8316319

Foster, Ricky E.

THE DEVELOPMENT AND USE OF SAMPLING AND SCOUTING PROCEDURES FOR CORN INSECTS AND THE RELATIONSHIP OF CORN ROOTWORM DENSITIES TO CORN YIELD

Iowa State University PH.D. 1983

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

The development and use of sampling and scouting procedures for corn insects and the relationship of corn rootworm densities to corn yield

by

Ricky E. Foster

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Entomology
Major: Entomology (Economic Entomology)

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1983

TABLE OF CONTENTS

INTRODUCTION

Justification for Study

One of the major agricultural enterprises in Iowa is growing corn, *Zea mays* L., for use as a feed grain. Over 5.5 million hectares of corn were planted for this purpose in Iowa in 1979 (Becker and Stockdale 1980). A complex of insects feeds on corn. The most important insect pests are the northern and western corn rootworms, *Diabrotica longicornis barberi* Smith and Lawrence and *D. virgifera virgifera* LeConte; the black cutworm, *Agrotis ipsilon* (Hufnagel); and the European corn borer, *Ostrinia nubilalis* (Hubner). To guard against crop losses, over half the corn grown in Iowa in 1978 and 1979 was treated with an insecticide (Becker and Stockdale 1980).

Pest management has been defined as "the intelligent selection and use of pest-control actions that will ensure favorable economic, ecological, and sociological consequences" (Metcalf and Luckmann 1982). The National Academy of Sciences Publication (1969) puts forth two basic principles of pest management: (1) No control measures should be undertaken against a pest unless it is known that the pest is present, and (2) No control measures should be undertaken unless it is known that the pest is present in sufficient numbers to cause economic loss.

With these basic ideas in mind, one can delineate five general steps in the development of a pest management system that somewhat follow those listed by Gonzales (1970).

1. Acquisition of a basic knowledge of the biology of the pest and the host. This step includes correct identification of the pest, an understanding of the pest's life cycle, and its pest status relative to the specific host.
2. Development of reliable and efficient sampling procedures.
3. Determining how the biotic and abiotic environment and the agronomic practices of the grower influence the pest and the response of the host to the pest.
4. Understanding the economic impact of the pest on the host (pest density/yield loss relationship).
5. Determining the potential economic gain from pest control measures.

In corn, as in most crops, pest control practices often have included only steps 1 and 5. A study in Indiana showed that 93% of the insecticide applications for control of corn rootworms were made with little or no knowledge of the insect population density present (Turpin 1977). The economic thresholds currently used for each of the three major corn pests are based on limited data at best. Only recently has progress been made toward development of a corn insect pest management system. A number of recent papers have dealt with sampling different life stages of the corn rootworm (Tollefson 1975, Foster et al. 1979, Bergman et al. 1981, Hein 1981, Steffey et al. 1982).

This project was initiated to supply some of the missing information needed to develop a corn insect pest management system. The specific objectives were:

1. To define the pest status of the three major corn insect pests in Iowa.
2. To improve current sampling procedures for corn rootworm beetles.
3. To assess the value of corn rootworm adult and egg population estimates as predictors of larval damage and corn yield loss.
4. To identify those environmental and agronomic factors that influence the potential for corn yield loss due to corn rootworms.

Literature Review

Sampling

Southwood (1978) defined two basic types of sampling programs that satisfy very different objectives. Intensive sampling programs are useful for population dynamics studies such as life tables. Southwood recommends 10% precision for intensive studies, which usually means a large number of samples and, therefore, relatively high costs. The second type of sampling program is extensive sampling, which is frequently used for area wide surveys of insect populations to predict possible damage and determine the need for control measures. It usually requires less precision, about 25% according to Southwood. This means fewer samples are required and, therefore, the cost per field is reduced.

Frequently, the level of precision used in a sampling program is limited by the availability of resources. Southwood (1978) lists four ways to improve net precision: (1) selection of the optimal sample unit; (2) selection of the optimal number of samples; (3) changing the pattern of sampling from random to stratified random or systematic; and (4) reducing the costs of sampling. One method of reducing the costs is by employing sequential sampling, where the number of samples required is determined as sampling progresses.

Sequential sampling, as described by Waters (1955), classifies populations into decision categories and can often result in savings in time of up to 50%. Three fundamental pieces of information are needed to develop a sequential sampling plan; the mathematical distribution of the insect counts for the sample unit used, an estimate of the damage threshold density, and the acceptable risk of being wrong (Waters 1955). Morris (1955) used sequential sampling for insect populations when he developed a plan for the spruce budworm. Bellinger et al. (1981) reduced sampling time for the Mexican bean beetle, *Epilachna varivestis* Mulsant, in soybeans by 31 to 68% using sequential sampling. Connola et al. (1959) saved 45% in sampling time for red-pine sawfly, *Neodiprion nanulus* Schedl. Finally, Harcourt (1966) reduced sampling time for the imported cabbageworm, *Pieris rapae* (L.) on cabbage by 75%. Many other examples of reducing sampling time with sequential sampling are available. Pieters (1978) has published a bibliography of sequential sampling plans for insects.

In 1969, Kuno developed a new form of sequential sampling that allows the sampler to estimate the insect density at a fixed level of precision rather than placing the population into a category. This type of sequential sampling is more conducive to research needs than the classification type.

Economic-Injury Levels

The concept of the economic-injury level (EIL) is a basic tenet of pest management. Smith (1969) stated, "The determination of the levels of tolerable pest damage in agricultural crops and forests is an essential prerequisite to the development of integrated pest control programs." In their classic paper, Stern et al. (1959) defined an EIL as "the lowest population density that will cause economic damage." Economic damage is defined as the amount of damage whose value equals the cost of management procedures. The other basic term, economic threshold, is defined as "the density at which control measures should be determined to prevent an increasing pest population from reaching the economic-injury level" (Stern et al. 1959). By definition, an economic threshold must always be less than or equal to its corresponding EIL.

Surprisingly, EILs have received relatively little attention from entomological researchers. As a result, most pesticide applications are made as prophylactic measures (Stern 1973). Poston et al. (1983) called EILs the weakest part of most management programs. They also questioned the concept of EILs because it attempts to oversimplify very complex agroecosystems that may include several pests, variable environmental and agronomic conditions and different host responses. Simple, calculated EILs are usually an improvement over no or "best-guess" levels, but they cannot be the final solution with regard to optimization of crop production. Martin et al. (1980) listed a number of factors that may complicate the development of EILs for fall armyworms, *Spodoptera frugiperda*, (J. E. Smith), on sorghum and coastal bermudagrass. They considered the development of refined EILs to be quite an expensive task, which may help explain the lack of progress toward such EILs for any pest on any crop. They predicted that as progress is made toward holistically-managed systems, the usefulness of the EIL concept will diminish.

Poston et al. (1983) discussed four approaches to quantifying the effects of insect pests on crop yields. The first is observation of natural populations. This is the simplest method and involves regressing insect numbers on subsequent plant yield. This approach is most appropriate for perennial and severe pests. The second technique is modification of natural populations. This may involve reduction of pest numbers through the use of insecticides or natural enemies or enhancement of pest numbers with baits, trap crops and attractant isolines. The third approach is to create synthetic pest populations by rearing and releasing the pests in the plots. The final method is to simulate insect damage by manually damaging the plant. This method allows the researcher the most flexibility in that he can precisely control the amount of damage. But it must be carefully researched beforehand to ensure fidelity with actual insect damage.

Stern (1973) warns against putting too much faith in yield data generated from small plots. For example, he used 3.7 by 335 m plots to measure the effects of two aphid species on barley. He emphasized the importance of taking yields from plots with and without insecticide treatments in the same field at the same time with all other variables remaining constant.

European Corn Borer

The European corn borer, *Ostrinia nubilalis* (Hubner), first appeared in Iowa in 1942 (North Central-105 Committee 1972). Since that time, the corn borer has established itself as a frequent pest of corn, although the damage is seldom devastating. Losses due to corn borers have been estimated to range from 2.3 to 6.8% over three year periods in six Corn Belt states. However, losses in individual states in single years have been estimated to be as high as 18% (North Central-105 Committee 1972).

Corn borers generally have two generations per year in the Corn Belt, although they may have more or fewer depending on the latitude and the weather. They overwinter as large larvae in crop residue in the field. The moths emerge in June, mate, and oviposit on the underside of corn leaves, usually near the midrib. The eggs hatch in three to seven days and the larvae feed on the leaf material in the whorl. When the larvae get larger, they bore into the stalk to feed and later pupate there. The moths from the first generation emerge in July and August and oviposit on recently tasseled corn. The second generation larvae feed on silks, kernels, and cobs and also tunnel into the shank and the stalk, where they overwinter.

European corn borers cause yield loss in two general ways. First, they cause physiological yield loss by disrupting nutrient flow and the loss of leaf tissue. This reduced plant efficiency results in smaller yields. Secondly, yields are reduced due to mechanical damage such as broken stalks and dropped ears. Mechanical damage is often a greater concern than the physiological loss.

There are several procedures recommended for corn borer control. Selection of corn hybrids which contain lethal concentrations of the chemical DIMBOA glucoside, which imparts resistance to the first generation, can reduce losses to corn borers. Also, some hybrids have stronger stalks and ear shanks than others, which may help to protect against mechanical losses. Early planted corn is usually more attractive to ovipositing female corn borers. However, early planted corn usually has enough of a yield advantage over later planted corn to offset any increased losses to corn borers and, therefore, early planting is recommended.

Fall plowing destroys many overwintering larvae, but is usually not recommended due to concerns about soil erosion. Iowa State University extension entomologists suggest insecticide treatments when more than 35% of the plants are infested during the first generation or more than 50% during the second generation (Stockdale et al. 1982).

Black Cutworm

The black cutworm, *Agrotis ipsilon* (Hufnagel), occurs throughout most of the world and feeds on a wide variety of hosts, including more than 30 economically important crops (Maxwell-Lefroy and Ghosh 1908, Rings et al. 1975). The larvae damage seedling corn by cutting the plant at or below the soil surface. Sherrod and Luckmann (1976) identified six field characteristics that increase the chances for a cutworm infestation.

1. Previous history of cutworm problems.
2. Soybeans planted the previous year.
3. Presence of weeds prior to spring tillage.
4. Reduced tillage practices utilized.
5. Permanent adjacent vegetation.
6. Poor field drainage.

The origin of cutworm populations that damage corn in the Midwest is somewhat unclear. However, most entomolgists now believe that moths flying in from the South in the spring lay the eggs that result in the damaging larvae (Sherrod et al. 1979). Cutworms may have several generations per year in the Corn Belt, but only the first generation is significant to corn growers. Iowa extension recommendations are for an insecticide treatment when two to three percent of the corn plants are cut or wilted and small worms are present (Stockdale et al. 1982).

Corn Rootworms

Description, history, and control

Thomas Say originally described the northern corn rootworm as *Galeruca longicornis* in 1824 while on an expedition to the Rocky Mountains. The name was changed to *Dibrotica longicornis* by Dr. John L. LeConte (1868). Smith and Lawrence (1967) divided the species into subspecies, with the one damaging corn being designated *D. longicornis barberi*. The western corn rootworm, *D. virgifera* LeConte, was first collected feeding on wild gourd near Fort Wallace, Colorado in 1867 by Dr. LeConte (1968). This species was also divided into two subspecies with the western corn rootworm being named *D. virgifera virgifera* LeConte (Krysan et al. 1980).

C.V. Riley (1880) positively connected the larvae of the northern with damage to corn roots in 1878 by rearing beetles from larvae collected from a farm near Eureka, Missouri. C.P. Gillette (1912) reported the western larvae to be a pest on land that had been planted to corn for two or more successive years.

As early as 1894, Forbes recommended crop rotation as a simple and complete control procedure for corn rootworms. Rotation remained the primary control method until the late 1940s when gamma-benzene hexachloride applied to the soil was shown to effectively control the larvae (Hill et al. 1948). Shortly thereafter, aldrin, dieldrin, and heptachlor were added to the insecticide arsenal (Lilly 1954). As a result, crop rotation became a less popular control practice. These chlorinated hydrocarbons provided inexpensive and effective control throughout most of the decade. In 1959 and 1960, increasing problems were reported in rootworm control in Nebraska (Weekman 1961). By 1963, resistance to chlorinated hydrocarbons had been verified in Nebraska, Minnesota and Illinois and was suspected in other states as well (Ball and Weekman 1963, Bigger 1963).

Weekman (1962) found diazinon to be effective at controlling rootworm larvae. Diazinon belongs to a different chemical class of insecticides, the organophosphates. In recent years, a number of other members of this class, as well as several members of another insecticide class, the carbamates, have been used for rootworm control. Resistance has not yet been definitely identified in either the carbamates or organophosphates (See Ball 1973).

In 1974, Pruess et al. proposed that rootworms be controlled by killing the adults with aerial applications of insecticides prior to oviposition. This technique has been tried in several Corn Belt states with unsatisfactory results (Sechriest et al. 1978). The possibility of needing two applications makes it less desirable economically than application of soil insecticides at planting time.

Biology Chiang (1973) published a thorough review of the bionomics of both the northern and western corn rootworms. Luckmann et al. (1974) compiled a bibliography of rootworm literature that was updated by Irwin (1977). Therefore, no attempt will be made here to discuss at length the biology of the corn rootworms. The reader is encouraged to go to the previously mentioned sources for more information.

Both species of rootworms are univoltine. They overwinter in the soil as eggs. The eggs usually hatch in early June, depending on the accumulation of heat units. The larvae feed predominantly on corn roots, although they can survive on the roots of other hosts (Branson and Ortman 1970). There are three larval instars, with the third being the most damaging. After about a month, the larvae cease feeding and pupate in cells constructed in the soil.

Adult emergence begins in early to mid-July and increases to its peak in late July or early August. Males usually emerge first and females are usually mated shortly after emergence. The females undergo a one to three week pre-oviposition period. Oviposition peaks in mid to late August and declines until all the beetles have died, usually at the first frost. Oviposition occurs in the soil, generally in the vicinity of corn plants. The adults feed on leaves, silks, pollen, and kernels, but are seldom an economic problem.

Sampling Sampling for adult corn rootworms is faster and easier than sampling for either eggs or larvae and is, therefore, the most frequently used measure of rootworm population densities (Steffey et al. 1982). Adult sampling does have some drawbacks such as: the length of time between beetle counts and the actual larval damage, the possible necessity of repeated samples, and the influence of environmental conditions on the population estimates.

Peters and Burkhardt (1961) surveyed rootworm beetle numbers in Kansas by making four, 25-plant counts per field. Chiang and Flaskerd (1965) compared two sampling methods, 10-plant count and 10-minute collection, and concluded that the 10-plant count was the superior method. Peters (1969) used beetle counts in a scouting program, but concluded that he would not use the results to recommend withholding insecticide treatment the following year, if the field were planted to corn.

Luckmann et al. (1975) recommended 25-50, ear-tip samples per field to estimate rootworm beetle densities in sweet corn fields. Tollefson (1975) compared six adult sampling techniques and found that four methods were significantly correlated with subsequent larval damage. Tollefson et al. (1979) found that plant counts and ear-tip collections were not influenced by sampler variation, although timed collections were subject to such variation. Steffey et al. (1982) devised sampling plans for corn rootworm adults using three sampling methods at various levels of precision. They concluded that the plant count was the most reliable and practical method. Thirty percent precision could be obtained by taking 27,two-plant counts per field, which would require approximately 1 man-hour. Hein (1981) found Pherocon AM® traps to equal plant counts as predictors of larval damage.

Sampling for rootworm eggs has also received considerable attention as a possible predictor of subsequent larval damage. Rootworm egg samples are less subject to variation from the sampler or environmental conditions than adult samples, but are much more expensive and require special equipment.

Several articles have been published that describe methods of separating the eggs from the soil (Chandler et al. 1966, Lawson and Weekman 1966, Matteson 1966, and Shaw et al. 1976). The procedure described by Shaw et al. is the most common method. Gunderson (1964) proposed that all Corn Belt states use a uniform procedure for egg sampling with a 10-cm golf course cup cutter. However, the proposal was made with no knowledge of the reliability of the procedure. Howe and Shaw (1972) compared three soil sampling techniques and concluded that a 5-cm bulb setter was more efficient than a trowel or a cup cutter. Foster et al. (1979) compared five sampling methods and again the bulb setter was the most time efficient, but a 10-cm trench across the width of the row was more accurate. They found that with the bulb setter, one could get a density estimate within 20% of the mean in about 4 man-hours. Gerrard and Chiang (1970) developed a procedure to estimate egg densities based on the frequency of samples containing at least one egg. Chiang et al. (1969) devised a plan to convert eggs per sample to density estimates.

Lawson (1968) found that fields that averaged more than five eggs per pint of soil (0.47 l) had sufficient larvae to warrant insecticide treatment. Tollefson (1975) found that none of the six egg sampling techniques he employed gave density estimates that were significantly correlated with subsequent larval damage. Thus, he concluded that egg sampling had little potential as a predictor of rootworm larval damage. However, Apple et al. (1977) found a highly significant correlation between egg density and percentage yield loss.

Despite the fact that the larvae are the damaging stage, surprisingly little attention has been paid to sampling corn rootworm larvae. Bergman et al. (1981) compared two sampling methods, three storage methods, and three extraction methods. The procedure of choice utilized 17.5 cm cubes of soil, stored in a freezer, and extracted with a washing-flotation technique. Twenty percent precision could be achieved by taking 217 such cubes at a cost of 73.8 man-hours per field.

The amount of rootworm larval damage to corn traditionally has been measured by digging corn plants and rating the roots on a 1-6 scale described by Hills and Peters (1971). The categories of the system are:

1. No damage or only a few feeding scars.
2. Feeding scars evident, but no roots eaten off to within 3.75 cm of the plant.

3. Several roots eaten off to within 3.75 cm of the plant, but never the equivalent of an entire node of roots destroyed.
4. One node of roots completely destroyed.
5. Two nodes of roots completely destroyed.
6. Three or more nodes of roots destroyed.

More recently, a 1-9 rating scale has been proposed by Apple et al. (1977) that is used by many researchers. It provides more of a breakdown of the ratings in the 3-range on the 1-6 scale. The classifications are:

1. No feeding damage.
2. Light feeding damage but no pruning.
3. Feeding damage with only an occasional pruned root (1-2 pruned roots per root mass).
4. Feeding damage and some pruning (less than 10% of roots pruned 7.5 cm or less).
5. Feeding damage and moderate pruning (10-50% of roots pruned 7.5 cm or less).
6. Feeding damage and severe pruning (more than 50% of roots pruned 7.5 cm or less).
7. One node of roots destroyed (root stubs less than 2.5 cm long).
8. Two nodes of roots destroyed.
9. Three or more nodes of roots destroyed.

Damage and economic thresholds Corn rootworm larvae feed on the roots of corn plants and cause yield loss due to physiological stress and harvesting problems as a result of lodged plants. Apple et al. (1977) reported yield losses due to rootworm damage of over 50 q per ha. Most test fields, however, had much smaller losses. In Iowa, losses to corn rootworms were reported to exceed $60 million annually (Turpin et al. 1972).

In 1975, Shaw et al. proposed an economic threshold of one beetle per plant for corn rootworms. This density was only established as a guideline and was not based on any data. Nevertheless, one beetle/plant is still employed as the threshold for corn rootworm adults. Luckmann et al. (1975) used the same threshold for rootworms in canning sweet corn. Taylor (1975) used one beetle per plant as the threshold in an economic analysis of the returns using three strategies for controlling rootworms in Illinois: always treat, never treat, and scout and treat when necessary. He concluded that the scouting and never-treating strategies were about equal and the always-treat strategy was inferior to both of the other two. However, Taylor used equations relating adult density and yield that were based on limited data and used an unrealistic scouting cost of $0.25 per ha.

Shaw et al. (1975) established a conservative economic threshold of 12.4 million corn rootworm eggs per ha based on observations in four fields in one year. Apple et al. (1977) calculated a threshold of five eggs per pint (0.47 l), which is roughly equivalent to 12.4 million eggs per ha. Using artificial infestation techniques, Branson et al. (1980) found significant yield reduction at the lowest level of infestation, 100 eggs per 30.5 row centimeters. However, Chiang et al. (1980) did not get significant yield loss at 1200 eggs per plant in a wet year or 600 eggs per plant in a dry year.

Petty et al. (1969) estimated that each rootworm larva feeding on a plant would reduce the yield by an average of 0.765 percent. Smith (1979) reported that the loss per larva would be 2.5%. However, both studies used visual counts to sample for larvae, which Bergman et al. (1981) found to be somewhat unreliable, especially for first instar larvae.

Turpin et al. (1972) calculated that fields with mean root ratings greater than 2.50 on the 1-6 scale would suffer economic yield loss. They presented a regression equation describing the relationship between root rating and yield. Branson et al. (1980) found a highly significant relationship between root ratings and yield, although it is based on only six data points.

There are a number of factors that may influence the amount of damage corn rootworms will inflict. Turpin et al. (1972) identified seven variables that explained 35% of the variation in root ratings. The variables were slope, drainage, percentage clay, planting date, soil K, soil P, and plant population. Obviously, some measure of the corn rootworm density could have improved the predictability of the model. Musick et al. (1980) and Mayo (1980) found that later planting tended to reduce the amount of rootworm damage.

The objective of this study was to provide some of the information necessary to develop a pest management system for corn insects in Iowa, especially corn rootworms. More specifically, the goals were to improve sampling procedures and to quantify the impact of the pests on the crop.

PART 1. FREQUENCY AND SEVERITY OF ATTACK OF SEVERAL PEST INSECTS ON CORN IN IOWA

Corn is the most widespread crop grown in Iowa, with about 5.5 million ha planted annually. Approximately 40% of this total is corn following corn (Becker and Stockdale 1980). Corn grown in Iowa is subject to attack by a number of insect pests in various degrees of severity. The more important pests include the northern and western corn rootworms, *Diabrotica longicornis barberi* Smith and Lawrence and *D. virgifera virgifera* LeConte; the black cutworm, *Agrotis ipsilon* (Hufnagel); the European corn borer, *Ostrinia nubilalis* (Hubner); and several genera of wireworms, including *Melanotus*, *Agriotes*, and *Limonius*.

Corn rootworms are considered to be the premier corn pests in the Corn Belt. Adults oviposit predominantly in cornfields during August and September, and egg hatch produces the damaging larval stage the following June. The larvae feed on roots and cause yield loss due to physiological stress and harvesting problems as a result of lodged plants. Soil insecticides were applied to control corn rootworm larvae on more than 2.7 million ha in Iowa in 1979 (Becker and Stockdale 1980). The adult stage is the one most commonly monitored to attempt to predict the potential for subsequent larval damage. The generally accepted economic threshold is an average density of 1 beetle per plant (Shaw et al. 1975).

Black cutworms are a sporadic, but sometimes devastating, pest of corn. Moths fly in from the south in early spring and oviposit on green vegetation (Sherrod et al. 1979). The larvae begin feeding on the weed host and may move to corn when their former host plant is destroyed during tillage before planting. The larvae cause damage by cutting seedling plants. The amount of damage varies considerably from year to year. In 1979, about 92,000 ha were treated to control black cutworms in Iowa (Becker and Stockdale 1980). Iowa extension entomologists estimate that approximately 400,000 ha in Iowa had economically damaging levels of cutworms in 1981, a cutworm outbreak year throughout much of the state (D. E. Foster, Department of Entomology, Iowa State University, Personal Communication). Scouting for cutworms involves estimating the average number of cut or damaged plants in the field. Iowa extension recommendations are for treatment when 2 to 3 percent of the plants are wilted or cut and small worms are present (Stockdale et al. 1982).

European corn borers are a ubiquitous pest of corn. They infrequently reach sufficient densities to cause economic damage, which for the first generation is estimated to be 35% of the plants showing leaf feeding with larvae present (Stockdale et al. 1982). Corn borers overwinter as large larvae in crop residue. The moths emerge in June, mate, and lay eggs on the underside of corn leaves. Fields should be monitored in late June and early July for larval feeding. More than 72,000 ha were treated for first generation corn borer control in Iowa in 1978 (Becker and Stockdale 1980).

Wireworms have been an important pest of corn in the past, infesting as many as 53% of fields (Bigger and Decker 1966). Wireworms have dramatically declined in importance because of changing rotation practices by farmers (Turpin and Thieme 1978). Wireworms cause damage to corn by tunneling into seeds or the base of seedling plants, resulting in death or injury to the plant. Scouting involves determining the percentage of dead or stunted plants.

The objective of this study was to observe the frequency and severity of attack of corn by these four important corn insect pests.

Materials and Methods

This study was part of larger project that involved conducting a research pest management scouting program in three areas of Iowa from 1979 through 1982. The study areas were Cass County in southwestern Iowa, Story County in central Iowa, and Fayette County in the northeastern part of the state. The total number of fields in the study were 31, 43, 44, and 37 fields in 1979, 1980, 1981, and 1982, respectively. Fields were scouted throughout the growing season, except in 1982 when scouting was discontinued after scouting for first generation European corn borers.

In late May and early June, fields were scouted for black cutworms by observing the number of cut plants from 20 consecutive plants in 5 locations in the field. The soil adjacent to the cut plants was inspected to confirm the presence of black cutworms. When cutworm damage was observed, the sample size was increased to 100 plants in each of five areas to better estimate the severity of the infestation. Wireworms were not scouted for specifically, but the scouts remained alert for possible wireworm damage while scouting for cutworms.

Fields were scouted in late June and early July for first generation European corn borers. The number of plants showing whorl feeding was observed on 100 plants in each of 5 locations per field. Several damaged whorls were inspected to confirm the presence of small corn borer larvae. Fields in Story County were not scouted for European corn borers.

Adult corn rootworms were monitored from late July until early September. The technique used was "plant counts," as recommended by Steffey et al. (1982). The sample size in 1979 was 27, two-plant counts, which according to Steffey et al. (1982), would give an estimate of the beetle density with 30% precision. In 1980 and 1981, Kuno's method of sequential sampling was used, as described by Foster et al. (1982). This method also gave an estimate of the density with 30% precision, but allowed earlier termination of sampling in most cases. Weekly visits were made to each field when possible.

Check strips with no planting-time application of soil insecticides were left in most fields where rootworm beetles had been monitored the previous year. During late July, 20 plants were dug from each of these strips, and the rootworm larval damage was rated on the Iowa 1 to 6 scale (Hills and Peters 1971).

Results and Discussion

Over a four-year period, only 10 of 151 fields scouted for black cutworms had more than 3% of the plants cut (Table 1). Eight of those 10 fields with economic damge were found in 1981. These results agree with our classification of black cutworms as a sporadic pest. No fields scouted had a damaging wireworm infestation.

Table 2 shows the percentage of plants showing whorl feeding from first generation European corn borers. The number of fields exceeding the economic threshold of 35% feeding is given in Table 3. At least one field surpassed the economic threshold each year, and county means infestation levels ranged from 7 to 23%. Every field scouted had some plants damaged, and the means for individual fields ranged from 0.8 to 76%. Extremely rainy weather in 1982 virtually halted corn planting from May 10 until June 1. First generation corn borer moths had few fields to choose from that were suitable for oviposition. Therefore, the eggs were concentrated in fields planted early. All four of the fields with damaging populations in Cass County in 1982 were planted before May 10. In 1979, portions of six fields in Fayette County were treated by air with 1.12 kg active ingredient of 10% carbofuran granules for first generation corn borer control. The infestations ranged from 20 to 42% of the plants showing feeding. The yields were higher in the treated area of each field, and the yield increases ranged from 1.3 to 22.5%.

Almost 95% of the fields scouted had corn rootworm beetle densities exceeding the economic threshold of one beetle per plant (Table 4). The county averages ranged from 1.4 to 6.2 beetles per plant (Table 5). Table 6 shows the mean root damage ratings in those fields with untreated strips during the following growing season. More than 83% of the fields scouted had mean root ratings exceeding 2.50 (Table 7), indicating that those fields had sufficient root damage to result in economic yield loss according to Turpin et al. (1972).

In conclusion, our scouting program indicates that wireworms are rarely a problem in Iowa. Black cutworms are a sporadic problem, and European corn borers are present in almost all fields but seldom at economically significant levels. Corn rootworms are consistently present in densities above the economic threshold, with the resulting damage frequently above economic levels as well.

Table 1. Number of Iowa cornfields in scouting program with economic damage by black cutworms (> 3% plants cut). Number of fields scouted in parentheses

	Year				
County	1979	1980	1981	1982	Total
Cass	1 (11)	0 (19)	5 (22)	1(16)	7 (68)
Fayette	0 (9)	0 (15)	1 (13)	0 (9)	1 (46)
Story	------	0 (13)	2 (12)	0 (12)	2 (37)
Total	1 (20)	0 (47)	8 (47)	1 (37)	10 (151)

Table 2. Average percentage of corn plants showing whorl feeding due to first generation European corn borers in Iowa

County	Year 1979	1980	1981	1982	Average
Cass	15	7	10	27	14
Fayette	23	10	--	10	14
Average	18	8	10	19	14

Table 3. Number of cornfields in scouting program exceeding 35% whorl feeding by European corn borers in Iowa. Number of fields scouted in parentheses

	Year				
County	1979	1980	1981	1982	Total
Cass	1 (11)	0 (13)	1 (20)	4 (11)	6 (55)
Fayette	1 (9)	1 (15)	0 (12)	0 (9)	2 (45)
Total	2 (20)	1 (28)	1 (32)	4 (20)	8 (100)

Table 4. Number of cornfields in scouting program exceeding economic threshold for corn rootworm beetles in Iowa (1 beetle/plant). Number of fields scouted in parentheses

	Year			
County	1979	1980	1981	Total
Cass	10 (10)	16 (16)	21 (21)	47 (47)
Fayette	8 (9)	15 (15)	12 (12)	35 (36)
Story	7 (12)	12 (12)	11 (11)	30 (35)
Total	25 (31)	43 (43)	44 (44)	112 (118)

Table 5. Average number of corn rootworm beetles/plant in Iowa at peak beetle density

County	Year			Total
	1979	1980	1981	
Cass	5.3	6.2	5.1	5.5
Fayette	3.0	4.7	3.0	3.7
Story	1.4	2.8	4.0	2.6
Average	3.2	4.7	4.2	4.2

Table 6. Mean root rating (1-6) scale in untreated areas of continuous cornfields in Iowa

County	Year			Average
	1979	1980	1981	
Cass	3.19	4.11	2.86	3.33
Fayette	3.54	3.16	3.41	3.34
Story	2.87	3.05	2.64	2.86
Average	3.13	3.35	2.96	3.15

Table 7. Number of fields in Iowa scouting program with with root rating (1-6 scale) exceeding 2.50. Number of fields with roots rated in parentheses

County	Year 1980	1981	1982	Total
Cass	5 (6)	7 (7)	9 (10)	21 (23)
Fayette	6 (7)	11 (11)	7 (9)	23 (27)
Story	11 (12)	8 (11)	6 (10)	25 (33)
Total	22 (25)	26 (29)	22 (29)	69 (83)

PART 2. SEQUENTIAL SAMPLING PLANS FOR ADULT CORN ROOTWORMS

The northern and western corn rootworms, *Diabrotica longicornis barberi* Smith and Lawrence and *D. virgifera virgifera* LeConte, are the most serious pests of corn in the Midwest. Losses to corn rootworms in Iowa have been reported to exceed $60 million annually (Turpin et al. 1972). In 1979, almost 50% of the corn grown in Iowa was treated with insecticides for the control of corn rootworms (Becker and Stockdale 1980). A survey conducted in 1977 found that 91% of the corn following corn was treated for corn rootworm control (Jennings and Stockdale 1978). In Indiana, another study showed that 93% of the insecticide applications for corn rootworms were made with little or no knowledge of the insect population level present (Turpin 1977). Therefore, for both economic and ecological reasons, the development of a corn rootworm pest management system should be a high priority.

The viability of any pest management system is limited by the quality of the sampling procedures used. Sampling for corn rootworm beetles serves as a predictor of larval damage the following season. Tollefson (1975) found significant correlations between beetle numbers and larval damage. Steffey et al. (1982) developed a procedure for estimating beetle populations at various levels of precision with three sampling methods. He found "whole plant counts," which involves counting all the beetles on a corn plant, to be the most accurate and practical and demonstrated that 30% precision could be achieved by making 27, two-plant counts per field. Current recommendations in Iowa are for soil insecticide treatment or crop rotation in fields that had more than 1.0 beetle per plant during the previous season (Shaw et al. 1975).

Sequential sampling frequently results in dramatic savings in time and effort. Waters (1955) reported that savings in time of up to 50% are not uncommon. There are two general methods for devising a sequential sampling scheme. Waters' method has fixed upper and lower decision lines, and sampling is terminated when the cumulative number of insects counted falls outside the decision lines for a given sample size. This method classifies the population into a category and does not attempt to quantify the population level. The second method, proposed by Kuno (1969), involves sampling until a preset level of precision is reached, giving the sampler an estimate of the population present.

Our objectives were a). to develop two sequential sampling schemes for corn rootworm adults and b). to compare the amount of time expended by using each method with the time involved in sampling with a fixed sample size.

Materials and Methods

Steffey et al. (1982) found corn rootworm adults to be aggregated in their distribution as measured by six different dispersion indices. According to Southwood (1978), values of k of less than eight indicate that the population is aggregated in its distribution. Using a procedure described by Iwao (1968), we calculated a common k of 5.81 from ca. 1,600 sets of whole-plant counts taken throughout Iowa in 1976, 1977, and 1979. The equations for the decision lines as described by Waters (1955) were derived by using the common k, the risk of rejecting a true hypothesis (α) equal to 0.05, and the risk of accepting a false hypothesis (β) equal to 0.05. The lower and upper class limits were set at 0.77 and 1.33 beetles per plant, respectively, so as to give 30% precision around the threshold.

Kuno's "stop line," which determines when the desired level of precision has been reached, is described by the following equation for populations that fit a negative binomial distribution:

$$T = \frac{1}{(\frac{1}{2} D_o)^2 - \frac{1}{nk}} \qquad (1)$$

where T = the cumulative number of beetles counted, D = the desired level of precision, and n = the number of samples. The stop line was calculated for 30% precision.

In August 1980, an experiment was conducted to determine how much time would be saved by using each of the sequential sampling methods compared with a fixed sample size. The desired precision level was 30%, so 54 was set as the maximum number of samples to be taken with any method (Steffey et al. 1982). Eight Iowa cornfields, two in each of four population categories, were sampled with each of the three methods in a randomly assigned order. The population categories in beetles per plant were: (1) 0-0.49; (2) 0.5-1.49; (3) 1.5-3.99: and (4) 4.0 or more.

The fields chosen for the study were rectangular with straight rows and ranged from 6 to 16 ha. The sampling pattern used in each field was a uniform "U" shape, and sampling was initiated 50 paces past the end rows. The two members of a pair of samples were separated by enough distance to insure that sampling the beetles on one plant did not affect the beetles on the second plant. Pairs of samples were separated by 25 paces when sampling was along the row, and by 25 rows when sampling was across rows. The time measured was the total amount of time the sampler spent in the field.

In 75 visits to cornfields in a scouting program, the amount of time necessary to sample each field for rootworm beetles by using Kuno's method was recorded and regressed against the number of samples taken. The resulting equation would allow one to predict the amount of time needed to take a given number of samples. In 2 complete days of scouting, all actions taken by the scout were timed and recorded to determine the actual proportion of time spent in the field sampling.

Results and Discussion

The decision lines for Waters' method are described by the equation:

$$d_{1,2} = 1.01n \pm 6.63 \qquad (2)$$

where d = the total number of beetles counted and n = the number of plants sampled. Table 1 presents the classification guide. Table 2 shows the stop points for

Kuno's method.

Table 3 presents the mean times for sampling fields in the four population categories with each of the three methods. The data reveal that Kuno's method is no better than the fixed sample size at populations below 1.5 beetles per plant but is much faster at larger populations. The analysis of variance bears out the advantage of the sequential sampling methods (Table 4). The two sequential methods are significantly faster than the fixed sample size, and Waters' method is significantly faster than Kuno's method. The interactions indicate that the difference between times for sequential sampling and fixed sample size sampling are greatest at population levels above 1.5 beetles per plant and that differences between the two sequential methods are fairly constant over all population levels.

The regression of sampling time (T_s) vs. the number of samples (n) yielded the equation:

$$T_s = 0.20 + 1.41n - 0.0123n^2 \quad (r = 0.87) \qquad (3)$$

The study of how a scout's time is divided gave the following results: in field, 65%; out of field, 3%; driving, 11%; and lunch and breaks, 21%. Based on equation 3, the use of Waters' method rather than the fixed sample size in a scouting program covering 43 Iowa cornfields would have reduced the sampling time expended from 34.06 to 15.06 h, or a savings of 55.8%. This would convert to an overall savings of 36%.

Of course, saving time would be of no consequence if the sampling scheme failed to give accurate results. In the 43 fields in the previously mentioned scouting program, Waters' method reached a decision that agreed with that of the fixed sample size in every instance. If each visit to a field is considered separately, the agreement in 225 visits was greater than 96%.

For research purposes, an estimate of the population level is usually necessary. For a pest management scouting program, it would be necessary only to reach a decision concerning the need for the implementation of a control alternative. At higher population levels, Kuno's method of sequential sampling can significantly reduce the amount of time necessary to estimate corn rootworm beetle populations, thus reducing the costs of conducting research. Waters' method can greatly decrease the time for a scout to cover his fields, while still maintaining a high degree of reliability.

Table 1. Sequential table for classifying populations of corn rootworm beetles (Waters' method)

Plants		Cumulative no. Beetles Intermediate, Continue Sampling	
10		3-17	
12		5-19	
14		7-21	
16		9-23	
18		11-25	
20	No	13-27	
24	Control	17-31	Control
28	Necessary	21-35	Necessary
32		25-39	
36		29-43	
40		33-48	
44		37-52	
48		41-56	
52		45-60	
54		47-62	

Table 2. Stop points for sequential sampling for corn rootworm beetles (Kuno's method)

Plants	Cumulative No. Beetles
10	189
12	123
14	98
16	85
18	77
20	72
24	65
28	61
32	58
36	56
40	55
44	54
48	53
52	52
54	52

Table 3. Mean sampling time (min) for sampling fields for corn rootworm beetles in 4 population categories with 3 sampling schemes

Population Level (Beetles/Plant)	Fixed	Method Kuno	Waters
0-0.49	32.23	32.23	16.43
0.5-1.49	29.37	31.26	11.00
1.5-3.99	40.02	24.00	10.01
4.0 or more	54.59	21.16	7.18

Table 4. Analysis of variance in sampling for corn rootworm beetles with 3 sampling methods at 4 population levels

Source		df		ss	F
POPULATION LEVEL		3		59.54	1.38
<1.5 vs. >1.5	(C1)		(1)	3.57	0.25
<0.5 vs. >0.5 and <1.5	(C2)		(1)	28.55	1.99
>1.5 and <4 vs. >4	(C3)		(1)	27.42	1.91
SAMPLING METHOD		2		3135.81	109.17**
Sequential vs. Fixed	(C4)		(1)	2105.56	146.61**
Kuno vs. Waters	(C5)		(1)	1030.25	71.74**
POPULATION LEVEL*SAMPLING METHOD		6		968.35	11.24**
C4 * C1			(1)	742.60	51.71**
C4 * C2			(1)	0.08	0.01
C4 * C3			(1)	199.99	13.93**
C5 * C1			(1)	15.66	1.09
C5 * C2			(1)	9.92	0.69
C5 * C3			(1)	0.01	0.00
ERROR		12		172.34	

**Significant at the 0.01 level.

PART 3. CORN ROOTWORM ADULT AND EGG POPULATION ESTIMATES AS PREDICTORS OF LARVAL DAMAGE AND CORN YIELD LOSS

The larvae of the northern and western corn rootworms, *Diabrotica longicornis barberi* Smith and Lawrence and *D. virgifera virgifera* LeConte, damage corn by feeding on the roots. Yield loss occurs due to physiological stress and harvesting problems as a result of lodged plants. Because they are subterranean, the larvae are difficult and time consuming to sample. Bergman et al. (1981) estimated that it would require approximately 47 man-hours to estimate larval density within 25% of the mean. By the time the larvae are detected, a growers's options would be limited to no action or a cultivation treatment with a soil insecticide. Additionally, if weather conditions are adverse, the grower may not have the opportunity to implement control measures. Therefore, it is more practical to sample a prior stage of the insect, either eggs or adults, during the previous year. This would allow an earlier decision as to the necessity for control action which may include crop rotation as well as insecticides.

Corn rootworm eggs can be efficiently separated from soil using the method described by Shaw et al. (1976).

Gunderson (1964) proposed a uniform field sampling procedure employing a 10 cm golf course cup cutter. Howe and Shaw (1972) compared three sampling methods and found a 5.4 cm diameter bulb setter to be the most efficient. A bulb setter was the fastest of five methods compared by Foster et al. (1979), although a 10 cm wide trench dug across the corn row proved to be the most accurate. Tollefson (1975) tried six egg sampling methods and found that none of the methods were significantly correlated with larval damage the following year. Shaw et al. (1975) proposed an economic threshold of 12.4 million rootworm eggs per ha.

Tollefson (1975) also compared six methods of sampling rootworm beetles for predicting larval damage, of which four methods were found to be reliable. Steffey et al. (1982) developed sampling plans for three different beetle sampling methods and found "plant-counts" to be the most practical. Sequential sampling plans for rootworm beetles using plant counts were developed by Foster et al. (1982). Hein (1981) found a sticky trap to be comparable to plant-counts both in efficiency and in correlation with damage. Shaw et al. (1975) proposed a threshold of one beetle per plant, which has been widely accepted throughout the Corn Belt.

Corn rootworm larval damage has traditionally been estimated using some form of root damage rating scale. Turpin et al. (1972) calculated a regression equation relating root ratings with yield. They calculated that economic damage could be expected when the mean root rating exceeded 2.5 on the 1-6 scale (Hills and Peters 1971), which converts to about 3.6 on the 1-9 scale (Apple et al. 1977, Hein 1981). Branson et al. (1980) also regressed root damage on yield. The experiment was conducted in a uniform small plot that was artificially infested with rootworm eggs. Although the resulting equation was statistically significant, root ratings accounted for only 29% of the variation in yields. Chiang et al. (1980) found that rainfall was important in determining the amount of yield loss in rootworm damaged plots.

The objectives of this study were a). to assess corn rootworm adult and egg population estimates as predictors of larval damage and corn yield loss and b). to evaluate the reliability of current economic thresholds for corn rootworms.

Materials and Methods

The cornfields used in this study were located in three counties in Iowa: Cass Co. in the southwest, Story

Co. in central Iowa, and Fayette Co. in the northeast. In 1979, fields were scouted weekly as possible from late July until early September for corn rootworm beetles by making 27, two-plant counts in each field as described by Steffey et al. (1982). This provided an estimate of beetle density within 30% of the mean. In 1980 and 1981, fields were scouted in a similar manner except that Kuno's method of sequential sampling was employed as described by Foster et al. (1982).

Egg population densities were estimated by taking 32 samples per field. Each sample was a 0.47 l (one pint) subsample of a composite of ten, 10 cm diameter cores taken to a depth of 10 cm. Sixteen of the samples were from composites of cores taken between rows of corn and sixteen were from composites of cores taken at the base of the plants. The samples were processed using the method suggested by Shaw et al. (1976) and the eggs keyed to species by observing the chorion pattern as described by Atyeo et al. (1964).

During the growing season following rootworm scouting, growers were asked to not treat a portion of their scouted fields with planting-time soil insecticides. These untreated strips ranged in size from 4 rows by 60 m to 12 rows by 500 m. In late July, 20 randomly selected roots were dug from the untreated strip. The roots were washed and rated for rootworm damage using both the 1-6 scale and the 1-9 scale. In the fall, both the treated and untreated areas were harvested with a combine and yields checked with a weigh wagon. The corn moisture level was determined and the yields converted to 15.5% moisture, No. 2 shelled corn. Harvest data was collected in 23, 29, and 25 fields in 1980, 1981, and 1982, respectively. Fourteen fields were hand-harvested by picking ears from 0.00025 ha areas in at least 12 locations per strip.

Results and Discussion

Table 1 shows the relationship between the various population parameters and the measures of rootworm damage. The peak number of beetles per plant was significantly correlated with root ratings on the 1-9 scale and the difference in yield between the treated and untreated plots. The correlations were slightly better for counts from individual weeks rather than the peak density. Beetle counts made during week 32, approximately the second week in August, gave the best estimation of root ratings and week 31 gave the best estimation of yield loss. However, the R^2's were quite low (<0.20), indicating that most of the variation in damage and yield loss was not accounted for by the rootworm density estimates.

The combined northern and western corn rootworm egg density was not significantly correlated with either damage or yield loss. The northern corn rootworm egg density was highly significantly correlated with damage on both scales, although not with yield loss. The 1-6 damage ratings were significantly correlated with yield loss, and the 1-9 ratings were nearly significantly correlated. Again, the R^2's were low, with the highest being 0.243 for root ratings (1-9 scale) and northern eggs per ha.

The currently accepted economic thresholds for eggs and adults were arrived at empirically. The threshold for root damage (1-6 scale) was calculated by Turpin et al. (1972). Table 2 compares those thresholds with those calculated from the regression equations in Table 1. It was assumed that a yield loss of 2.5 q per ha would be economic, based on current corn and insecticide prices (Corn = \$8.87 per q; Insecticide = \$22.23 per ha). No threshold could be calculated for eggs because the Y-intercept of the line exceeded the economic damage level. The calculated levels for beetle counts and the two root rating scales were fairly close to the current levels.

Due to the low R^2's (Table 1), little confidence can be placed in these thresholds. In addition, insecticide costs and corn prices fluctuate from year to year, making a static threshold inoperable. At the very least, economic thresholds should take into account these two prices. As an example, Table 3 gives the calculated threshold densities for rootworm beetles during week 31 with various combinations of corn and insecticide prices. Similar tables could be derived for other pest population parameters using the equations in Table 1.

When using an economic threshold, one assumes that if the insect density is below the economic threshold the damage or yield loss will be below economic levels. Likewise, when the economic threshold is exceeded, one can assume that the damage or yield loss will be greater than economic levels. If those assumptions cannot be verified by field trials, then one must question the utility of the threshold. Therefore, we evaluated each of the current corn rootworm thresholds for its accuracy in predicting larval damage and corn yield loss. The results are presented in Table 4. Categories I and IV, in which the predicted and actual damage agree, were considered correct predictions. Categories II and III, in which the predicted and actual damage disagreed, were considered incorrect predictions.

Beetle counts correctly predicted damage on the 1-6 scale 83% of the time, but did not do as well on the 1-9 scale. Egg counts were not as good predictors in either case. More importantly, however, beetle counts, egg counts and even root damage ratings were not accurate in predicting if the yield loss would be at an economic level. None of the four parameters were correct appreciably more than half the time.

These results indicate that the economic threshold concept, as first proposed by Stern et al. (1959), may not be adequate for corn rootworms. Stern et al. developed the threshold concept from studies of multivoltine insect pests in which the damaging stage of the insect was sampled. This dynamic situation demanded a fairly rapid decision as to the necessity for treatment to prevent the pest density from reaching even higher levels.

Corn rootworms, on the other hand, are univoltine, and sampling takes place 8 to 10 months before the larvae damage the corn roots. The situation is static in that the density of the damaging stage cannot be monitored periodically to determine if it will reach economic levels. The treatment or no-treatment decision must be made before the larvae are present. The time lag between sampling and damage makes it possible for many factors to influence the amount of damage the larvae will inflict and the yield response of the corn plant to that damage.

Poston et al. (1983) proposed the idea of "comprehensive economic levels" which takes into account the variable environmental and agronomic conditions and different host responses as well as the pest density. They suggested that comprehensive economic levels will replace the simple, calculated, economic injury levels proposed by Stern et al. Our results seem to indicate that a comprehensive economic threshold for corn rootworms may be the only available alternative. The inability of the pest density estimates alone to predict damage and yield loss suggests that other factors have an important impact on the corn rootworm-corn plant interaction. Those factors must be identified and quantified before yield loss due to corn rootworms can be accurately predicted.

Table 1. Regression equations describing relationship between several measurements of corn rootworm density and larval damage and corn yield loss in Iowa. Equations are of the form Y = a + bX. (n = no. of observations)

Regression Equation		n	R^2	P>F
Root Rating (1-6 Scale)	= 2.95 + 0.06(Peak Adults)	82	.035	.091
	= 2.96 + 0.11(Wk32 Adults)	67	.067	.035*
	= 3.87 + 0.55(Total Eggs/ha)	59	.040	.127
	= 2.79 + 0.06(NCR Eggs/ha)	56	.192	.001**
Root Rating (1-9 Scale)	= 3.71 + 0.22(Peak Adults)	70	.062	.037*
	= 3.59 + 0.40(Wk32 Adults)	55	.165	.002**
	= 4.90 + 0.28(Total Eggs/ha)	48	.048	.136
	= 3.65 + 0.13(NCR Eggs/ha)	45	.243	.001**
Yield Loss	= 1.37 + 0.68(Peak Adults)	77	.078	.014*
	= 1.54 + 1.03(Wk31 Adults)	65	.101	.001**
	= 3.04 + 0.15(Total Eggs/ha)	57	.015	.358
	=-3.65 + 2.35(Root Rating:1-6)	77	.081	.012*
	=-0.20 + 0.81(Root Rating:1-9)	66	.052	.064

*Statistically significant at the 0.05 level.

**Statistically significant at the 0.01 level.

Table 2. Comparison of currently accepted economic thresholds for corn rootworms on corn with calculated thresholds in Iowa. (Based on economic yield loss of 2.5 q/ha.)

Method	Current Threshold	Source	Calculated Threshold
Adult Counts	1.0/Plant	Shaw et al. 1975	0.95
Egg Counts	12.4×10^{6}/ha	Shaw et al. 1975	----
Root Ratings (1-6 Scale)	2.50	Turpin et al. 1972	2.62
Root Ratings (1-9 Scale)	3.60	Hein MS Thesis 1981	3.33

Table 3. Economic thresholds for corn rootworm beetle counts during week 31 at various corn and insecticide prices in Iowa. (Based on equation Yield Loss = 1.54 + 1.03(Wk31 Adults) from Table 1.)

	Economic Threshold (Beetles/Plant)				
	Insecticide Cost ($/ha)				
Corn Price ($/q)	14.83	19.77	24.71	29.65	34.59
7.88	0.37	0.95	1.56	2.17	2.78
8.87	0.13	0.68	1.22	1.76	2.31
9.85	----	0.46	0.95	1.44	1.93
10.84	----	0.28	0.73	1.17	1.62
11.82	----	0.13	0.54	0.95	1.36
13.79	----	----	0.25	0.60	0.95

Table 4. Accuracy of current corn rootworm economic thresholds in predicting if subsequent larval damage or corn yield loss exceeded economic levels in Iowa

Comparison	No. of Observations: Category I	II	III	IV	% Correct Predictions
Peak Adults vs Root Rating (1-6 Scale)	0	4	10	68	83
Peak Adults vs Root Rating (1-9 Scale)	2	0	24	44	66
Eggs/ha vs Root Rating (1-6 Scale)	3	6	13	37	68
Eggs/ha vs Root Rating (1-9 Scale)	4	11	11	22	54
Peak Adults vs Yield Loss	2	2	37	36	49
Eggs/ha vs Yield Loss	10	6	17	24	60
Root Rating (1-6 Scale) vs Yield Loss	6	3	33	35	53
Root Rating (1-9 Scale) vs Yield Loss	13	11	22	20	50

Category I contains those observations in which both the predicted and the actual damage were below the threshold.

Category II contains those observations in which the predicted damage was below the threshold and the actual damage was above the threshold.

Category III contains those observations in which the predicted damage was above the threshold and the actual damage was below the threshold.

Category IV contains those observations in which both the predicted and the actual damage were above the threshold.

PART 4. FACTORS INFLUENCING POTENTIAL CORN YIELD LOSS BECAUSE OF CORN ROOTWORMS IN IOWA

The concept of the economic-injury level (EIL) is a basic tenet of pest management. Stern et al. (1959) defined an EIL as "the lowest population density that will cause economic damage." Economic damage is the amount of damage whose value equals the cost of management procedures. The philosophy of pest management requires that control measures be taken only when the pest density has reached or will reach the EIL.

Surprisingly, EILs have received relatively little attention from entomological researchers. And as a result, most pesticide applications are made as prophylactic measures (Stern 1973). Poston et al. (1983) called EILs the weakest part of most management programs. They also questioned the concept of EILs because it attempts to oversimplify very complex agroecosystems that may include several pests, variable environmental and agronomic conditions, and different host responses. Simple, calculated EILs are usually an improvement over no or "best-guess" levels, but they cannot be the final solution with regard to optimization of crop production. Martin et al. (1980) listed a number of factors that may complicate the development of refined EILs for fall armyworms, *Spodoptera frugiperda*, (J. E. Smith), on sorghum and coastal bermudagrass. They considered the development of refined EILs to be quite an expensive task, which may help explain the lack of progress toward such EILs for any pest on any crop. They predicted that as progress is made toward holistically-managed systems the usefulness of the EIL concept will diminish.

The northern and western corn rootworms, *Diabrotica longicornis barberi* Smith and Lawrence and *D. virgifera virgifera* LeConte, are the premier insect pests of corn in the Midwest. The larvae damage corn by feeding on the roots, resulting in physiological stress to the plant and harvesting problems because of lodging. A study in Indiana showed that 93% of the insecticide applications for corn rootworms were made with little or no knowledge of the insect population level present (Turpin 1977). Sampling procedures have been developed for the adult stage, which is the one most likely to be monitored (Steffey et al. 1982, Foster et al. 1982). Shaw et al. (1975) proposed a simple EIL of one beetle per plant for corn rootworms. However, Foster et al. (1983) found one beetle per plant to be inadequate for predicting if the yield loss would reach economic levels. Turpin et al. (1972) identified seven variables that explained 35% of the variation in root ratings on the 1-6 scale (Hills and Peters 1971). The variables were slope, drainage, percentage clay, planting date, soil potassium, soil phosphorous, and plant population. Some measure of the corn rootworm density may have improved the predictability of the model. Musick et al. (1980) and Mayo (1980) found that later planting tended to reduce the amount of rootworm damage.

The objectives of this study were a). to identify the edaphic and agronomic factors that influence rootworm damage and corn yield loss because of rootworm damage and b). to develop mathematical models to predict larval damage and corn yield loss.

Materials and Methods

A research pest management scouting program was conducted in three counties in Iowa from 1979 through 1982. Corn rootworm beetles were monitored weekly as possible from late July until early September. The technique used was "plant counts," as recommended by Steffey et al. (1982). The sample size in 1979 was 27, two-plant counts, which according to Steffey et al. (1982) would give an estimate of the beetle density with 30% precision. In 1980 and 1981, Kuno's method of sequential sampling was used, as described by Foster et al. (1982). This method also gave an estimate of the density with 30% precision, but allowed earlier termination of sampling in most cases. Thirty-one, 43, and 44 fields were monitored in 1979, 1980, and 1981, respectively.

Check strips without planting-time application of soil insecticides were left in most fields where rootworms had been monitored the previous year. These untreated strips ranged in size from 4 rows by 60 m to 12 rows by 1200 m. In late July, 20 randomly selected roots were dug from the untreated area. The roots were washed and rated for rootworm larval damage on both the 1-6 scale and the 1-9 scale (Apple et al. 1977). In the fall, both the treated and untreated areas were harvested with a combine and yields checked with a weigh wagon. The corn moisture level was determined and yields converted to 15.5% moisture, No. 2 shelled corn. Harvest data were collected in 23, 29, and 25 fields in 1980, 1981, and 1982, respectively. Fourteen fields were hand-harvested by picking ears from 0.00025 ha areas in at least 12 locations per strip.

The edaphic and agronomic variables evaluated in this study are listed in Table 1. Soil pH, organic matter, and the amount of phosphorous and potassium needed were determined from soil samples analyzed by the Iowa State University Soil Testing Laboratory. The percentage clay and sand were estimated by Dr. T.E. Fenton of the Iowa State University Agronomy Department. The slope and drainage were determined from soil maps. The drainage was measured on a 1-7 scale where 1 = very poorly drained and 7 = excessively drained soil. Rainfall data were gathered for each month from April through August either from on-farm rain gauges or the nearest weather station. The fertilizer application rates and planting dates were obtained from the grower. The yield potential of the variety grown was estimated from the Iowa Corn Yield Test Report of the Iowa State University Cooperative Extension Service. Plant populations were estimated by making stand counts in late June.

Results and Discussion

The correlation between each of the edaphic and agronomic variables with root ratings on each scale and corn yield loss are listed in Table 2. Those variables with a P>R of less than 0.20 were included in the development of a general model. The results indicated that the 1-9 root damage scale was much more sensitive than the 1-6 scale. Therefore, only the 1-9 scale was included in further analysis. The variables chosen for inclusion in the general model for root damage were organic matter, June rainfall, % sand, drainage, nitrogen applied, varietal yield potential, and planting date. The selected variables for yield difference were soil pH, phosphorous needed, % sand, June rainfall, nitrogen applied, varietal yield potential, and plant population.

Next to be decided was which measure of the rootworm beetle density to include in the regression equation. Table 3 shows the correlation of different beetle density estimates with root damage and yield loss. The population parameters chosen for further analysis for root damage were the peak beetle density and the densities in weeks 32, 34, and 35. Week 32 is approximately the second week of August. The parameters investigated further for yield loss were the peak and the density during week 31.

The selected population parameters and edaphic and agronomic variables were used to develop the final model. Higher R^2's relative to damage were obtained using the peak beetle density than using the densities from individual weeks. Even though the peak beetle density was significantly correlated with damage (Table 3), it made almost no contribution to the final damage model. This lack of importance may be due to the significant correlation between the peak density and organic matter (R = -0.26) and nitrogen applied (R = 0.25), which were included in the final model. This may have been only an artifact of our data. Nevertheless, the final model (Table 4) included no measure of the rootworm density. The addition of more edaphic and agronomic variables added little to the model. Decreased rootworm damage was associated with higher organic matter, later planting dates, and the planting of higher yielding varieties. The application of nitrogen fertilizers was associated with increased rootworm damage. Only planting date was also included in the final regression equation derived by Turpin et al. (1972).

Higher R^2's relative to yield loss were obtained using the beetle density from week 31 than using the peak beetle density. The population estimate made a substantial contribution to the model and, therefore, was retained in the final equation for yield loss (Table 5). As might be expected, the predictability of the equation for yield loss was not as good as for the equation for root damage. Greater yield loss was associated with increased rootworm beetle density, higher levels of nitrogen fertlizer, increased need for phosphorous, and greater June rainfall. Reduced yield loss was associated with higher plant populations and higher soil pH. If the model were to be used for pest management decisions, June rainfall could be removed and the R^2 would only drop to 0.38.

Our study has shown that root damage by corn rootworms can be predicted relatively well. Surprisingly, no measure of the population density was included in the final model. An observational study of this type can only suggest relationships between variables and cannot show cause and effect. Those factors that appeared to influence the amount of root damage need to be evaluated under controlled experimental conditions to determine the underlying cause and effect relationships. Our model did not predict yield loss nearly as well as root damage. The depth of the problem is shown by the fact that root damage is not significantly correlated with yield loss ($R = 0.23$). One source of variation that was not evaluated here because of small sample size was the grower's choice of soil insecticide. Obviously, some insecticides would perform better than others, resulting in greater difference between the yields in the treated and untreated areas.

Our greatest lack of knowledge concerning the rootworm-corn plant interaction is how the rootworm damage affects the growth of the corn plant and how the plant response is modified by changes in the environment. To understand these interactions, a series of experiments is needed in which treatments include different rootworm densities as well as different levels of the edaphic and agronomic variables identified in this study. Numerous destructive and non-destructive measurements of the corn plant growth are needed to determine specifically how rootworms affect the grain production of the corn plant. Until the rootworm-corn plant interaction is more fully understood, rootworm beetle counts should not be used to determine the necessity for planting-time insecticide treatments. Because of the lack of ability to predict yield loss, all continuous cornfields in those regions where corn rootworms are present should receive propylactic soil insecticide treatments.

Table 1. Edaphic and agronomic variables measured in study fields of research pest management scouting program

Variables	
Edaphic	Agronomic
Soil pH	Nitrogen Applied
Organic Matter	Phosphorous Applied
Phosphorous Needed	Variety Yield Potential
Potassium Needed	Planting Date
% Clay	Planting Population
% Sand	
% Slope	
Drainage	
Rainfall (April-August)	

Table 2. Correlation of edaphic and agronomic variables with rootworm larval damage and corn yield loss in Iowa

Independent Variable	Root Rating (1-6 Scale)	Root Rating (1-9 Scale)	Corn Yield Loss
	Correlation Coefficients		
	Dependent Variables		
Soil pH	-0.11	-0.11	-0.19*
Organic Matter	-0.19*	-0.20*	-0.08
P Needed	0.11	0.08	0.30**
K Needed	-0.06	-0.03	0.09
% Clay	-0.14	-0.15	0.10
% Sand	-0.27**	-0.26**	-0.16*
% Slope	0.09	0.08	-0.04
Drainage	0.23**	0.32**	0.01
April Rainfall	0.11	0.20*	0.02
May Rainfall	-0.09	-0.10	0.00
June Rainfall	0.19*	0.29**	0.18*
July Rainfall	0.07	0.09	0.00
August Rainfall	0.08	0.15	-0.02
Nitrogen Applied	0.37**	0.36**	0.28**
Phosphorous Applied	-0.05	-0.19*	-0.12
Varietal Yield Potential	-0.16	-0.43**	-0.24*
Planting Date	-0.39**	-0.44**	-0.04
Plant Population	0.05	0.06	-0.32**

*Significant at the 0.20 level.
**Significant at the 0.05 level.

Table 3. Correlation of corn rootworm beetle density estimates with root damage ratings (1-9 scale) and corn yield loss in Iowa

Density Estimate	Root Rating (1-9 Scale)		Yield Loss	
	n	R	n	R
Peak	70	0.25**	77	0.28**
Week 31***	55	0.01	65	0.32**
Week 32	55	0.41**	63	0.01
Week 33	56	0.19*	65	0.20*
Week 34	62	0.25**	62	-0.04
Week 35	51	0.41**	59	0.21*
Week 36	43	0.20*	45	-0.11
Mean of wk31-35	70	0.22*	77	0.19*

*Significant at the 0.20 level.
**Significant at the 0.05 level.
***Week 31 = approximately the first week in August.

Table 4. Components of final regression equation for corn rootworm larval damage on the 1-9 scale

($R^2 = 0.70$)

Variable	Coefficient	PR>T
Intercept	14.787	0.0001
Organic Matter (%)	-0.667	0.0001
Planting Date (Julian Date)	-0.049	0.0001
Nitrogen Applied (kg/ha)	0.023	0.0001
Varietal Yield Potential (q/ha)	-0.058	0.0053

Table 5. Components of final regression equations for corn yield loss because of corn rootworms in Iowa

(R^2 = 0.42)

Variable	Coefficient	PR>T
Intercept	21.444	0.1256
Beetles/Plant (Week 31)	0.799	0.1627
Nitrogen Applied (kg/ha)	0.100	0.0033
Plant population (Plants/ha)	-0.0025	0.0028
Phosphorous Needed (kg/ha)	0.049	0.2565
Soil pH	-2.763	0.1401
June Rainfall (cm)	0.478	0.0883

SUMMARY

The widespread implementation of the concepts of pest management would be beneficial to almost all segments of society. Growers would benefit by more efficiently managing their pest problems, resulting in increased profits. Part of this increased crop production efficiency would be passed on to consumers in the form of lower commodity prices. Most of society would benefit if environmental contamination were reduced because of less use of pesticides. Two of the most important aspects of pest management are the development of accurate and efficient sampling techniques and quantifying the impact of the pest insect on the crop yield. In this study, we attempted to make some progress toward these two goals for pest insects on corn in Iowa, particularly the corn rootworms.

Our scouting program in three Iowa counties helped to determine the status of four pests of corn in Iowa. Wireworms were not found in damaging numbers in any scouted fields and, therefore, were considered a rare pest. Black cutworms were an occasional pest and were much more serious in some years than in others. European corn borers were almost always present, but seldom reached damaging levels. The corn rootworms were severe pests because they almost always reached densities considered to be potentially damaging.

Two types of sequential sampling plans were devised for corn rootworm adults to make sampling for that pest more efficient. Waters' method of sequential sampling classifies the population into categories and is useful for pest management decision-making. Kuno's method gives an estimate of the population density present and is useful for research purposes. Both methods for corn rootworm beetles were significantly faster than sampling with a fixed sample size and Waters' method was significantly faster than Kuno's method. Waters' method reduced overall scouting time in a pest management program by 36% and gave more than 96% correct decisions.

Regression equations were developed relating rootworm adult and egg densities with larval damage and corn yield loss. Although the equations were statistically significant, the correlation coefficients were quite low, indicating that most of the variation was unexplained. Calculated economic thresholds closely approximated current thresholds for adult counts and root ratings. However, an economic threshold could not be calculated for egg counts. Adult counts were accurate in predicting if the larval damage would reach economic levels, but were not accurate in predicting economic yield loss. Egg counts did not predict damage or yield loss accurately.

A four variable model accounted for 70% of the variation in root damage ratings. The variables were organic matter, planting date, nitrogen applied, and the yield potential of the corn variety planted. A six variable model accounted for 42% of the variation in yields. The variables were rootworm beetle density in week 31, nitrogen applied, plant population, phosphorous needed, soil pH, and June rainfall.

Our studies, coupled with the recent efforts of other researchers, have begun to make some progress toward the development of a pest management system for corn insects in the Midwest. However, much work remains to be done. Primary among the needed knowledge is a thorough understanding of how corn rootworms cause yield loss in corn. To achieve this will require large scale experiments in which many destructive and non-destructive measurements are made on corn plants suffering from different levels of rootworm attack under different conditions. Observational studies such as we conducted are useful to point toward those areas where additional research is needed. But experiments, under controlled conditions, must be conducted before real cause and effect relationships can be delineated.

LITERATURE CITED

Apple, J. W., H. C. Chiang, L. M. English, L. K. French, A. J. Keaster, G. F. Krause, Z B Mayo, J. D. Munson, G. J. Musick, J. C. Owens, E. E. Rasmussen, R. E. Sechriest, J. J. Tollefson, and J. L. Wedberg. 1977. Impact of northern and western corn rootworm larvae on field corn. North Cent. Reg. Publ. No. 239. 10 pp.

Atyeo, W. T., G. T. Weekman, and D. E. Lawson. 1964. The identification of Diabrotica species by chorion sculpturing. J. Kans. Entomol. Soc. 37:9-11.

Ball, H. J. 1973. Western corn rootworm: A ten-year study of potential resistance to diazinon and phorate in Nebraska. J. Econ. Entomol. 66:1015-1018.

Ball, H. J., and G. T. Weekman. 1963. Differential resistance of corn rootworms to insecticides in Nebraska. J. Econ. Entomol. 56:553-555.

Becker, R., and H. Stockdale. 1980. Pesticides used in Iowa crop production in 1978 and 1979. Iowa Coop. Ext. Serv., Iowa Agric. Home Econ. Exp. Stn. Pamphlet Pm-964. 23 pp.

Bellinger, R. G., G. P. Dively II, and L. W. Douglas. 1981. Spatial distribution and sequential sampling of Mexican bean beetle defoliation on soybeans. Environ. Entomol. 10:835-841.

Bergman, M. K., J. J. Tollefson, and P. N. Hinz. 1981. Sampling scheme for estimating populations of corn rootworm larvae. Environ. Entomol. 10:986-990.

Bigger, J. H. 1963. Corn rootworm resistance to chlorinated hydrocarbon insecticides in Illinois. J. Econ. Entomol. 56:118-119.

Bigger, J. H., and G. C. Decker. 1966. Controlling root feeding insects of corn. Ill. Agric. Exp. Stn. Bull. 641. 28 pp.

Branson, T. F., and E. E. Ortman. 1970. The host range of larvae of the western corn rootworm: Further studies. J. Econ. Entomol. 63:800-803.

Branson, T. F., G. R. Sutter, and J. R. Fisher. 1980. Plant response to stress induced by artificial infestations of western corn rootworms. Environ. Entomol. 9:253-257.

Chandler, J. H., G. J. Musick, and M. L. Fairchild. 1966. Appratus and procedure for separation of corn rootworm eggs from soil. J. Econ. Entomol. 59:1409-1410.

Chiang, H. C. 1973. Bionomics of the northern and western corn rootworms. Ann. Rev. Entomol. 18:47-72.

Chiang, H. C., and R. G. Flaskerd. 1965. Sampling methods of adult populations of the corn rootworms. Proc. N. Cent. Br. Entomol. Soc. Amer. 20:67-68.

Chiang, H. C., L. K. French, and D. E. Rasmussen. 1980. Quantitative relationship between western corn rootworm population and corn yield. J. Econ. Entomol. 73:665-666.

Chiang, H. C., V. Sisson, and D. Rasmussen. 1969. Conversion of results of concentrated samples of egg and larval populations of the northern corn rootworm. J. Econ. Entomol. 62:578-583.

Connola, D. P., W. E. Waters, and E. R. Nason. 1959. A sequential sampling plan for red-pine sawfly, Neodiprion nanules Schedl. J. Econ. Entomol. 52:600-602.

Forbes, S. A. 1894. Noxious and beneficial insects of Illinois. Ill. State Entomol. Rept. 18 for years 1891 and 1892, pp 154-165.

Foster, R. E., W. G. Ruesink, and W. H. Luckmann. 1979. Northern corn rootworm egg sampling. J. Econ. Entomol. 72:659-663.

Foster, R. E., J. J. Tollefson, and K. L. Steffey. 1982. Sequential sampling plans for adult corn rootworms. J. Econ. Entomol. 75:791-793.

Foster, R. E., J. J. Tollefson, and G. L. Hein. 1983. Corn rootworm adult and egg population density estimates as predictors of larval damage and corn yield loss. Submitted for publication in J. Econ. Entomol.

Gerrard, D. J., and H. C. Chiang. 1970. Density estimation of corn rootworm egg population based on frequency of occurrence. Ecology 51:237-245.

Gillette, C. P. 1912. Diabrotica virgifera LeC. as a corn rootworm. J. Econ. Entomol. 5:364-366.

Gonzales, D. 1970. Sampling as a basis for pest management strategies. Proc. Tall. Timber Conf. on Ecol. An. Cont. by Hab. Manag. pp. 83-101.

Gunderson, H. 1964. Proposal on uniform sampling techniques for rootworm eggs. Proc. N. Cent. Br. Entomol. Soc. Am. 19:97.

Harcourt, D. G. 1966. Sequential sampling for the imported cabbageworm, Pieris rapae (L.). Can. Entomol. 98:741-746.

Hein, G. L. 1981. Comparison of adult corn rootworm sampling techniques as population estimates and as predictors of subsequent larval damage. M.S. Thesis. Iowa State University, Ames. 75 pp.

Hill, R. E., E. Hixson, and M. H. Muma. 1948. Corn rootworm tests with benzene hexachloride, DDT, nitrogen fertilizers and crop rotations. J. Econ. Entomol. 41:392-401.

Hills, T. M., and D. C. Peters. 1971. A method of evaluating postplanting insecticide treatments for control of western corn rootworm larvae. J. Econ. Entomol. 64:764-765.

Howe, W. L., and J. Shaw. 1972. Soil sampling techniques for estimating rootworm egg populations. Proc. N. Cent. Br. Entomol. Soc. Am. 27:123-127.

Irwin, B. J. 1977. A bibliography of the northern corn rootworm and the western corn rootworm: An updating through 1976. Ill. Nat. Hist. Surv. Biol. Notes No. 101. 8 pp.

Iwao, S. 1968. A new regression method for analyzing the aggregation pattern of animal populations. Res. Popul. Ecol. 10:1-20.

Jennings, V., and H. Stockdale. 1978. Herbicides and soil insecticides used in Iowa corn and soybean production, 1977. Iowa Coop. Ext. Serv., Iowa Agric. Home Econ. Exp. Stn. Pamphlet Pm-845. 6 pp.

Krysan, J. L., R. F. Smith, T. F. Branson, and P. L. Guss. 1980. A new subspecies of Diabrotica virgifera : Description, distribution, and sexual compatibility. Ann. Entomol. Soc. Am. 73:123-130.

Kuno, E. 1969. A new method of sequential sampling to obtain the population estimates with a fixed level of precision. Res. Popul. Ecol. 11:127-136.

Lawson, D. E. 1968. Predicting rootworm infestations by soil sampling for eggs. Proc. N. Cent. Br. Entomol. Soc. Am. 23:112.

Lawson, D. E., and G. T. Weekman. 1966. A method of recovering eggs of the western corn rootworm from the soil. J. Econ. Entomol. 59:657:659.

LeConte, J. L. 1868. New Coleoptera collected on the survey for the extension of the Union Pacific Railway, E. D. from Kansas to Fort Craig, New Mexico. Trans. Am. Entomol. Soc. 2:49-59.

Lilly, J. H. 1954. Insecticidal control of the corn rootworm in 1953. J. Econ. Entomol. 47:651-658.

Luckmann, W. H., H. C. Chiang, E. E. Ortman, and M. P. Nichols. 1974. A bibliography of the northern corn rootworm, Diabrotica longicornis (Say), and the western corn rootworm, Diabrotica virgifera LeConte (Coleoptera: Chrysomelidae). Illinois Natur. Hist. Surv. Biol. Notes No. 90. 15 pp.

Luckmann, W. H., J. T. Shaw, D. E. Kuhlman, R. Randell, and C. D. LeSar. 1975. Corn rootworm pest management in Canning sweet corn. Ill. Natur. Hist. Surv. Circ. 54. 10 pp.

Martin, P. B., B. R. Wiseman, and R. E. Lynch. 1980. Action thresholds for fall armyworm on grain sorghum and coastal bermudagrass. Fla. Entomol. 63:375-405.

Matteson, J. W. 1966. Flotation technique for extracting eggs of Diabrotica spp. and other organisms from soil. J. Econ. Entomol. 59:233-234.

Maxwell-Lefroy, H., and C. C. Ghosh 1908. The Indian surface caterpillar of the genus Agrotis. Mem. Dept. Agric. India Entomol. Ser. 1:253-274.

Mayo, Z B. 1980. Influence of planting dats on the efficacy of soil insecticides applied to control larvae of the western and northern corn rootworm. J. Econ. Entomol. 73:211-212.

Metcalf, R. L., and W. H. Luckmann. 1982. Introduction to Insect Pest Management. Wiley-Interscience, New York. 577 pp.

Morris, R. F. 1955. The development of sampling techniques for forest insect defoliators, with particular reference to the spruce budworm. Can. J. Zool. 33:225-294.

Musick, G. J., H. C. Chiang, W. H. Luckmann, Z B Mayo, and F. T. Turpin. 1980. Impact of planting dates of field corn on beetle emergence and damage by the western and the northern corn rootworms in the corn belt. Ann. Entomol. Soc. Am. 73:207-215.

National Academy of Sciences. 1969. Insect-pest management and control. National Academy of Sciences Pub. 1695. 308 pp.

North Central-105 Committee. 1972. The European corn borer and its control in the north central states. North Cent. Reg. Pub. No. 22 (Revised). 8 pp.

Peters, D. C. 1969. Some results from a "rootworm scouting" program. Proc. N. Cent. Br. Entomol. Soc. Am. 24:142-143.

Peters, L. L., and C. C. Burkhardt. 1961. Corn insect surveys for survey entomologists. Proc. N. Cent. Br. Entomol. Soc. Am. 16:114-116.

Petty, H. B., D. E. Kuhlman, and R. E. Sechriest. 1969. Corn yield losses correlated with rootworm larval populations, 1968. Proc N. Cent. Br. Entomol. Soc. Am. 24:141-142.

Pieters, E. P. 1978. Bibliography of sequential sampling plans for insects. Entomol. Soc. Am. Bull. 24:372-374.

Poston, F. L., L. P. Pedigo, and S. M. Welch. 1983. Economic-injury levels: Reality and practicality. Bull. Entomol. Soc. Am. (In Press).

Pruess, K. P., J. F. Witkowski, and E. S. Raun. 1974. Population suppression of western corn rootworm by adult control with ULV malathion. J. Econ. Entomol. 67:651-655.

Riley, C. V. 1880. A new enemy to corn- the long-horned Diabrotica. Am. Entomol. 3:247.

Rings, R. W., F. J. Arnold, and B. A. Johnson. 1975. Host range of the black cutworm on vegetables: A bibliography. Bull. Entomol. Soc. Am. 21:229-234.

Say, T. 1824. Descriptions of Coleopterous insects collected in the late expedition to the Rocky mts, performed by order of Mr. Calhoun, Sec. of War, under the command of Major Long. J. Acad. Natur. Sci. Philadelphia 3:403-462.

Sechriest, R. E., D. E. Kuhlman, and J. L. Wedberg. 1978. Aerial application of insecticides to prevent rootworm egg-laying. Pages 103-108 in Twenty-seventh Illinois custom spray operators training school. Coop. Ext. Serv. Univ. of Illinois, Urbana-Champaign, Illinois.

Shaw, J. T., W. H. Brink, D. W. Sherrod, and W. H. Luckmann. 1975. Predicting infestations of wireworms, corn rootworms, and black cutworms in Illinois cornfields. Pages 74-79 in Twenty-seventh Illinois custom spray operators training school. Coop. Ext. Serv. Univ. of Illinois, Urbana-Champaign, Illinois.

Shaw, J. T., R. O. Ellis, and W. H. Luckmann. 1976. Apparatus and procedure for extracting corn rootworm eggs from soil. Illinois Natur. Hist. Surv. Biol. Notes No. 96. 4 pp.

Sherrod, D. W., and W. H. Luckmann. 1976. Concepts on black cutworm biology and oviposition. Unpublished Master's Thesis. University of Illinois, Urbana-Champaign.

Sherrod, D. W., J. T. Shaw, and W. H. Luckmann. 1979. Concepts on black cutworm field biology in Illinois. Environ. Entomol. 8:191-195.

Smith, B. C. 1979. Population changes of the northern corn rootworm and corn yield losses in southwestern Ontario. Proc. Entomol. Soc. Ont. 110:85-91.

Smith, R. F. 1969. The importance of economic injury levels in the development of pest control programs. Qual. Plant. Mater. Veg. 17:81-92.

Smith, R. F., and J. F. Lawrence. 1967. Clarification of the status of the type specimens of Diabroticites (Coleoptera, Chrysomelidae, Galerucinae). Univ. Calif. Publ. Entomol. 45. 174 pp.

Southwood, T. R. E. 1978. Ecological methods with particular reference to the study of insect populations. Second edition. Chapman and Hall, London. 524 pp.

Steffey, K. L., J. J. Tollefson, and P. N. Hinz. 1982. Sampling for population estimation of northern and western corn rootworm adults in Iowa cornfields. Environ. Entomol. 11:287-291.

Stern, V. 1973. Economic thresholds. Ann. Rev. Entomol. 18:259-280.

Stern, V. M., R. F. Smith, R. van den Bosch, and K. S. Hagen. 1959. The integrated control concept. Hilgardia 29:81-101.

Stockdale, H. J., D. Foster, D. R. Lewis, S. Quisenberry, and L. Buntin. 1982. Summary of Iowa insect pest control recommendations for 1982. Iowa Coop. Ext. Serv., Iowa Agric. Home Econ. Exp. Stn. (Publ.) IC-328. 52 pp.

Taylor, C. R. 1975. The economics of control of northern and western corn rootworms in Illinois. Ill. Agric. Econ. 15:11-13.

Tollefson, J. J. 1975. Corn rootworm adult- and egg-sampling techniques as predictors of larval damage. Ph.D. Dissertation. Iowa State University, Ames. 131 pp.

Tollefson, J. J., J. F. Witkowski, J. C. Owens, and P. N. Hinz. 1979. Influence of sampler variation on adult corn rootworm population estimates. Environ. Entomol. 8:215-217.

Turpin, F. T. 1977. Insect insurance: Potential management tool for corn insects. Bull. Entomol. Soc. Am. 23:181-184.

Turpin, F. T., and J. M. Thieme. 1978. Impact of soil insecticide usage on corn production in Indiana: 1972-1974. J. Econ. Entomol. 71:83-86.

Turpin, F. T., L. C. Dumenil, and D. C. Peters. 1972. Edaphic and agronomic characters that affect potential for rootworm damage to corn in Iowa. J. Econ. Entomol. 65:615-1619.

Waters, W. E. 1955. Sequential sampling in forest insect surveys. For. Sci. 1:68-79.

Weekman, G. T. 1961. Problems in rootworm control. Proc. N. Cent. Br. Entomol. Soc. Am. 16:32-34.

Weekman, G. T. 1962. Corn rootworm control results-1961. Proc. N. Cent. Br. Entomol. Soc. Am. 17:46-48.

ACKNOWLEDGEMENTS

Many people played important roles in assisting in this study. Most importantly, I would like to thank Dr. Jon J. Tollefson, who for the past four years has been my advisor, teacher, running partner, and friend. I also thank the other members of my committee for their assistance. The various members of the Corn Project have also been of invaluable aid. Fellow students such as Marlin Bergman, Bob Bruss, and Gary Hein assisted me in all phases of the research. Hourly helpers such as Randy Martin, Joel Schlatter, Mark Taylor, Kelly Custer, and Denis Schulte worked many long days under adverse conditions on the project. Special thanks go to Jim Oleson, who was always available when I needed help.

Working with people of this caliber made each day something that I looked forward to, even days that began at 5:00 A.M. Finally, I would like to thank my wife, Julie, and my daughter, Karen, who made going home something to look forward to as well.