 1993) in fields such that all quadrants are sampled (Tollefson 1986). However, for small corn fields (<5 ha) typical of those found in the mid-Atlantic states, approximately 2 sticky traps are needed per ha of corn.

Visual counts of corn rootworm adults in the ear-zone region of corn may also prove to be a reliable sampling method. In our study, ear-zone counts explained 41% of the variability in subsequent root damage ratings. An action threshold of 0.30 adult per ear-zone correctly predicted economic damage to corn nearly 77% of the time, and resulted in 9% serious errors of failing to predict economic damage to corn. Although our results showed this method to be not as accurate as the Olson sticky trap, ear-zone counts would serve as an adequate alternative method for sampling corn rootworms, and in some cases, may prove to be less time-consuming and more cost efficient than sticky traps (Matin et al. 1984). In addition, sequential sampling plans have been proposed for plant-count sampling techniques which can further reduce the overall time needed for sampling (Foster et al. 1982).

The effects of agronomic and environmental variables on the severity and potential for root damage in corn also must be considered. Although variables such as planting date, plant density, soil type, and monthly precipitation did not significantly improve the model of adult counts as a predictor of subsequent damage in our experiment, their importance to corn rootworm biology and/or plant response to damage has been well documented (Turpin et al. 1978, Chiang et al. 1980, Foster et al. 1986, Fisher et al. 1991). Moreover, lack of variability in some of the agronomic and climatic parameters among the fields sampled in my study may have masked the importance of these factors to subsequent corn rootworm damage.

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CHAPTER 4

SEX RATIO AND SEXUAL DIMORPHISM IN WESTERN CORN ROOTWORM (COLEOPTERA: CHRYSOMELIDAE) ADULTS ON YELLOW STICKY TRAPS IN CORN

ABSTRACT

Field studies were conducted in 1993 to investigate a possible sexual dimorphism in the elytra coloration pattern of western corn rootworm, *Diabrotica virgifera virgifera* LeConte, adults, and to compare the sex ratio of adults captured on 2 types (Olson and Pherocon AM) of commercial yellow sticky traps with those obtained by aspiration. Striped and solid variations in elytra pattern were found in both sexes. Of the western corn rootworm adults that exhibited the solid elytra pattern, >99% captured on yellow sticky traps and 97% collected by aspiration were male. In contrast, of those adults which exhibited the striped elytra pattern, 79% captured on yellow sticky traps and 42% collected by aspiration were male. Sex ratio of adults varied significantly over time and among sampling methods. Sticky traps captured a significantly greater proportion of males compared with aspiration. No significant difference in sex ratio was found between the 2 types of sticky traps; however, the Olson trap captured significantly more corn rootworm adults overall than the modified Pherocon AM trap.

INTRODUCTION

A number of studies have investigated gender-based differences in the population dynamics of corn rootworm adults. Hill and Mayo (1980) indicated that female western corn rootworm adults disperse out of fields in which they emerged more readily than do males. Nearly twice as many females as males were captured in sweep-net samples taken outside of corn fields. However, a greater proportion of males were captured within corn fields. Differences in the dispersal behavior of the sexes could account for differences in female density among corn fields. Godfrey and Turpin (1983) studied western corn rootworm adults in corn of different cropping sequences and found a significantly greater proportion of females in 1st-yr corn fields than in continuous corn fields. Moreover, Naranjo and Sawyer (1988) investigated the effect of host plant phenology on corn rootworm adults and found that planting date and plant variety can affect the proportion of females in the population. The sex ratio of emerging adults was progressively female-skewed in plots that flowered later in the season (Naranjo and Sawyer 1988). Because the size of corn rootworm larval populations is determined by the number of eggs oviposited by females, knowledge of the proportion of female corn rootworms in a population may improve our ability to predict subsequent larval damage to corn.

Corn rootworm scouting programs typically rely on whole-plant counts of corn rootworm adults for predicting corn fields at risk to subsequent larval damage (Midgarden et al. 1993). More recently, counts of corn rootworm adults on yellow sticky traps have been shown to be as reliable as whole-plant counts in predicting larval damage in corn fields the following season (Hein and Tollefson 1985). The Pherocon AM yellow sticky trap (Trécé, Salinas, CA) has been shown to be an effective scouting tool for western corn rootworm adults (Hein and Tollefson 1984, 1985; Karr and Tollefson 1987). Additional research (R.R.Y., unpublished data) has shown that another yellow sticky trap manufactured by Olson, (Medina, OH) catches significantly more western corn rootworm adults than the Pherocon AM trap and is substantially less expensive. However, knowledge of the ability of either the Pherocon AM or the Olson yellow sticky trap to accurately detect the field sex ratio of corn rootworm adults in the population has not been reported.

Analysis of the sex ratio of any population requires an objective and reliable method for sex determination. A number of methods for determining the sex of the western corn rootworm have been investigated. The sex of western corn rootworm pupae can be determined by a pair of prominent papillae which are located on the venter near the tip of the abdomen on females only (Krysan 1986). The sex of any of the *Diabrotica* adults can be determined by a distinctive supra-anal sclerite, possessed only by the male (Smith and Allen 1931, White 1977). The supra-anal sclerite causes the anal tip of the abdomen of the male to end more abruptly, and appear blunt in lateral view. In contrast, the anal tip of the abdomen of the female tapers narrowly, and appears more pointed in lateral view (White 1977). In addition to the supra-anal sclerite, other morphological differences have been observed between male and female western corn rootworm adults. Krysan (1986) reported that the antennae are noticeably longer in males than in females. Moreover, the 2nd and 3rd antennal segments are equal in size in males, whereas in females the 3rd segment is slightly, but distinctly, longer.

Although all of the aforementioned characters can be useful in determining the sex of western corn rootworm adults, field studies which involve the sampling of adults often requires a more rapid method of sex determination. Gillette (1912) reported a very obvious morphological character for determining the sex of western corn rootworm adults. He reported that males had black wing covers except for the narrow yellow margins and yellow tips, whereas females were yellow with three black stripes running down the length of the wing covers. Gillette (1912) noted that the 2 forms were often taken *in copula* and that eggs were often found in the striped form late in the season, but never in the solid form. No subsequent studies have confirmed this sexual dimorphism in the elytra coloration pattern of the western corn rootworm.

The objectives of this study were to determine if the difference in striped and solid elytra coloration patterns found in western corn rootworm adults is a sexual dimorphic trait, and to compare the proportions of female western corn rootworm adults captured on 2 commercial yellow sticky traps with field proportions determined by aspiration.

MATERIALS & METHODS

The study was conducted during July and August 1993 in four corn fields located in Montgomery County, Virginia. The fields, which ranged in size from 9 to 20 ha, were planted within the first 11 d of May at 59,000-62,000 kernels per hectare. All 4 fields received a granular insecticide at planting and had been planted in corn continuously for at least 4 yr before the start of this study.

Western corn rootworm adults were collected weekly for 5 wk in each field from 14 July to 11 August. Four Olson yellow sticky traps coated with Stiky Stuff (Olson) and 4 Pherocon AM sticky traps coated with Tangletrap (Tanglefoot, Grand Rapids, MI) were placed in each field. The Pherocon AM traps were cut in half so that the size of each trap was 14.0 by 22.9 cm. The size of each Olson trap was 10.1 by 15.2 cm. All traps were fastened at ear-zone level to corn stalks with a 5-cm roofing nail and placed ≈50 m apart, and at least 50 m from field borders. Traps were collected weekly from each field and sealed individually in plastic bags for later examination. In addition, an aspirator was used to collect western corn rootworm adults from corn plants in each field and sample date. All sampling with the aspirator was done between 0800 and 1200 hours EDST under sunny to partly cloudy skies. Aspirated adults were taken from all regions of arbitrarily selected corn plants until ≈100 adults were collected from each field, except for the last week of sampling, when ≈50 adults were collected from each field because of declining populations. Insects were placed in sample vials containing 70% ethanol for later examination.

All western corn rootworm adults captured on sticky traps were dissolved free from the trap adhesive by applying Livos Thinner (Livos, Wieren, Germany) to the trap surface. Adults were classified as either striped or solid according to their elytra coloration patterns (Fig. 4.1.) and sexed under a dissection scope according to Smith and Allen (1931). The numbers of each sexual morph (striped male, striped female, solid male, and solid female) were recorded for each of the treatments.

For each sample date, the proportion of each sexual morph among the treatments was analyzed with a 2-way analysis of variance, which included partitioning the treatment source of variation into two orthogonal contrasts (Steel and Torrie 1980). Western corn rootworm sex ratios among the trapping and aspiration methods were analyzed by sample date using a chi-square 2 x 3 contingency table (Zar 1984). A comparison of weekly adult western corn rootworm trap catch between the Olson trap and the modified Pherocon AM trap was made using student *t*-test for 2 independent samples.

RESULTS

Just under ten thousand western corn rootworm adults were captured during the 5-wk sampling period. In total, 6,007 adults were captured with the Olson sticky trap, 2,058 with the Pherocon AM trap, and 1,917 by aspiration. The numbers of western corn rootworm adults on Olson sticky traps peaked by the 2nd wk (19 July) of sampling (133.7 adults per trap), and steadily decreased over the remaining 3 wk. The highest numbers of western corn rootworm adults caught on the modified Pherocon AM traps occurred on the 1st wk (14 July) of sampling with a mean of 45.9 adults per trap. Significantly more western corn rootworm adults were captured on Olson sticky traps compared with the modified Pherocon AM traps for all sample weeks ($P < 0.05$).

Examination of the elytra pattern of all 9,982 western corn rootworm adults revealed that both striped and solid patterns were present in males and females; however, solid females were found in <1% of the total adults examined. The overall percentages of each sex morph of the total western corn rootworm adults captured varied among sampling methods (Table 4.1). Percentages were similar between the 2 sticky traps, but differed substantially from those collected by apiration. Significant interactions between sampling date and trapping device were detected in striped females ($F = 2.60$; df = 8, 42; $P = 0.02$), solid females ($F = 1.88$; df = 8, 42; $P = 0.09$), and striped males ($F = 4.10$; df = 8, 42; $P = 0.001$). Consequently, the proportions of each sex morph were analyzed separately by week.

The proportion of solid males collected by aspiration when compared with the sticky traps was significantly lower for 14 July ($F = 19.19$; df = 1, 6; $P = 0.005$), 28 July ($F = 12.32$; df = 1, 6; $P = 0.013$), and 11 August ($F = 14.79$; df = 1, 6; $P = 0.009$) according to the ANOVA orthogonal contrast (Fig. 4.2). With aspiration, the proportion of solid females generally increased with time; however, on sticky traps the proportion remained constant with time (Fig. 4.2). The proportion of solid females collected by aspiration was significantly higher than that of sticky traps for 28 July ($F = 23.31$; df = 1, 6; $P = 0.003$), 4 August ($F = 14.78$; df = 1, 6; $P = 0.009$), and 11 August ($F = 23.44$; df = 1, 6; $P = 0.003$).

Similarly, the proportion of striped males collected by aspiration when compared with the sticky traps was significantly lower for 21 July ($F = 13.84$; df = 1, 6; $P = 0.01$), 28 July ($F = 17.88$; df = 1, 6; $P = 0.006$), 4 August ($F = 42.95$; df = 1, 6; $P < 0.001$), and 11 August ($F = 186.28$; df = 1, 6; $P < 0.001$) (Fig. 4.2). In contrast, the proportion of

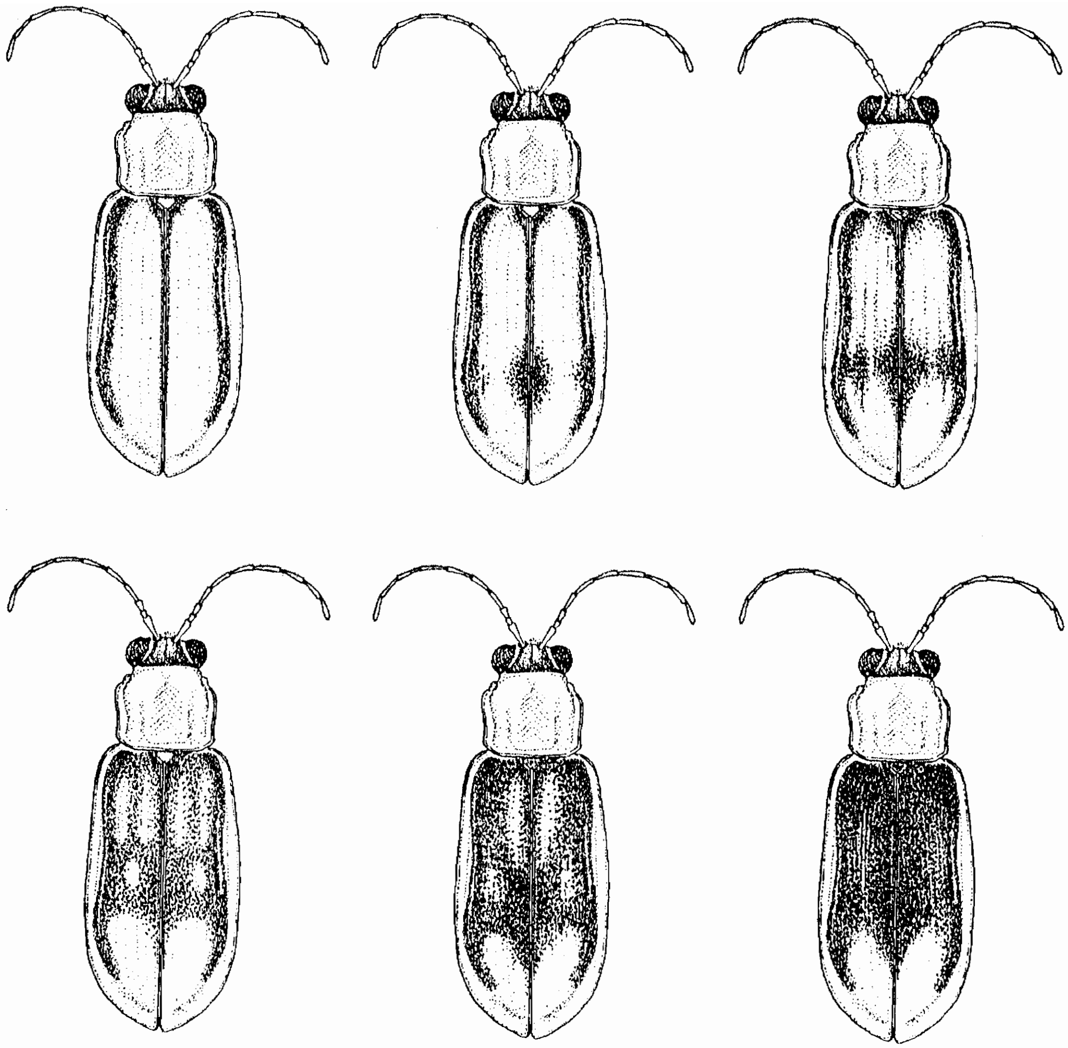

Fig. 4.1. Elytra coloration patterns of the western corn rootworm. Top row represents variability in the striped morphs, bottom row represents variability in the solid morphs.

Table 4.1. Percentage of distribution of sex and morph of the total western corn rootworm adults captured by each sampling method.

	Sampling device		
Sex morph	Aspirator (*n* = 1,917)	Olson sticky trap (*n* = 6,007)	Modified Pherocon AM trap (*n* = 2,058)
solid males	37.4	50.2	52.4
solid females	2.3	0.5	0.5
striped males	25.4	39.6	36.0
striped females	34.9	9.7	11.1

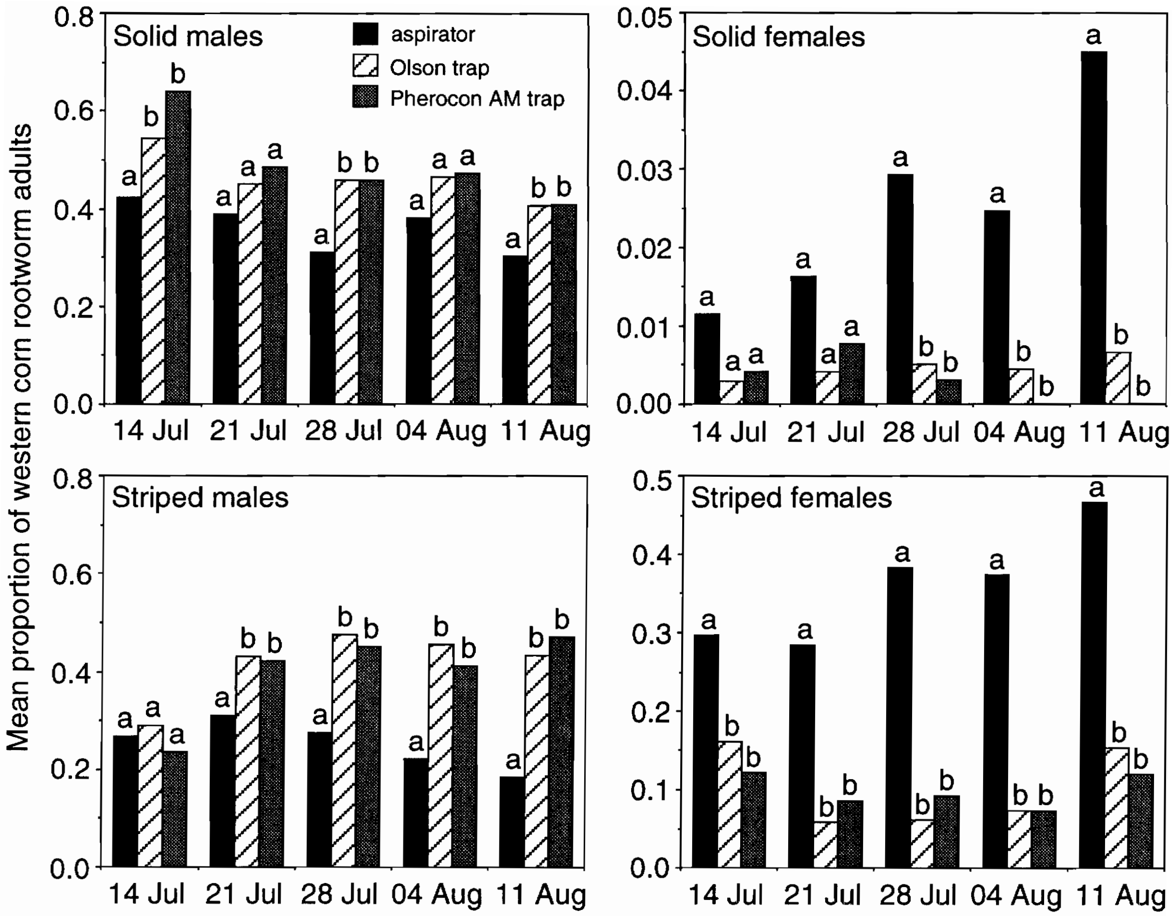

Fig. 4.2. Proportion of solid male, solid female, striped male, and striped female western corn rootworm adults captured by three sampling methods. Same letters above bars (within sampling dates) indicate nonsignificant orthogonal contrasts at *P* > 0.05 level.

striped females collected by aspiration when compared with the sticky traps was significantly higher on all 5 sample weeks: 14 July ($F = 10.10$; df = 1, 6; $P = 0.019$), 21 July ($F = 55.33$; df = 1, 6; $P < 0.001$), 28 July ($F = 107.35$; df = 1, 6; $P < 0.001$), 4 August ($F = 100.17$; df = 1, 6; $P < 0.001$), and 11 August ($F = 94.12$; df = 1, 6; $P < 0.001$). No significant orthogonal contrast was detected among the proportions of solid males, solid females, striped males, or striped females between the 2 sticky traps for any sample week (Fig. 4.2).

The ratio of females to males, as indicated by aspiration, generally increased with sampling week (Table 4.2). For all sample weeks, a significantly higher percentage of female to male western corn rootworm adults was captured by aspiration than by either of the sticky traps ($P < 0.005$, χ^2 test). Both types of sticky traps generally captured similar ratios of females to males. However, in 2 of the 5 wk, a significantly higher percentage of females to males was captured by the modified Pherocon AM trap compared to the Olson trap ($P < 0.05$, χ^2 test), and in the last week, there was a significantly higher percentage of females captured by the Olson trap than by the modified Pherocon AM trap ($P < 0.05$, χ^2 test).

DISCUSSION

Both striped and solid elytra coloration patterns were found in male and female western corn rootworm adults. Overall, 98% of the solid adults captured were male. The sex ratio of striped adults varied with time and sampling method. With regard to the sticky traps, >79% of the striped adults were male. With regard to aspiration, 42% of the striped adults were male. Hence, the conclusion drawn by Gillette (1912) that the solid forms of the western corn rootworm adult are males and the striped forms are females is not completely accurate. However, it may be reasonable enough in adult sampling

Table 4.2. Sex ratio of western corn rootworm adults captured among the sampling methods by week; sample sizes are given in parentheses.

Sample week	Sex ratio of females to males		
	Aspirator	Olson sticky trap	Modified Pherocon AM trap
14 Jul	1:2.4a (446)	1:4.7b (1,703)	1:5.7b (733)
21 Jul	1:2.3a (421)	1:14.7c (2,138)	1:9.4b (353)
28 Jul	1:1.4a (381)	1:16.0c (1,054)	1:9.1b (495)
04 Aug	1:1.5a (405)	1:11.7b (723)	1:10.6b (326)
11 Aug	1:1.0a (264)	1:5.5b (389)	1:6.6c (151)

Ratios followed by the same letter within each row are not significantly different ($P > 0.05$, χ^2 test).

programs and in research involving rapid sex ratio assessment to classify solid morphs as males. The sex of the striped morphs, however, cannot be determined accurately by simple visual inspection of the elytra pattern alone.

Knowledge of the sex ratio, or proportion of female western corn rootworm adults in a field population can be important for predicting subsequent larval damage to corn. The presence of more females in a corn field could likely result in greater oviposition in the soil and a higher larval damage potential the following year (Godfrey and Turpin 1983). Results from my study indicate that the proportion of females captured by the aspiration method is greater than the proportion of females captured by either type of sticky trap. One explanation for this difference is that male corn rootworm adults are most active in the ear-zone region of the corn plant (Witkowski et al. 1975). Consequently, sticky traps placed at ear-zone level would be expected to capture a high proportion of males. Similar results were found by Godfrey and Turpin (1983). Another explanation for this phenomenon might be that virgin western corn rootworm females continue to release their sex pheromones after capture on sticky traps, and thus, create a natural sex lure for males. In either case, the high number of males captured by sticky traps may distort population estimates of corn rootworms, influencing the ability of sticky traps used in sampling programs to effectively predict subsequent larval damage. No significant difference was found in the proportion of female adults captured on the 2 sticky traps. However, the Olson sticky trap captured significantly more corn rootworm adults overall than the modified Pherocon AM trap, and may prove to be a more sensitive trap for sampling western corn rootworm adults. Additional studies (R. R. Youngman and T.P.K, unpublished data) further investigate the trapping differences between the Pherocon AM and Olson sticky traps.

Researchers agree that a more accurate sampling threshold is needed to improve the ability of current western corn rootworm adult sampling methods to predict subsequent larval damage (Foster et al. 1986, Levine and Gray 1994). Current thresholds do not take into account the sex of corn rootworms sampled. A sampling threshold based on female counts (particularly during the oviposition period) should more accurately forecast which corn fields are at risk to damage the following season (Levine and Gray 1994). Based on the results of this study, all western corn rootworm adults exhibiting a solid elytra pattern would not be counted as females. In addition, the sex ratio of striped adults could possibly be estimated with the use of a predictive model based on a number of variables which have been shown to influence sex ratio of corn rootworms. Such variables may include sampling method (Godfrey and Turpin 1983, VanWoerkom et al. 1983), sampling date or crop phenology (Naranjo 1991), corn planting date (Naranjo and Sawyer 1988, Fisher et al. 1991), and number of years in continuous corn (Godfrey and Turpin 1983). More investigation of this possible enhancement to western corn rootworm adult sampling is needed.

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CHAPTER 5

SUMMARY

The western corn rootworm is one of the most damaging pests of continuously-grown corn in the United States. Although only recently detected in southwestern Virginia (in 1985), the insect has spread throughout virtually all of the corn growing regions of the state (Youngman & Day 1993). Knowledge of the risk of damage to corn by this insect was lacking for mid-Atlantic states such as Virginia. Root damage and silage loss was assessed in 32 continuously-grown corn fields across seven counties in Virginia to determine the risk of corn rootworm damage (chapter 2). Approximately 28% of the fields examined had economic root damage in corn plots not treated with a soil insecticide. In addition, 19% of the fields overall had an economic loss in silage due to corn rootworm damage. Because most of the continuous corn acreage in Virginia is treated preventively with soil insecticides for corn rootworms, my results suggest that a large percentage of this insecticide use is unnecessary.

The relationship between root-damage rating and yield loss in corn is very complex. A number of environmental and agronomic parameters can affect plant response to root injury making it difficult to quantify economic damage levels. As a result, there is some discrepancy among researchers concerning exactly which root damage rating level induces a yield loss in corn equivalent to the cost of applying an insecticide. Results of my study showed that fields with root ratings at or below a level of 3.5 (based on 1-6 root damage rating scale) in the untreated corn had a mean silage yield reduction of only 1 to 3%. Fields with root damage ratings >3.5-4.0, however, had a mean silage yield reduction of 12.8% which exceeded the economic level for silage loss in corn. Thus, for Virginia silage corn at least, 3.5 appears to be the root damage level that induces a yield loss equivalent to or greater than the cost of applying an insecticide.

As a whole, scouting programs for corn rootworms have not been widely accepted by growers or crop consultants in this country due, in part, to the lack of accuracy and relatively high cost of the sampling techniques currently used (Levine & Oloumi-Sadeghi 1991). Youngman et al. (1996) showed that a compact yellow sticky trap, manufactured by Olson Products Inc. (Medina, OH), was more efficient at capturing corn rootworm adults and cost approximately one-fifth as much as the Pherocon AM trap, the current sampling tool of choice for corn rootworm scouting (Hein & Tollefson 1984, 1985). The Olson trap was shown to be a reliable sampling tool for predicting economic rootworm damage to corn planted the following season (chapter 3). Adult corn rootworm counts on traps obtained in Aug wk 3 explained 65% of the variability in subsequent root damage ratings ($r^2 = 0.65$). Use of an economic threshold of 20 adults per trap per wk correctly predicted economic damage (root rating >3.5) to corn 81% of the time, and resulted in only one serious error of failing to predict economic damage in a field which had root ratings exceeding 3.5 in corn planted the following season. Previous studies on sampling corn rootworms using whole-plant visual counts (Hein & Tollefson 1984) or Pherocon AM sticky traps (Hein & Tollefson 1985) have resulted in coefficients of variability (r^2) of 0.27 and 0.26, respectively, and prediction accuracies of 77 and 73%, respectively. Thus, the Olson yellow sticky trap may prove to be a less expensive and more accurate alternative to currently-used methods for sampling corn rootworm adults (Youngman et al. 1996).

Because the size of corn rootworm larval populations is determined by the number of eggs oviposited by females, knowledge of the proportion of female corn rootworms in a population may improve our ability to predict subsequent larval damage to corn. However, knowledge of the ability of either the Pherocon AM or the Olson yellow sticky trap to accurately detect the field sex ratio of corn rootworm adults in a population has not been reported previously to my study (chapter 4). My results showed that unbaited yellow sticky traps captured primarily male western corn rootworm adults, and did not accurately reflect the true sex ratios of the field populations.

Determining the sex of western corn rootworm adults based on elytra coloration pattern has been reported in the literature (Gillette 1912), and numerous extension publications. However, no scientific data has been reported to support the use of elytral dimorphism to determine the sex of adults. My results showed that both striped and solid elytra coloration patterns were found in male and female western corn rootworm adults (chapter 4). Overall, 98% of the solid adults captured were male. The sex ratio of striped adults varied with time and sampling method. With regard to the sticky traps, >79% of the striped adults were male. With regard to aspiration, 42% of the striped adults were male. Hence, the conclusion drawn by Gillette (1912) that the solid forms of the western corn rootworm adult are males and the striped forms are females is not completely accurate. However, it may be reasonable enough in adult sampling programs and in research involving rapid sex ratio assessment to classify solid morphs as males. The sex of the striped morphs, however, cannot be determined accurately by simple visual inspection of the elytra pattern alone.

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VITA

Thomas P. Kuhar was born in Baltimore, Maryland on March 29, 1969. He graduated from Sparrowspoint High School in 1987. In autumn of 1987 he began his studies in biology at Towson State University (TSU), Towson, Maryland. While at TSU, he was employed by Dr. Donald C. Forrester as an undergraduate teaching assistant and by Dr. Aubrey G. Scarbrough as a research assistant. He conducted systematic research on robber flies (Diptera: Asilidae) of Maryland and Delaware and completed a travel study investigating the diversity of bee flies (Diptera: Bombyliidae) of San Salvador, Bahamas. He was honored by the TSU biology department with the James Moniodis Scholarship and the Lois D. Odell Award for outstanding biology student, and received his bachelor of science in 1992. Two days following graduation from TSU he moved to Blacksburg, Virginia and began his Master's work in the Department of Entomology at VPI & SU. Under the direction and supervision of Dr. Roger R. Youngman, he investigated the western corn rootworm in Virginia. While pursuing his Master's degree at VPI & SU, he served as President of the W. B. Alwood Entomological Society, Chairman of the Graduate Student Committee of the Entomological Society of America (Eastern Branch), and received the Dow Elanco Entomology Award in 1993, the James McD. Grayson Scholarship in 1994, and the Michael Kozstarab Systematics Award in 1995. Tom was awarded a University Cunningham Doctoral Fellowship in 1995 to continue his studies at VPI & SU.

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