AREAWIDE MANAGEMENT OF MEXICAN CORN ROOTWORM (COLEOPTERA: CHRYSOMELIDAE) THROUGH ADULT SUPPRESSION AND CROP ROTATION

A Dissertation

by

PETER SCOTT LINGREN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 1999

Major Subject: Entomology

UMI Number: 9943529

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

AREAWIDE MANAGEMENT OF MEXICAN CORN ROOTWORM (COLEOPTERA: CHRYSOMELIDAE) THROUGH ADULT SUPPRESSION AND CROP ROTATION

A Dissertation

by

PETER SCOTT LINGREN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved as to style and content by:

George L. Teetes
(Co-Chair of Committee)

James R. Coppedge
(Co-Chair of Committee)

L. Ted Wilson
(Member)

James H. Matis
(Member)

Raymond E. Frisbie
(Head of Department)

August 1999

Major Subject: Entomology

ABSTRACT

Areawide Management of Mexican Corn Rootworm (Coleoptera: Chrysomelidae)

through Adult Suppression and Crop Rotation. (August 1999)

Peter Scott Lingren, B.S., Oklahoma State University;

M.S., Louisiana State University

Co-Chairs of Advisory Committee: Dr. George L. Teetes
Dr. James R. Coppedge

Components for Mexican corn rootworm, *Diabrotica virgifera zeae* Krysan and Smith, areawide management were assessed in Bell County, TX, during 1995, 1996, and 1997. Foliar insecticide applied in a 1,366 ha area to corn, *Zea mays* L., where corn rootworm adult abundance exceeded treatment thresholds, reduced abundance of adults by 99.1% compared with a non-treated area. In the season following foliar insecticide application, numbers of adults that emerged from corn were reduced by 93.5% in the treated area compared with a non-treated area. Soil insecticide reduced numbers of adults that emerged by 52.3%. Foliar and soil insecticide reduced corn root damage caused by larvae by 2 and 1-fold, respectively, compared with non-treated corn. Corn yield was not affected significantly by foliar insecticide, but was 7.8% greater in corn treated with soil insecticide than in that not treated with soil insecticide.

Factors were investigated that potentially contributed to failure of crop rotation using sorghum, *Sorghum bicolor* (L.) Moench, to prevent damage by Mexican corn rootworm to corn. Prolonged diapause of eggs was not observed. Emergence of adults from sorghum was 3.0-11.2% of that from corn. Oviposition by adults in sorghum was similar to oviposition in corn, suggesting movement of adults for oviposition from corn to sorghum. Oviposition in cotton, *Gossypium hirsutum* L., soybean, *Glycine max* (L.) Merrill, and Texas panicum, *Panicum texanum* Buckley, was 23.9, 17.7, and 7.4% of that in corn.

Four methods for monitoring Mexican corn rootworm were evaluated to determine if a single method could be used to assess adult abundance and emergence patterns for justification and timing of foliar insecticide applications. Standard methods for assessing adult abundance and emergence patterns were plant inspections and emergence traps, respectively. Numbers of adults captured in baited non-sticky traps and sticky traps were compared to those obtained by using standard methods. The r^2 values for the relationships evaluated revealed the strongest relationship between numbers of adults found by inspecting plants and in emergence traps. Coefficients of variation demonstrated that inspecting plants was more precise than other methods.

DEDICATION

This dissertation is dedicated to my parents, Pete and Bonnie Lingren, and to my wife, Kimberly Lingren. I can only hope that I will be able to repay their love, kindness, and generosity.

ACKNOWLEDGMENTS

I would like to express my gratitude to Dr. James R. Coppedge for serving as my graduate committee co-chairman and for providing me with the opportunity to pursue this degree at Texas A&M University. I also would like to thank Dr. George L. Teetes for agreeing to serve as co-chairman of my graduate committee. I am indebted to both Drs. James R. Coppedge and George L. Teetes, as well as to the other members of my graduate committee, Drs. L. Ted Wilson and James H. Matis, for their reviews of this manuscript and professional advice. I would like to extend my gratitude to Dr. John F. Edwards for serving as my Graduate Council Representative. Appreciation also is given to Dr. Bonnie B. Pendleton for her review of this manuscript.

Thanks are given to the staff of the United States Department of Agriculture, Agricultural Research Service, Areawide Pest Management Research Unit who were always available to help. I am especially grateful to the student workers, Russell Baker, Zac Kay, Clint Tracey, and Laura Vogt, for their hard work and commitment to this project. I also would like to express my sincere gratitude to Dr. W. Clint Hoffmann not only for his contributions to and assistance with this project, but also for his loyal and devoted friendship.

I wish to extend thanks to Jesse Cock, Jr. and James Davis whose contributions were invaluable. This project would have been impossible without the cooperation of many corn growers in Bell County, TX. Their participation in this project is greatly appreciated. Finally, I would like to thank the Agricultural Research Service, BASF, Incorporated, and Microflo Company, Incorporated for funding this research.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (CONTINUED)

TABLE Page

LIST OF TABLES (CONTINUED)

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The concept of integrated pest management (IPM) has evolved over time from being defined simply as the integration of biological control and chemical control (Stern et al. 1959) to a multidisciplinary, ecological approach to pest management based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment (Smith 1978, Kogan 1998). In practice, integrated management of insect pests in agricultural ecosystems has been addressed most often on a field-to-field basis (Knipling 1972). However, as an ecological approach, IPM must take into account a much larger geographical scale within the ecosystem, especially in the case of mobile insect pest species (Knipling 1972, Henneberry and Phillips 1996). Mobile insect pests may disperse to reinfest small areas where control strategies have been implemented, and sustainable management of these pests often is unattainable on a field-to-field basis (Frisbie et al. 1994, Henneberry and Phillips 1996). Wilson et al. (1994), for example, demonstrated that the probability and rapidity of the reinfestation of cotton, *Gossypium* spp., in an area by boll weevil, *Anthonomus grandis grandis* Boheman, was in part a function of the distance of that area from the nearest infested area. Knipling (1979) suggested that management of such mobile pest species is best accomplished on an areawide basis (Knipling 1972, Henneberry and Phillips 1996). This areawide approach to IPM has been termed areawide pest management (Henneberry and Phillips 1996).

This dissertation follows the style of the Journal of Economic Entomology.

The first example of a successful areawide pest management program was the eradication of the screwworm, *Cochliomyia hominivorax* (Coquerel), from the United States (Metcalf and Metcalf 1994). A serious pest of livestock, this insect species was estimated to annually cause more than $100 million in damage in the United States prior to its eradication (Metcalf and Metcalf 1994). In 1962, after pilot studies resulted in eradication of screwworm from the island of Curacao and from Florida, an eradication program that utilized insecticides and large-scale release of sterile male screwworm flies was initiated along the United States-Mexico border (Metcalf and Metcalf 1994). This areawide approach to IPM resulted in the eradication of the screwworm from the United States by 1979.

Another excellent example of areawide pest management was the eradication of the boll weevil from >810,000 ha of cotton land in the United States (Frisbie et al. 1994). Eradication was achieved through the use of regulated cultural practices such as uniform planting dates and stalk destruction, along with properly timed insecticide applications. In areas free of boll weevil, insecticide use decreased 60-75% and the land area devoted to cotton production increased by 0.25 million ha. The ultimate goal is to completely eradicate boll weevil from the United States. It should be stressed, however, that eradication is not always the goal of areawide management (Henneberry and Phillips 1996).

Mexican corn rootworm, *Diabrotica virgifera zeae* Krysan and Smith, western corn rootworm, *D. virgifera virgifera* LeConte, and northern corn rootworm, *D. barberi* Smith and Lawrence, are 3 related pest species identified as candidates for areawide management (Comis 1997). Western corn rootworm and northern corn rootworm are pests of corn throughout the Midwestern United States (Krysan 1986). Mexican corn rootworm is found in Texas, Oklahoma, New Mexico, and Mexico (Krysan 1986). The life cycle of each species is similar (Krysan 1986). Adults are present in corn, *Zea mays* L., fields during the summer, where they feed on corn pollen, silks, and leaves. Some adults disperse from corn fields and are capable of actively traveling ≤ 39.6 km in a 24-h period (Coats et al. 1986). Eggs typically are laid in the soil around corn plants, where they overwinter. Eggs hatch in the spring and the larvae feed on the roots of corn, resulting in plant lodging and yield loss (Chiang et al. 1980, Spike and Tollefson 1991, Godfrey et al. 1993). Annual yield losses and control costs associated with these insects in the United States are estimated to exceed $1 billion (Metcalf 1986b).

Several control strategies have been utilized to manage corn rootworm. Among the most commonly used are soil insecticides, crop rotation, and foliar insecticides. At-planting application of soil insecticide targets the larval stage of corn rootworm. The effects of soil insecticide on corn yield are highly variable, but soil insecticide usually protects corn roots from damage by corn rootworm larvae (Sutter et al. 1990, Davis and Coleman 1997). Plants are capable of compensating for root injury, depending on variables such as moisture availability, nitrogen availability, plant density, and amount of lodging (Spike and Tollefson 1988, 1989a, 1989b, 1991). Of great concern from the perspective of pest management, is the effect of soil insecticide on corn rootworm abundance. Gray et al. (1992), in a 3-yr study, found that application of soil insecticide resulted in a significant decrease in the number of western corn rootworm adults that emerged from the soil 1 year, a significant increase in the number that emerged the following year, and had no effect on the number that emerged during the 3rd year. In a 4-yr study, Sutter et al. (1991) found that soil insecticides reduced western corn rootworm larval survival by an average of <50%. Similarly, Cocke et al. (1994) found, during a 1-yr study, that soil insecticide reduced the number of Mexican corn rootworm adults emerging from the soil by 64%. This level of suppression is not adequate to ensure that soil insecticide would not be needed again the following season if fields were replanted with corn (Sutter et al. 1991, Gray et al. 1992). In fact, soil insecticide often is applied each year to corn as a preventative measure (Sutter et al. 1991; Gray et al. 1992, 1993; Cocke et al. 1994).

Unlike soil insecticides, crop rotation is an effective method for reducing corn rootworm abundance, and currently is recommended for corn rootworm control in many states (Hill et al. 1948, Stewart et al. 1995). Because corn rootworm larvae feed almost exclusively on corn, larvae hatching from eggs laid in other crops should not survive (Branson and Ortman 1970, 1971; Branson et al. 1982). Furthermore, corn rootworm adults that migrate into crops other than corn are not expected to oviposit, because soil around corn plants is preferred for oviposition (Shaw et al. 1978, Johnson and Turpin 1985, Tonhasca and Stinner 1991, Boetel et al. 1992). Maximum benefits can be realized if a large number of growers in an area practice crop rotation, thereby reducing the abundance of corn rootworm in a region (Gray and Luckmann 1994). However, failure of crop rotation to prevent damage by northern corn rootworm was reported as early as 1932 (Bigger 1932). While early reports of the ineffectiveness of crop rotation were infrequent, these reports have become more and more prevalent. Crop rotation failed to prevent damage to corn where soybean, *Glycine max* (L.) Merrill, was rotated with corn to avoid northern corn rootworm and western corn rootworm (Steffey et al. 1992, Levine and Oloumi-Sadeghi 1996) and where sorghum, *Sorghum bicolor* (L.) Moench, was rotated with corn to avoid Mexican corn rootworm (Stewart et al. 1995).

An alternative to both crop rotation and soil insecticide is application of foliar insecticide to reduce abundance of corn rootworm adults. The goal of this approach is to reduce adult abundance with foliar insecticide applied after the majority of adults have emerged from the soil but before significant oviposition has occurred, resulting in fewer eggs laid in the soil (Pruess et al. 1974). A subsequent corn crop would be infested with fewer corn rootworm larvae, and the need for a soil insecticide would be reduced (Pruess et al. 1974). Achieving this goal against mobile corn rootworm adults has not been possible on a field-to-field basis (Beardmore 1975). Utilization of this strategy on an areawide basis, however, greatly reduced abundance of western corn rootworm adults in the subsequent seasons (Pruess et al. 1974).

Detailed knowledge of corn rootworm adult abundance and pattern of emergence is required to justify and properly time foliar insecticide applications to reduce abundance of corn rootworms (Pruess et al. 1974, Beardmore 1975). Several sampling procedures have been used to monitor adult corn rootworm abundance. These methods include whole plant inspection, sticky traps, and non-sticky traps (Hein and Tollefson 1985, Stamm et al. 1985, Hesler and Sutter 1993, Levine and Gray 1994). Non-sticky traps usually are baited with non-pheromonal attractants (Hesler and Sutter 1993) or with feeding stimulants (Levine and Gray 1994). Various trap designs have been used to monitor the pattern of adult corn rootworm emergence from the soil (Fisher 1984, Matin et al. 1984, Cocke et al. 1994). An areawide management program for corn rootworms may require that both an adult abundance monitoring method and a method for monitoring the pattern of adult emergence be used over a large area. Matin et al. (1984), however, found that numbers of northern corn rootworm adults captured in sticky traps and in emergence traps was highly correlated to that found by plant inspection. These findings suggest that 1 monitoring method could be used to assess both adult abundance and the pattern of adult emergence.

Adult control and crop rotation are 2 control strategies that could be integrated over large areas to develop an areawide management program for corn rootworm. Before such a program can be initiated, however, several obstacles must be overcome. First, the validity of adult control as a viable control measure must be determined. To accomplish this, the effect of adult control treatments on larval damage to corn roots, corn yield, and adult abundance the subsequent season must be measured. Secondly, factors responsible for failure of crop rotation to prevent damage by corn rootworm must be identified to permit integration of this management tactic into an areawide program. Finally, a simple and effective method for monitoring both adult abundance and adult emergence patterns should be identified to facilitate sound insecticide treatment decisions. The objectives of this study were to address each of these concerns as they relate to Mexican corn rootworm in Texas.

CHAPTER II

AREAWIDE MANAGEMENT OF MEXICAN CORN ROOTWORM ADULTS USING AN INSECTICIDE BAIT

Areawide pest management is a term used to describe the use of integrated pest management (IPM) over large geographical areas (Henneberry and Phillips 1996). This areawide approach was conceived in response to the limited success in management of mobile insect pest species on a field-to-field basis (Knipling 1972, Henneberry and Phillips 1996). Areawide management has been used successfully in eradication programs for several insect pests including screwworm, *Cochliomyia hominivorax* (Coquerel), and boll weevil, *Anthonomus grandis grandis* Boheman (Frisbie et al. 1994, Metcalf and Metcalf 1994). Areawide management, however, does not necessarily imply eradication, but may be used to reduce pest abundance to acceptable levels (Henneberry and Phillips 1996).

Mexican corn rootworm, *Diabrotica virgifera zeae* Krysan and Smith, western corn rootworm, *D. virgifera virgifera* LeConte, and northern corn rootworm, *D. barberi* Smith and Lawrence, are 3 related pest species that have been identified as candidates for areawide management (Comis 1997). These univoltine insect pests overwinter in the egg stage (Krysan 1986). Larvae hatch in the spring and feed on corn, *Zea mays* L., roots, resulting in plant lodging and yield loss (Krysan 1986). Adults emerge from the soil in the late spring and feed on corn pollen, silks, and leaves, as well as on other plants (Branson and Krysan 1981, Krysan 1986). Adults are capable of traveling ≥39.6 km in a

24-h period (Coats et al. 1986) and may oviposit either in the field of origin or in surrounding areas (Branson and Krysan 1981, Sammons et al. 1997). Corn rootworms are managed most frequently on a field-to-field basis using soil insecticide applied at planting (Sutter et al. 1991; Gray et al. 1992, 1993; Cocke et al. 1994). Soil insecticide targets corn rootworm larvae and has been demonstrated to reduce the amount of damage by corn rootworm larvae to corn roots. Soil insecticide also has been shown to reduce by 50-65% the number of larvae surviving to adulthood. This level of suppression, however, allows adequate numbers of adults to reproduce and cause economic infestation of corn planted the following year. As a result, soil insecticide often must be applied annually to corn grown in continuous production (Metcalf 1986b; Sutter et al. 1991; Gray et al. 1992, 1993; Cocke et al. 1994). It has been estimated that annual yield losses and control costs attributable to corn rootworms are >$1 billion (Metcalf 1986b).

Corn rootworm areawide management requires a control strategy that is more efficacious than soil insecticide in reducing abundance of migrating and ovipositing adults. Annual rotation of corn with other crops and the use of foliar insecticide are 2 alternative management strategies that have been demonstrated to reduce corn rootworm abundance (Hill et al. 1948, Pruess et al. 1974, Branson and Krysan 1981). However, crop rotation often is not practiced because of economic and agronomic reasons (Gray and Luckmann 1994). In addition, extended diapause of corn rootworm eggs and adult migration and oviposition outside of corn fields have allowed corn rootworms to circumvent the effects of crop rotation (Ludwig and Hill 1975, Hill and Mayo 1980, Krysan et al. 1986, Levine et al. 1992b, Sammons et al. 1997). Unlike soil insecticide, foliar insecticide targets corn rootworm adults. When used on an areawide basis, foliar insecticide has been demonstrated to reduce abundance of corn rootworm adults by ≤99% (Hill et al. 1948, Pruess et al. 1974, Beardmore 1975, Hoffmann et al. 1996). Additionally, proper timing of foliar insecticide applications can reduce oviposition and, thus, the number of larvae present the subsequent season (Pruess et al. 1974). Pruess et al. (1974) used malathion applied ultra-low-volume (ULV) to corn in a 2,072-ha area to reduce abundance of western corn rootworm adults both immediately after application and in the season following application. However, applications were made without the use of an economic threshold. Pruess et al. (1974) suggested that future areawide management programs to reduce abundance of corn rootworm adults should use a treatment threshold of 1 adult per plant. This threshold is based on the relationship between adult abundance in 1 season and damage to corn roots by larvae in the subsequent season, and previously has been used to predict the need for soil insecticide (Pruess et al. 1974, Godfrey and Turpin 1983, Stamm et al. 1985).

In addition to the use of a treatment threshold, insecticide baits can adequately reduce adult abundance with less insecticide (Metcalf et al. 1987; Lance and Sutter 1990, 1992; Weissling and Meinke 1991; Hoffmann et al. 1996). Cucurbitacins are secondary plant compounds produced by plants in the family Cucurbitaceae that act as arrestants and phagostimulants for corn rootworm adults (Metcalf 1986a). The foliar application of cucurbitacin in formulation with a toxicant has been shown to reduce abundance of adult Mexican corn rootworm, western corn rootworm, and northern corn rootworm by ≤95%

(Metcalf et al. 1987, Lance and Sutter 1990, Weissling and Meinke 1991, Lance and Sutter 1992, Hoffmann et al. 1996). Slam® (Microflo Company, Lakeland, FL) is a commercially available product that combines the toxicant carbaryl with cucurbitacin. Because cucurbitacin is used in the formulation, the amount of carbaryl applied per hectare is only 2% of the application rate recommended for carbaryl applied alone (Lance and Sutter 1992). This study was conducted to compare the efficacy of Slam® applied on an areawide basis with that of soil insecticide in suppressing Mexican corn rootworm abundance and to determine the effects of these management strategies on corn root damage and yield.

Materials and Methods

Experiments were conducted during 1996 and 1997 on privately owned and managed farms in Bell County, TX. The experimental design in 1996 was a completely randomized design with 2 treatments. Treatments were Slam® treated and Slam® non-treated. These treatments subsequently will be referred to as foliar insecticide-treated and foliar insecticide non-treated, respectively. A contiguous 1,366-ha dryland area was selected as the foliar insecticide-treated area. This area was composed of corn (908 ha); sorghum (270 ha), *Sorghum bicolor* (L.) Moench; wheat (79 ha), *Triticum aestivum* L.; cotton (45 ha), *Gossypium hirsutum* L.; and pasture or other non-crop land (64 ha). Four corn fields were selected randomly inside the area and 4 corn fields were selected randomly outside the area to serve as replications. All corn fields selected were planted in corn during the previous season. Because of drought conditions and poor plant growth, however, only 2 fields outside the area were used. Corn cultivar, planting date, and plant density in the selected fields are shown in Table 2.1. Because treatments were not assigned randomly to fields, this study does not conform to the constraints of a completely randomized design. However, the study does represent an approximation of a completely randomized design, considering the large scale of the study.

For timing and evaluation of Slam® application, the pattern of Mexican corn rootworm adult emergence was monitored and adult abundance was assessed in each selected field. Five sites in each of 2 rows were selected in each field. Rows and sites selected were 50 m apart. Adult emergence was monitored and adult abundance was assessed at each site. Adult emergence was monitored using a modified, conical, wire-screen pecan weevil, *Curculio caryae* (Horn), emergence trap (1 m diameter at base) (Raney and Eikenbary 1969). One emergence trap was used at each site, and traps were placed over plants on 18 May 1996 when plants were in the 5-7 leaf stage of vegetative growth. Plants were pruned as needed to accommodate the trap (Fisher 1984). Adult abundance was estimated by counting the number of adults on 5 plants at each site. This method commonly is referred to as plant inspection and is the standard method for estimating abundance of adults (Steffey et. al. 1982). Emerging adults were counted and removed from traps, and plants were inspected twice weekly. Monitoring was terminated on 8 July 1996, after plants had senesced.

A treatment threshold of 1 adult Mexican corn rootworm per corn plant was used for Slam® application (Pruess et al. 1974). Once adult abundance in ≥1 of the selected fields exceeded the treatment threshold, abundance was assessed in all remaining corn and sorghum fields in the 1,366-ha area to identify fields that required treatment.

Table 2.1. Cultivar, planting date, and plant density of corn fields selected for timing and evaluation of foliar insecticide applied for control of Mexican corn rootworm, Bell County, TX, 1996

Field	Foliar insecticide	Cultivar	Planting date	Mean plant density (plants/ha)
1	Non-treated	Cargill 7997	19 March	49,420
2	Non-treated	Pioneer 3163	25 March	51,891
3	Treated	Triumph 2010	03 March	51,891
4	Treated	DeKalb 715	12 March	54,609
5	Treated	Asgrow	20 March	54,362
6	Treated	Cargill 7997	15 March	54,609

Abundance was assessed in sorghum fields because Stewart et. al. (1995) reported damage by Mexican corn rootworm larvae to corn where sorghum was grown the previous year. Abundance of Mexican corn rootworm adults in these additional fields was assessed twice weekly by counting the number of adults on 5 plants at each of 5 sites. Sites were selected in U-shaped pattern and were 50 m apart. Because plant density was greater in sorghum fields than in corn fields, a treatment threshold of 0.2 Mexican corn rootworm adults per sorghum plant was used.

Slam® was applied at a rate of 0.56 kg product/ha in 9.4 liters/ha of water to all corn and sorghum fields within the 1,366-ha area in which adult abundance exceeded the treatment threshold. Application of Slam® began on 13 June 1996 and was completed on 20 June 1996. Applications were timed to occur after peak adult emergence (Fig. 2.1). A Cessna Ag Husky airplane with a 13.7-m effective swath width was used to apply Slam®. The speed of the aircraft during application was 53.6 m/s. WindBreak® (Riverside/Terra Corp., Sioux City, IA) was added at a rate of 0.1% by volume to improve rainfastness.

The efficacy of Slam® in reducing abundance of Mexican corn rootworm adults in corn was determined by comparing adult abundance in the selected fields inside the 1,366-ha foliar insecticide-treated area to that in the selected fields outside the area at 0, 4, 7, and 14 d after application of Slam®. Before corn harvest, oviposition by Mexican corn rootworm also was measured in each selected corn field. A golf course cup cutter (Par Aide, Watson Distributing Co., Inc., Houston, TX) was used to extract three, 1.15-liter soil samples (10.5-cm diameter by 11-cm depth) from each of 10 sites in each field

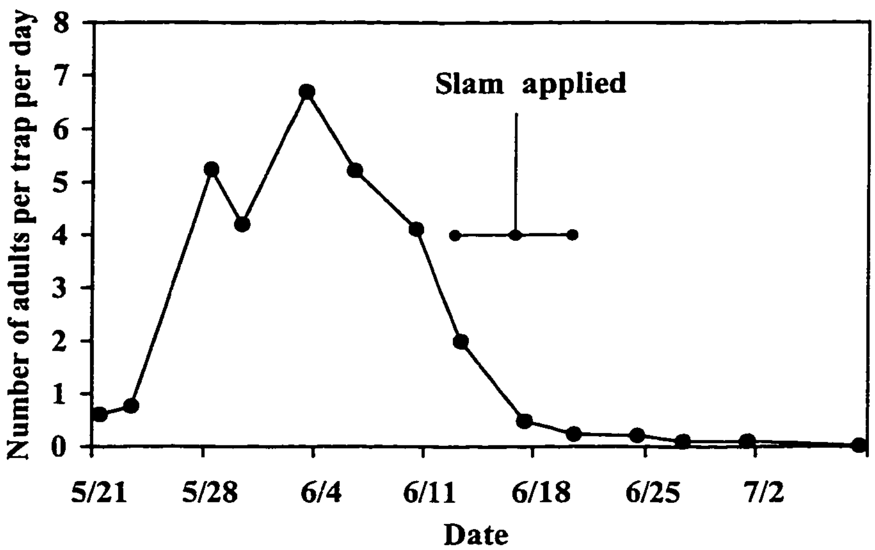

Fig. 2.1. Seasonal number of Mexican corn rootworm adults that emerged from selected corn fields in areas to be treated and not treated with foliar insecticide, Bell County, TX, 1996.

(Ruesink 1986) on 15 July 1996. Samples from each location were combined, and eggs in a 1-liter subsample from each location were counted. Eggs were separated from the soil using the Illinois egg-separating apparatus and separatory funnel technique described in detail by Ruesink (1986). The separatory funnel technique was modified by using a 1.75-M sucrose ($C_6H_{22}O_{11}$) solution instead of a 2-M magnesium sulfate ($MgSO_4$) solution. This modification was used because sucrose dissolved more readily in water and was easier to obtain than magnesium sulfate. This method resulted in a 91.4% recovery rate of Mexican corn rootworm eggs from artificially infested samples. Abundance data from plant inspections at 0, 4, 7, and 14 d after treatment were transformed using *ln* (X+1) to stabilize variances. Transformed data were subjected to analysis of variance using the General Linear Models procedure to identify significant differences between means at each sample date (SAS Institute 1990). Egg abundance data also were analyzed using the General Linear Models procedure to identify significant differences between treatment means.

The goal of reducing abundance of Mexican corn rootworm adults in 1996 was to reduce oviposition by adults, thereby reducing abundance in 1997. To determine if this goal was attained, adult abundance, damage to corn roots, and corn yield were measured in the foliar insecticide-treated area and in the foliar insecticide non-treated area in 1997. Additionally, the effects of soil insecticide application in 1997 on the same parameters were measured. Because foliar insecticide was applied over a large area, and soil insecticide can be applied over small areas, a split plot design was used to evaluate these 2 management strategies. Treatments were arranged in a 2 x 2 factorial. The whole plot was replicated 4 times, and the split plot was replicated 5 times. Whole plots were the 1,366-ha foliar insecticide-treated area and the foliar insecticide non-treated area from 1996. In 1997, the foliar insecticide-treated area was composed of corn (791 ha), sorghum (334 ha), wheat (95 ha), cotton (65 ha), and pasture or other non-crop land (81 ha). Four fields were selected inside the treated area and 4 fields were selected outside the area to serve as whole plot replications. Corn was grown in each of these fields in 1996. Split plots were established in each of the selected fields and replicated 5 times. Split plot treatments were soil insecticide-treated and soil insecticide non-treated. Soil insecticide was applied to entire fields, but 5 plots 3 rows wide and 30.5 m long in each field were not treated. Different growers used different planting dates, corn cultivars, plant densities, soil insecticides, and soil insecticide rates (Tables 2.2 and 2.3). Again, this study represented the approximation of a split plot design. The large scale of the study did not permit true replication of the whole plots.

The number of Mexican corn rootworm adults emerging from the soil in each treatment was measured using emergence traps previously described. These data were recorded as a measurement of adult abundance to determine the level of Mexican corn rootworm suppression achieved for each treatment combination. An emergence trap was used at each of 3 locations spaced 13.5 m apart along the center row of split plots. Traps were placed over plants on 28 May 1997, when plants were in the 5-7 leaf stage of vegetative growth. Adults were counted and removed from traps as previously described. Traps were removed from fields on 9 July 1997, after plants had senesced.

Table 2.2. Cultivar, planting date, and plant density of corn fields selected for evaluation of foliar insecticide applied for control of Mexican corn rootworm, Bell County, TX, 1997

Field	Foliar insecticide	Cultivar	Planting date	Mean plant density (plants/ha)
1	Non-treated	Pioneer 3223	20 March	51,891
2	Non-treated	Pioneer 3394	23 March	51,891
3	Non-treated	DeKalb 7015	27 March	55,597
4	Non-treated	Triumph 2010	26 March	54,609
5	Treated	Triumph 2010	24 March	54,609
6	Treated	Pioneer 3394	26 March	51,891
7	Treated	Pioneer 3394	24 March	51,891
8	Treated	Triumph 2010	27 March	51,891

Table 2.3. Soil insecticide and rate used in corn fields selected for evaluation of areawide application of foliar insecticide and for evaluation of soil insecticide for control of Mexican corn rootworm, Bell County, TX, 1997

Field	Foliar insecticide	Soil insecticide	Rate (kg [AI]/ha)
1	Non-treated	terbufos[a]	1.17
2	Non-treated	terbufos	1.17
3	Non-treated	terbufos	1.01
4	Non-treated	terbufos	1.46
5	Treated	terbufos	0.90
6	Treated	terbufos	1.17
7	Treated	terbufos	1.17
8	Treated	tefluthrin[b]	0.04

[a]Counter® 20CR (American Cyanamid, Princeton, NJ).
[b]Force® 1.5G (Zeneca Ag Products, Wilmington, DE).

Root damage by corn rootworm larvae was rated using a 1-6 scale (Hills and Peters 1971) on 20 June 1997, after peak adult emergence. A rating score of 1 indicated the least amount of damage, while a rating score of 6 indicated the greatest amount of damage. Damage was scored on the roots of 1 plant near each emergence trap. Corn was hand harvested from each split plot on 17 July 1997, by removing ears from all plants along a length of the center row equivalent to 0.0008 ha. A single-plant thresher (Specialized Agricultural Equipment, Allen Machine Company, Aimes, IA) was used to remove kernels from the ears. Moisture of samples was determined using a Steinlite Moisture Meter (Seedburo Equipment Company, Chicago, IL). Yields were adjusted to 13% moisture to compensate for variation in kernel moisture among plots. Emergence data were *ln* (X+1) transformed to stabilize the variance component. Data on corn root damage, total number of emerged adults, and yield were analyzed using the General Linear Models procedure (SAS Institute 1990). Type III sums of squares were used to identify significant treatment and interaction effects.

In 1997, adult abundance also was measured using plant inspections in the foliar insecticide-treated and foliar insecticide non-treated areas. Plant inspection procedures used in the selected and other fields were the same as in 1996, except that abundance was assessed at only 8 sites, instead of 10, per field. Because of the ability of corn rootworm adults to disperse, no attempt was made to monitor abundance in the smaller split plots. Abundance estimates made using plant inspections and emergence traps both were used to determine the level of suppression achieved from application of Slam® the previous year. Plant inspection counts also were used to identify a need for Slam®

treatment in 1997, as part of a continuing Mexican corn rootworm management program in Bell County. Godfrey and Turpin (1983) reported that a large proportion of western corn rootworm adults that migrated into corn fields where a different crop previously was grown were female, and suggested that a lower treatment threshold be used if corn was to be grown again the following season. In the present study, it was assumed that the majority of Mexican corn rootworm adults in the foliar insecticide-treated area were immigrants. Treatment thresholds were therefore adjusted to 0.5 adult per plant for corn and 0.1 adult per plant for sorghum. Slam® was applied using an Air Tractor 402B airplane traveling at 53.6 m/s with an effective swath width of 18.3 m. The rate of application was 0.37 kg/ha in 9.4 liters/ha of water. WindBreak® (Riverside/Terra Corp., Sioux City, IA) was added at a rate of 0.1% by volume to improve rainfastness. This lower rate of Slam® was used because of overall low Mexican corn rootworm adult abundance in the foliar insecticide-treated area (Hoffmann et al. 1996). Applications were made on 23 June 1997, after peak adult emergence (Fig. 2.2). Adult abundance data for 19 June 1997, just before application of Slam®, were used to determine the level of Mexican corn rootworm adult suppression achieved as a result of Slam® applied in 1996. Adult abundance data for this sample date were subjected to analysis of variance using the GLM procedure to identify significant differences between means for foliar insecticide treatments (SAS Institute 1990). Because only 1 field selected for replication inside the foliar insecticide-treated area required treatment in 1997, it was not possible to assess Slam® efficacy in that year.

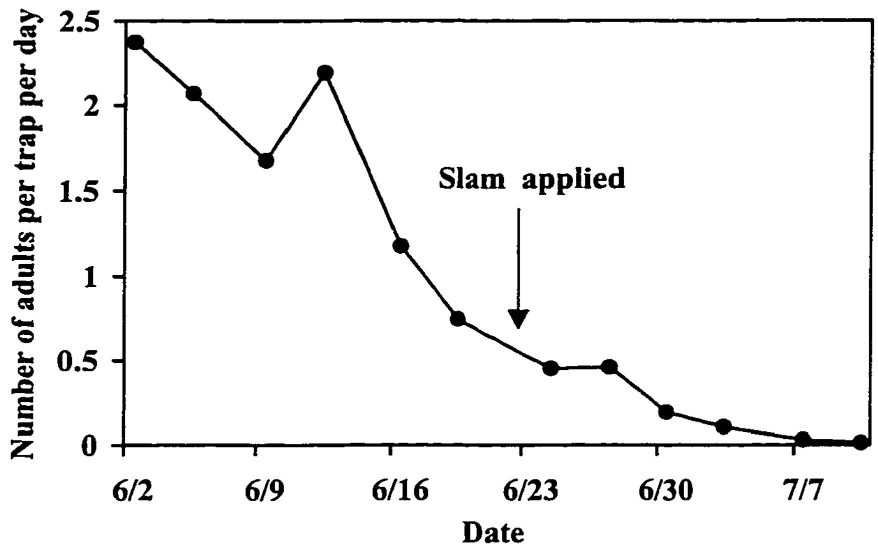

Fig. 2.2. Seasonal number of Mexican corn rootworm adults that emerged from selected corn fields in areas to be treated and not treated with foliar insecticide, Bell County, TX, 1997.

Results and Discussion

Slam® was applied to 728 ha of corn and 162 ha of sorghum in the foliar insecticide-treated area. No significant difference was detected in numbers of adults per plant before treatment in the foliar insecticide-treated area (1.96 per plant) and the foliar insecticide non-treated area (1.40 per plant) ($F = 2.86$; df = 1, 58; $P > 0.05$) (Table 2.4). At 4, 7, and 14 d after treatment, Mexican corn rootworm adult abundance in the foliar insecticide-treated area was reduced by 89.8 ($F = 49.87$; df = 1, 58; $P < 0.01$), 90.6 ($F = 62.57$; df = 1, 58; $P < 0.01$), and 99.1% ($F = 158.89$; df = 1, 58; $P < 0.01$) compared with the non-treated area (Table 2.4). Similar results were obtained by Pruess et al. (1974) who found western corn rootworm abundance was reduced by 80-96% as a result of application of ULV malathion to a 2,072-ha area. Suppression of western corn rootworm adults in smaller areas, however, was less successful. In an experiment by Beardmore (1975), for example, western corn rootworm abundance was reduced by only 74% by the application of carbaryl to 3.4-ha plots. Lance and Sutter (1992) utilized a semiochemical-based toxic bait similar to Slam® to reduce western corn rootworm and northern corn rootworm adult abundance by 77-85 and 55-92%, respectively, in 1-3 ha plots. Adult abundance in these small plots, however, returned to pretreatment levels within 1-2 wk after treatment. Collectively, these results demonstrated the importance of an areawide approach for using foliar insecticide to reduce abundance of corn rootworm adults. In the present study, Mexican corn rootworm abundance in the foliar insecticide non-treated area at each sample date was greater than the treatment threshold of 1 adult per plant. This threshold has been used not only to justify treatment with

Table 2.4. Mean number of Mexican corn rootworm adults per plant (± standard deviation) in selected corn fields in areas treated and not treated with foliar insecticide at 0, 4, 7, and 14 d after treatment, Bell County, TX, 1996

		Days after treatment[a]			
Treatment	*n*	0	4	7	14
Treated	40	1.96 ± 1.36 a	0.16 ± 0.26 b	0.17 ± 0.24 b	0.02 ± 0.05 b
Non-treated	20	1.40 ± 1.42 a	1.57 ± 1.33 a	1.82 ± 1.45 a	2.14 ± 1.75 a

Means followed by the same letter in a column are not significantly different ($P <$ 0.05, General Linear Models procedure [SAS Institute 1990]).
[b]Data were *ln* (X+1) transformed before analysis. However, non-transformed means are presented.

foliar insecticide (Pruess et al. 1974), but also to predict need for soil insecticide treatment the following year (Stamm et al. 1985). Using this threshold, all selected fields in the foliar insecticide non-treated area would have required treatment with soil insecticide in 1997.

Although the difference was not significant, 48.2% fewer Mexican corn rootworm eggs were found in the foliar insecticide-treated area than in the non-treated area (F = 1.58; df = 1, 58; $P > 0.1$) (Table 2.5). Similarly, Beardmore (1975) found 32% fewer western corn rootworm eggs in plots treated with carbaryl than in non-treated plots. Beardmore (1975) discovered that soil type and condition greatly affected the number of western corn rootworm eggs collected following application of carbaryl, and remarked that sampling eggs was not a reliable method for determining the efficacy of adult control.

During 1997, the number of Mexican corn rootworm adults emerging from the soil in the foliar insecticide-treated area was 93.5% lower than in the non-treated area (F = 41.00; df = 1, 3; $P < 0.01$) (Table 2.6). This difference closely resembled the difference in adult abundance observed between the 2 areas following Slam® application in 1996. In addition, these findings suggested that the 48.2% reduction in Mexican corn rootworm eggs after Slam® application in 1996 was, in fact, biologically significant. These results differ from those of Beardmore (1975), who found that application of carbaryl to 3.2-ha plots reduced by only 2% the number of western corn rootworm adults that emerged in the

Table 2.5. Mean number of Mexican corn rootworm eggs per 1-liter soil sample (± standard deviation) from selected fields in areas treated and not treated with foliar insecticide during 1996, Bell County, TX, 1996

Treatment	*n*	Mean number of Mexican corn rootworm eggs
Treated	40	0.9 ± 2.1 a
Non-treated	20	1.7 ± 2.9 a

Means followed by the same letter in a column are not significantly different ($P <$ 0.05, General Linear Models procedure [SAS Institute 1990]).

Table 2.6. Mean numbers of Mexican corn rootworm adults (± standard deviation) that emerged in 1997 from selected fields in areas treated and not treated in 1996 with foliar insecticide and from plots treated and not treated in 1997 with soil insecticide, Bell County, TX, 1997

		Mean number of Mexican corn rootworm adults captured per emergence trap	
Treatment	*n*	Foliar insecticide	Soil insecticide
Treated	120	1.4 ± 2.9 b	7.4 ± 13.1 b
Non-treated	120	21.5 ± 25.9 a	15.5 ± 26.0 a

Means followed by the same letter in a column are not significantly different ($P <$ 0.05, General Linear Models procedure [SAS Institute 1990]).

[a]Data were *ln* (X+1) transformed before analysis. However, non-transformed means are presented.

season following application. This disparity probably is a result of either improper timing of carbaryl application or immigration of western corn rootworm adults into these small plots after carbaryl application (Beardmore 1975).

The number of Mexican corn rootworm adults that emerged from soil insecticide-treated plots was 52.3% lower than from plots not treated with soil insecticide ($F = 13.67$; df = 1, 230; $P < 0.01$) (Table 2.6). These results support the findings reported by others that soil insecticide application reduced by an average of 50-65% the number of adults that emerged from the soil (Sutter et al. 1991; Gray et al. 1992, 1993; Cocke et al. 1994).

There was a significant foliar insecticide by soil insecticide interaction ($F = 12.40$; df = 1, 230; $P < 0.01$) as demonstrated in Fig. 2.3. This kind of graph often is used to illustrate interaction effects. These results demonstrate that soil insecticide had a greater effect in reducing the number of Mexican corn rootworm adults that emerged from the soil in the foliar insecticide non-treated area (solid line) than in the foliar insecticide-treated area (dashed line). The significance of this interaction is that if foliar insecticide is used on an areawide basis, the additional use of soil insecticide does not further reduce the number of Mexican corn rootworm adults that emerge from the soil.

The reduced numbers of Mexican corn rootworm adults that emerged from the soil in the foliar insecticide-treated area and in the soil insecticide-treated plots indicated that fewer larvae were present to damage corn roots. Mean corn root damage rating scores ranged from 2.0 in the foliar insecticide-treated area to 4.3 in the non-treated area ($F = 171.33$; df = 1, 3; $P < 0.01$) (Table 2.7). The range of mean corn root damage rating scores

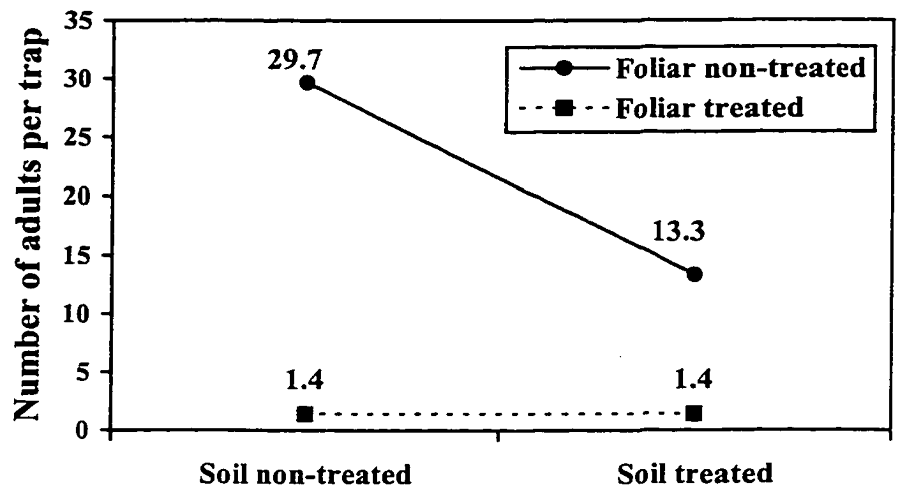

Fig. 2.3. Mean total number of Mexican corn rootworm adults captured per emergence trap in selected fields in areas treated and not treated with foliar insecticide and from plots treated and not treated with soil insecticide, Bell County, TX, 1997.

Table 2.7. Mean scores for corn root damage (± standard deviation) from selected fields in areas treated and not treated in 1996 with foliar insecticide and from plots treated and not treated in 1997 with soil insecticide, Bell County, TX, 1997

		Mean root damage score	
Treatment	*n*	Foliar insecticide	Soil insecticide
Treated	120	2.0 ± 0.6 b	2.8 ± 1.1 b
Non-treated	120	4.3 ± 1.1 a	3.5 ± 1.7 a

Means followed by the same letter in a column are not significantly different ($P <$ 0.05, General Linear Models procedure [SAS Institute 1990]).

in soil insecticide-treated was from 2.8 in the treated plots to 3.5 in the non-treated plots ($F = 46.60$; df = 1, 230; $P < 0.01$) (Table 2.7). Corn root damage rating scores of >2.5-3.0 generally have been accepted as indication of economic damage (Turpin et al. 1972, Sutter et al. 1990, Gray et al. 1992). Using these criteria, only corn in fields treated with foliar insecticide had an acceptably low level of root damage. A significant foliar insecticide by soil insecticide interaction demonstrated that soil insecticide was most effective in protecting corn roots from damage in the foliar insecticide non-treated area compared with the foliar insecticide-treated area ($F = 43.09$; df = 1, 230; $P < 0.01$) (Fig. 2.4). The biological significance of this finding is that soil insecticide appears to be more effective in protecting corn roots from damage when larger numbers of Mexican corn rootworm larvae are present. Beardmore (1975) found that both foliar application of carbaryl and application of soil insecticide significantly reduced damage to corn roots. However, Beardmore (1975) did not observe a significant interaction between the 2 treatment effects. This probably is because carbaryl application reduced by only 2% the number of western corn rootworm adults that emerged from the soil in the season following application. This infers that large numbers of larvae were present and that soil insecticide had greater opportunity to protect corn roots from damage.

Unlike the results for Mexican corn rootworm adult emergence and corn root damage, corn yield in the foliar insecticide-treated area (5,847 kg/ha) was similar to corn yield in the foliar insecticide non-treated area (5,834 kg/ha) ($F = 0.001$; df = 1, 3; $P > 0.10$) (Table 2.8). It seems counterintuitive that the reduction in Mexican corn rootworm abundance and corn

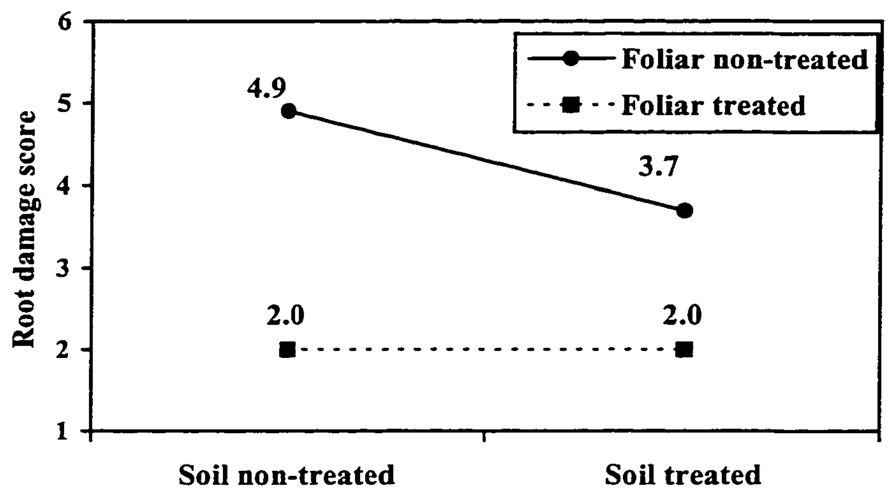

Fig. 2.4. Mean corn root damage ratings from selected fields in areas treated and not treated with foliar insecticide and from plots treated and not treated with soil insecticide, Bell County, TX, 1997.

Table 2.8. Mean corn yields [kg/ha (± standard deviation)] from selected fields in areas treated and not treated in 1996 with foliar insecticide and from plots treated and not treated in 1997 with soil insecticide, Bell County, TX, 1997

		Mean corn yield (kg/ha)	
Treatment	*n*	Foliar insecticide	Soil insecticide
Treated	80	5,874.0 ± 1759.7 a	6,073.7 ± 1922.1 a
Non-treated	80	5,834.0 ± 2200.1 a	5,634.7 ± 2036.1 b

Means followed by the same letter in a column are not significantly different ($P < 0.05$, General Linear Models procedure [SAS Institute 1990]).

root damage that resulted from foliar insecticide treatment also did not result in higher yields. As previously mentioned, Turpin et al. (1972) reported that root damage rating scores of 2.5-3.0 usually resulted in economic losses (Turpin et al. 1972). Sutter et al. (1990), however, found that these rating scores had to be ≥4.0 before losses were economically important (Sutter et al. 1990). The disparity between these 2 examples probably is the result of varying abilities of corn plants to compensate for root damage (Spike and Tollefson 1989b). Factors such as moisture stress and plant lodging can greatly decrease the ability of corn plants to compensate for root damage (Spike and Tollefson 1988, 1989a, 1991; Davis and Coleman 1997). Precipitation in Bell County from January through August 1997 was 19.8 cm above average, and very little lodging was observed. This moisture level probably allowed adequate regrowth of roots and a lower incidence of root lodging. As a result, roots scored for damage in mid-season could not be used to predict corn yield.

Corn yield was 7.8% higher in soil insecticide-treated plots than in soil insecticide non-treated plots ($F = 5.19$; df = 1, 230; $P < 0.05$) (Table 2.8). The foliar insecticide treatment by soil insecticide treatment interaction was not significant, indicating that the effect of soil insecticide on corn yield was similar in the foliar insecticide-treated area and in the foliar insecticide non-treated area ($F = 0.07$; df = 1, 230; $P > 0.10$) (Fig. 2.5). The idea that corn plants can compensate for root damage explains why corn yield was similar in the foliar insecticide-treated area compared with the foliar insecticide non-treated area. The higher yield observed in the soil insecticide-treated area compared with the soil insecticide non-treated area, however, is not explained by this idea. In soil insecticide-

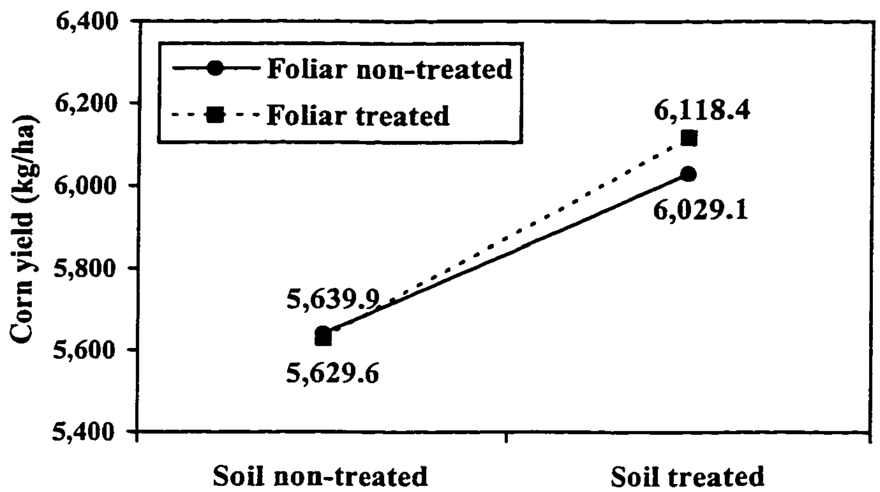

Fig. 2.5. Mean corn yield from selected fields in areas treated and not treated with foliar insecticide and from plots treated and not treated with soil insecticide, Bell County, TX, 1997.

treated plots, corn yield may have been influenced by organisms other than Mexican corn rootworm. For example, soil insecticide is recommended in Texas for control of southern corn rootworm, *Diabrotica undecimpunctata howardi* Barber. Similar to Mexican corn rootworm, southern corn rootworm is stimulated by cucurbitacin to feed, and adult abundance may be reduced by Slam®. However, the life cycle of the multivoltine southern corn rootworm is asynchronous with the timed applications of Slam®. In addition, adults and larvae of this species are polyphagous and not limited to the corn and sorghum habitats in which Slam® was applied. Nematodes also probably are not influenced by Slam®, but may be reduced in abundance as a result of soil insecticide application. Reducing abundance of nematodes has been shown to increase corn yield by ≤54% (Norton et al. 1978, Smolik 1978).

Plant inspections in 1997 revealed that abundance of Mexican corn rootworm adults exceeded the conservative Slam® treatment threshold of 0.5 adult per corn plant in 209 ha of corn in the foliar insecticide-treated area.. This was 26.4% of the total hectarage of corn in the foliar insecticide-treated area. The treatment threshold of 0.1 adult per sorghum plant was not exceeded during 1997 in any sorghum field in the foliar insecticide-treated area. In 1996, the less conservative Slam® treatment thresholds of 1 adult per corn plant and 0.5 adult per sorghum plant were exceeded in 80.2% of the corn hectarage and 60.0% of the sorghum hectarage in the same area. Corn fields exceeding the treatment threshold in the foliar insecticide-treated area in 1997 were treated with Slam® on 23 June 1997 as part of a continuing Mexican corn rootworm management program. Again, assessment of efficacy of 1997 applications was not possible because of the limited number of fields requiring treatment.

As an additional measurement of the efficacy of the 1996 Slam® application in suppressing Mexican corn rootworm abundance, plants in the foliar insecticide-treated and foliar insecticide non-treated areas were inspected visually for Mexican corn rootworm adults on 19 June 1997, before Slam® was applied. Again, because of the ability of Mexican corn rootworm adults to disperse, no attempt was made to assess adult abundance using plant inspections in the smaller soil insecticide treatments. Mexican corn rootworm adult abundance was 98.0% lower in the foliar insecticide-treated area than in the foliar insecticide non-treated area ($F = 60.15$; df = 1, 59; $P < 0.01$) (Table 2.9). This difference in the season following Slam® application, was similar to the reduction in adult abundance observed in 1996, immediately following application of Slam® (Table 2.4). Pruess et al. (1974) found slightly lower levels of western corn rootworm adult suppression (39-72%) in the seasons following ULV application of malathion. As in 1996, adult abundance in selected fields in the foliar insecticide non-treated area exceeded the treatment threshold of 1 adult per plant and would have required soil insecticide treatment again in 1998.

In summary, areawide application of Slam® was more effective than soil insecticide in reducing Mexican corn rootworm abundance and damage to corn roots. These findings demonstrated that Mexican corn rootworm is amenable to areawide management and support the idea that use of soil insecticide is not a viable long-term solution for management of corn rootworm. However, areawide application of Slam®

Table 2.9. Mean abundance of Mexican corn rootworm adults (± standard deviation) in selected fields in areas treated and not treated in 1996 with foliar insecticide, Bell County, TX, 1997[a]

Adult treatment	*n*	Mean number of Mexican corn rootworm adults per plant[b]
Treated	32	0.04 ± 0.12 b
Non-treated	32	2.01 ± 2.25 a

Means followed by the same letter in a column are not significantly different ($P < 0.05$, General Linear Models procedure [SAS Institute 1990]).

[a]Fields were sampled on 19 June 1997 before foliar insecticide application.

[b]Data were *ln* (X+1) transformed before analysis. However, non-transformed means are presented.

and the subsequent reduction in Mexican corn rootworm abundance and damage to corn roots did not significantly influence corn yield. Yield was improved significantly only by application of soil insecticide. It is suspected the yield response was from a combination of optimal growing conditions and the presence of other organisms that influenced corn yield. Further research, however, will be needed to identify the cause of the observed corn yield increase resulting from application of soil insecticide. Continued Mexican corn rootworm management and observation in the area will be required to determine if reducing Mexican corn rootworm adult abundance ultimately will lead to improved in corn yield.

CHAPTER III

FACTORS CONTRIBUTING TO THE FAILURE OF SORGHUM ROTATION TO PREVENT DAMAGE BY MEXICAN CORN ROOTWORM TO CORN

Cultural practices, such as crop rotation, as an integrated pest management (IPM) tactic for insect pests can have tremendous beneficial effects on the agricultural ecosystem. Rotating corn, *Zea mays* L., with soybeans, *Glycine max* (L.) Merrill, for example, improved yields of both crops (Peterson and Varvel 1989a, b), reduced incidence of pathogens in both crops (Lipps 1988, Adee et al. 1994), and, when wheat, *Triticum aestivum* L., was included in the rotation, increased abundance of insect predators in corn (Brust and King 1994). In addition, rotation of corn with any other crops reduced abundance of Mexican corn rootworm, *Diabrotica virgifera zeae* Krysan and Smith, western corn rootworm, *D. virgifera virgifera* LeConte, and northern corn rootworm, *D. barberi* Smith and Lawrence (Krysan 1986). The larvae of these univoltine insect pests are nearly monophagous, feeding primarily on the roots of corn (Krysan 1986). As a result, they cannot survive when corn is rotated with another crop. Failure of crop rotation to prevent damage by corn rootworm to corn, however, is occurring with increasing frequency, especially for Mexican corn rootworm (Stewart et al. 1995) and western corn rootworm (Sammons et al. 1997).

Until the 1990's, northern corn rootworm was the only 1 of these species thought to be involved in the loss in effectiveness of crop rotation (Branson and Krysan 1981, Sammons et al. 1997). Hill and Mayo (1980) suggested that damage by northern corn rootworm to corn planted in fields where soybeans had been grown the previous year was the result of adult feeding and oviposition in the previous crop. Northern corn rootworm adults feed more extensively on pollen from plant species other than corn and are found more frequently in grain stubble, soybeans, and pastures than are adults of western corn rootworm (Cinereski and Chiang 1968, Ludwig and Hill 1975, Hill and Mayo 1980). Northern corn rootworm also was shown to be the dominant corn rootworm species where corn commonly was rotated with other crops, whereas western corn rootworm was the dominant species where corn was grown in continuous production (Hill and Mayo 1980). Observations of northern corn rootworm oviposition behavior showed, in fact, that females oviposited 13-18% of their eggs in fields other than corn (Shaw et al. 1978, Gustin 1984, Boetel et al. 1992).

An alternative explanation for damage by northern corn rootworm to corn after rotation with another crop is prolonged diapause of northern corn rootworm eggs. Chiang (1965) first demonstrated that some northern corn rootworm eggs remained in diapause for ≥2 yr. A 2-yr egg diapause allows eggs to remain in diapause while the non-host crop is growing and hatch the following season when corn again is planted. Although Chiang (1965) found that only 0.3% of northern corn rootworm eggs exhibited prolonged diapause, subsequent studies found the frequency of prolonged diapause in northern corn rootworm eggs ranged from 9-51% (Krysan et al. 1986, Levine et al. 1992b). The percentage of northern corn rootworm eggs exhibiting prolonged diapause in an area was proportional to the amount of corn in that area rotated annually with other crops (Krysan et al. 1986, Levine et al. 1992b). Failure of crop rotation to prevent damage by northern corn rootworm to corn after rotation with another crop most probably is a result of both oviposition in crops other than corn and prolonged egg diapause.

Recently, western corn rootworm also was found to damage corn after rotation with soybeans (Brunoehler 1996, Levine and Oloumi-Sadeghi 1996). Unlike northern corn rootworm, prolonged diapause of western corn rootworm eggs is not a likely explanation, because it occurs only infrequently (from 0-0.75%) (Krysan et al. 1984, Levine et al. 1992a). A more feasible explanation is western corn rootworm migration to and oviposition in soybeans. Although adults of western corn rootworm have been shown to be less closely associated than northern corn rootworm with crops other than corn (Cinereski and Chiang 1968, Ludwig and Hill 1975, Hill and Mayo 1980), some western corn rootworm adults seem to prefer soybean over corn (Sammons et al. 1997). In addition, western corn rootworm oviposition appears regulated through long-range rather than short-range cues (Kirk et al. 1968, Levine and Oloumi-Sadeghi 1996). Kirk et al. (1968) demonstrated in laboratory experiments that western corn rootworm adults laid significantly more eggs in the soil near foxtail, *Setaria* spp., than in the soil near corn stalks or leaf litter. Western corn rootworm adults also did not show an oviposition preference between the soil near corn plants and that near soybean plants in the laboratory (Levine and Oloumi-Sadeghi 1996). Siegfried and Mullin (1990) found that western corn rootworm adults oviposited in soil near sunflower, *Helianthus annuus* L., and squash, *Cucurbita maxima* Duchesne, provided corn was nearby. Similarly, Tonhasca and Stinner (1991) found significantly more western corn rootworm eggs in soybeans intercropped with corn than in areas planted only with soybeans. Sammons et al. (1997) suggested that increased orientation toward soybeans in addition to a low level of oviposition site-preference could explain the ability of western corn rootworm to overcome the effects of rotating corn with soybeans.

Mexican corn rootworm recently was found to damage corn in fields where sorghum, *Sorghum bicolor* (L.) Moench, had been planted the previous season. Stewart et al. (1995) found that the previously effective Mexican corn rootworm management strategy of annually rotating corn with sorghum resulted in similar numbers of Mexican corn rootworm adults emerging from fields of rotated corn as from fields where corn had been grown without rotation (Cocke et al. 1994). Although no attempt has been made to identify the causal factors involved, both prolonged egg diapause and adult oviposition in rotational crops are possible causes. Under controlled conditions, Mexican corn rootworm eggs remained in diapause for a longer period of time than western corn rootworm eggs (Krysan and Branson 1977, Krysan et al. 1977). Mexican corn rootworm, thus, may be more likely than western corn rootworm to evolve a 2-yr egg diapause. Similar to northern corn rootworm adults, Mexican corn rootworm adults have been observed feeding extensively on plants other than corn (Branson et al. 1982, Branson and Reyes 1983). This feeding behavior increases the probability of Mexican corn rootworm adults ovipositing in crops other than corn. Mexican corn rootworm also may be able to circumvent the effects of crop rotation by surviving on the roots of plants other than corn. Branson et al. (1982) observed that ≤50% of Mexican corn rootworm larvae sampled in Central Mexico were found in the roots of weeds. Mexican corn rootworm larvae and pupae were found in the roots of the grasses *Urachloa plantaginea* (Link) Webster and *Panicum hallii* Vasey, and the sedge *Cyperus macrocephalus* Liebmann. Mexican corn rootworm adults were collected from emergence traps placed over the grasses *B. plantaginea, Eleusine indica* (L.) Gaertner, *Eragrostis mexicana* (Hornemann) Link, and *Digitaria ciliaris* (Retzium) Köler.

Crop rotation has been a valuable tool for corn growers practicing IPM. In Illinois, for example, increased frequency of crop rotation was credited with reducing the use of soil insecticide for control of corn rootworm between 1978 and 1990 by 32% (Levine and Gray 1996). In addition, crop rotation can be used in areawide management programs to reduce the number of hectares that must be monitored and treated with foliar insecticide for corn rootworm (Gray 1995). The failure of crop rotation to prevent damage by corn rootworm to corn, however, threatens the economic value of this strategy, and puts at risk the potential of utilizing crop rotation as a component of areawide management. The objective of this study was to take the necessary 1st step in mitigating the problem with Mexican corn rootworm by determining which of the above factors are involved in the failure of rotation with sorghum to prevent damage by Mexican corn rootworm to corn.

Materials and Methods

Prolonged egg diapause was investigated using eggs from field-collected adults. Approximately 2,000 adults were collected in Bell County, TX during 1996 from corn in a field where sorghum had been grown the previous year. Adults were placed in a cage (42 cm long by 32.5 cm wide by 34.5 cm tall) constructed from a wooden frame and fiberglass screen walls (Branson et al. 1988). The oviposition media was moist soil that had been sifted through 80-mesh wire screen (Jackson 1986). A petri dish (95 mm diameter by 15 mm deep) containing the sifted, moistened soil where adults could oviposit was placed in the cage to collect eggs. The petri dish of soil was replaced twice weekly until ≈50% of adults were dead. Petri dishes containing soil and eggs were stored in darkness at 26° C and 100% RH. These conditions were used because Krysan et al. (1984) found the rate of diapause termination of western corn rootworm eggs was similar for those stored under field conditions as for those stored at a constant temperature of 25° C. Before hatching began, a cohort of 450 eggs was removed from the soil, and placed in groups of 90 on moistened filter paper in each of 5 petri dishes (60 mm diameter by 15 mm deep). Eggs of the cohort were oviposited during a 10-d period. Neonate larvae and eggs infested with fungi were counted and discarded daily. Non-hatched eggs were transferred to new filter paper and petri dishes as needed to discourage fungal growth. Cumulative egg hatch data were logit transformed, $ln\ [X/(1-X)]$, where X is the cumulative number of eggs hatching on a given day. Values of 0 or 1 were omitted because the natural logarithm of these values is undefined. The SAS regression procedure (SAS Institute 1990) was used to regress the logit of cumulative egg hatch against time to identify when 50 and 90% of cumulative hatch had occurred.

Field experiments to compare the ability of Mexican corn rootworm larvae to survive on the roots of sorghum and on the roots of corn were conducted during 1996 on privately owned farms in Bell County, TX. One sorghum field and 1 corn field were selected randomly from 3 different areas in Bell County. In accordance with local farming practices, none of the fields were irrigated. Corn was grown in each of the selected fields in 1995. Cultivars and planting dates of crops in each selected field are shown in Table 3.1. Each area represented a block in a randomized block design. Five sites in each of 2 rows were selected in each field. Rows and sites were selected 50 m apart. Modified, conical, wire-screen pecan weevil, *Curculio caryae* (Horn), emergence traps (Raney and Eikenbary 1969) that covered 1 m of row were used to monitor the numbers of Mexican corn rootworm adults that emerged from the soil in each crop. This measurement was used as an indicator of larval survival. One emergence trap was placed at each site in each selected field on 20 May 1996, when corn plants were in the 5-7 stage of vegetative growth. Plants were pruned as needed to accommodate traps (Fisher 1984). Mexican corn rootworm adults captured in traps were counted and removed twice weekly. Traps were removed from fields on 15 July 1996, when corn plants began to senesce. Emergence data were transformed using ln $(X+1)$ to stabilize variances. Transformed data were subjected to analysis of variance using the General Linear Models procedure to identify significant differences in total mean number of emerged adults between crops (SAS Institute 1990).

The numbers of Mexican corn rootworm eggs laid in corn and in sorghum also were measured during 1996. One corn field and 1 sorghum field were selected randomly from 4 different areas in Bell County, TX. However, oviposition was measured in only 2 corn fields because of drought and poor plant growth in the other fields. Fields were not irrigated and were planted in corn during 1995. The cultivars and planting dates for each selected corn and sorghum field are shown in Table 3.2. Five sites were selected in each

Table 3.1. Cultivar, planting date, and plant density of corn and sorghum in fields sampled for Mexican corn rootworm adult emergence, Bell County, TX, 1996

Field	Crop	Cultivar	Planting date	Mean plant density (plants/ha)
1	Corn	Triumph 2010	3 March	51,891
2	Corn	Cargill 7997	19 March	49,420
3	Corn	DeKalb 668	1 April	56,833
4	Sorghum	Triumph TR65G	20 March	185,325
5	Sorghum	Cargill 737	20 March	185,325
6	Sorghum	DeKalb 59	1 April	185,325

Table 3.2. Cultivar, planting date, and plant density of corn and sorghum in fields sampled for Mexican corn rootworm oviposition, Bell County, TX, 1996

Field	Crop	Cultivar	Planting date	Mean plant density (plants/ha)
1	Corn	Cargill 7997	19 March	49,420
2	Corn	Pioneer 3163	25 March	51,891
3	Sorghum	Cargill 737	20 March	185,325
4	Sorghum	Asgrow Chaparral	20 March	185,325
5	Sorghum	Triumph TR65G	20 March	185,325
6	Sorghum	DeKalb 59	1 April	185,325

of 2 rows in each field. Before corn harvest, a golf course cup cutter (Par Aide, Watson Distributing Co., Inc., Houston, TX) was used to extract three, 1.15-liter soil samples (10.5 cm diameter by 11 cm depth) from each of 10 sites in each field (Ruesink 1986). The 3 samples from each site were combined, and eggs in a 1-liter subsample from each site were counted. Eggs were separated from the soil using the Illinois egg-separating apparatus and separatory funnel technique described in detail by Ruesink (1986). The separatory funnel technique was modified by using a 1.75-M sucrose ($C_6H_{22}O_{11}$) solution instead of a 2-M magnesium sulfate ($MgSO_4$) solution. This modification was used because sucrose dissolved more readily in water and was easier to obtain than magnesium sulfate. This method resulted in a 91.4% recovery rate of Mexican corn rootworm eggs from artificially infested samples. Oviposition data were subjected to analysis of variance using the General Linear Models procedure (SAS Institute 1990).

In 1997, an experiment was designed to compare Mexican corn rootworm larval survival, adult seasonal abundance, and adult oviposition in crops that potentially could be rotated with corn. The experiment was conducted on privately owned farms in Bell County, TX. A randomized block design with 5 treatments and 18 blocks was used. Treatments were corn, sorghum, cotton, *Gossypium hirsutum* L., soybean, and Texas panicum, *Panicum texanum* Buckley. Texas panicum was included to determine whether this common weed affected efficacy of crop rotation. The other crops are among the most commonly grown in central Texas. Corn, sorghum, cotton, and soybean were planted using a Precision Garden Seeder, Model 1001B (Esmay Products, Inc., Bristol, IN). Texas panicum was planted by hand. Varieties and planting dates for each plant species are listed in Table 3.3. Planting dates reflected local planting practices. Texas panicum seed was obtained from Valley Seed Service (Fresno, CA) and planted after the final cultivation of fields for weed control. Nine blocks were established in non-planted areas in each of 2 commercial corn fields, for a total of 18 blocks. Each block was 30 m long and 6 rows wide (0.95-m row spacing), with a 12-row buffer planted with corn between blocks. Plots within blocks were 5.4 m long with a non-planted buffer of 0.3 m at each end. Each treatment was assigned randomly to 1 plot in each block. Plots were hand weeded as necessary. The number of Mexican corn rootworm adults that emerged from each plot was assessed as an indicator of larval survival on the roots of each crop. One emergence trap of the design previously described was placed on 19 May 1997 over plants in the 3rd or 4th row of each plot. Emergence traps were monitored as previously described. Traps were removed on 30 July 1997, before corn harvest. Head capsule width and dry weight of adults captured in emergence traps were measured to help determine the suitability of different crops as hosts for larvae (Branson 1986). Adults removed from emergence traps were placed for 24 h at 80° C (Weiss et al. 1985) in a Thelco® Model 18 laboratory oven (Precision Scientific, Winchester, VA). Dried adults were weighed individually using an A-Series Model 200 DS analytical balance (Denver Instrument Company, Arvada, CO). A dissecting microscope equipped with an ocular micrometer was used to measure in millimeters at the widest point head capsules of adults.

Mexican corn rootworm adult abundance and crop growth stage were assessed in each plot twice weekly to determine seasonal variation in attractiveness of each crop to Mexican corn rootworm adults. Assessment began on 22 May and was terminated on 30 June 1997.

Table 3.3. Cultivar, planting date, and plant density of different species planted to study factors contributing to failure of crop rotation to prevent damage by Mexican corn rootworm to corn, Bell County, TX, 1997

Plant Species	Cultivar	Planting date	Mean plant density (plants/ha)
Corn	Cargill 7997	Reps 1-9: 22 March Reps 10-18: 27 March	99,414
Sorghum	Asgrow Chaparral	Reps 1-9: 27 March Reps 10-18: 01 April	117,031
Cotton	DP 50	Reps 1-9: 18 April Reps 10-18: 16 April	144,716
Soybean	DP 3478	Reps 1-9: 01 April Reps 10-18: 08 April	150,064
Texas panicum	--	Reps 1-9: 30 April Reps 10-18: 30 April	49,550

In corn, sorghum, and Texas panicum plots, abundance was assessed by counting the number of adults on 10 plants in each plot. Because adults are difficult to count visually in dense foliage, abundance in cotton and soybean plots was monitored by using a 38-cm-diameter sweep net (Bioquip Products, Inc., Gardena, CA). Because corn rootworm adults generally are most attracted to flowering plants (Hill and Mayo 1980), crop phenology was noted twice weekly as pre-flowering, flowering, or post-flowering. Plants were considered pre-flowering during vegetative growth, flowering if ≥10% of plants were flowering, and post-flowering if ≥90% had completed flowering. Flowering in corn was determined by the presence of green silks. As previously mentioned, plots were located in commercial corn fields. At the time of corn harvest, cotton plots were in the flowering stage of growth and were unavoidably destroyed by combines as the corn was harvested. Three, 1-liter soil samples were taken from each plot on 7 June 1997 to determine if oviposition by Mexican corn rootworm adults was occurring in other crops. Eggs were separated from soil as previously described. Two, 0.5-liter subsamples were processed from each sample.

Data for numbers of adults that emerged and numbers of eggs were transformed using $ln\ (X+1)$ to stabilize the variance components. Transformed data were analyzed using the General Linear Models procedure (SAS Institute 1990). Means were separated using Tukey's Honestly Significant Difference test (HSD). Data on head capsule width and dry weight of adults were subjected to analysis of variance using the General Linear Models procedure. Significant differences among means were identified using Tukey's HSD. Because of the low numbers of adults captured in emergence traps placed over cotton, soybean, and Texas panicum plants, data from these treatments were omitted from analyses of head capsule width and dry weight. Adult abundance data for the different plant species were analyzed using the General Linear Models procedure, with plant growth stage as a treatment effect. Significant differences in among plant growth stages in abundance of corn rootworm adults were identified using Tukey's HSD.

Results and Discussion

Of the 450 Mexican corn rootworm eggs observed, 368 (82%) hatched, 76 (17%) died, and 6 (1%) were unaccounted for. A significant cubic relationship was found between the logit of cumulative egg hatch and time in days ($r^2 = 0.9870$; $P < 0.0001$; $n = 25$). The regression equation was $Y = 4.49508X - 0.02822X^2 + 0.00006X^3 - 238.09578$, where Y = logit of cumulative percentage of eggs hatched and X = number of days after oviposition. The observed and predicted values for cumulative percentage of Mexican corn rootworm eggs hatched were plotted against days after oviposition (Fig. 3.1). Eggs of the cohort began to hatch 263 d after oviposition, 50% of the eggs hatched after 269 d, 90% of the eggs hatched after 280 d, and no eggs hatched beyond 323 d. After 323 d, 3 (0.7%) eggs had not hatched but appeared healthy. These 3 eggs died at 376, 392, and 420 d, respectively. The percentage of eggs that hatched was similar to the 84% of eggs that Krysan et al. (1977) found hatched and greater than the 63% of eggs Krysan and Branson (1977) found to hatch. Krysan et al. (1977) and Krysan and Branson (1977) reported 50% of Mexican corn rootworm eggs obtained from Mexico had hatched at 220 and 278 d after oviposition, respectively. The results obtained in the present study suggested that prolonged diapause of Mexican corn rootworm eggs did not occur at levels that could be detected with the sample size used. Because 0.7% of the eggs sampled remained in

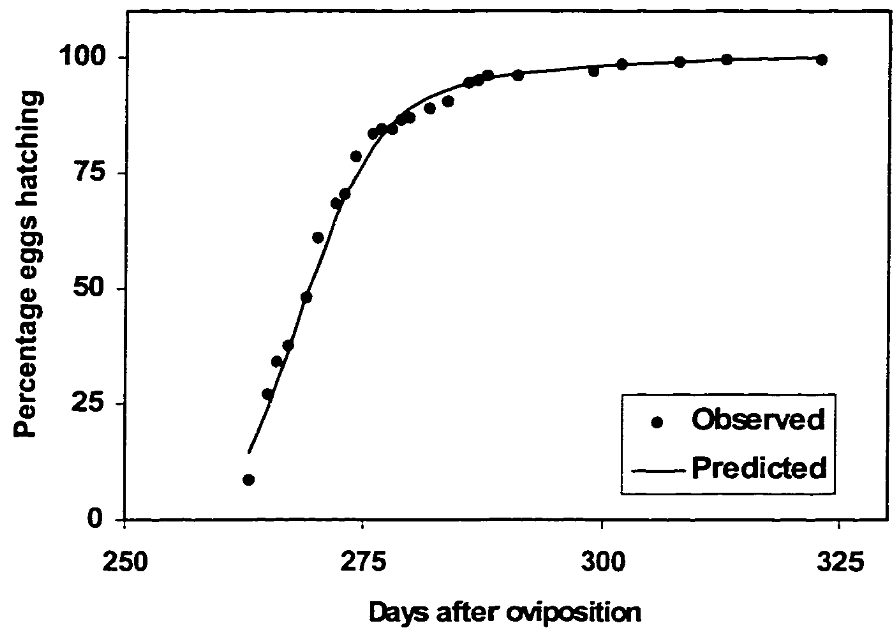

Fig. 3.1. Observed and predicted hatch over time of eggs laid by field-collected Mexican corn rootworm adults, Bell County, TX, 1997.

diapause for >1 yr, however, intense selection pressure such as annual crop rotation could select for a strain of Mexican corn rootworm with a 2-yr egg diapause. For example, Chiang (1965) found only a small proportion of northern corn rootworm eggs capable of prolonged diapause. Prolonged diapause of northern corn rootworm eggs, however, now is believed a key factor in the failure of crop rotation to prevent damage by northern corn rootworm to corn (Krysan et al. 1986, Levine et al. 1992b).

In 1996, the number of Mexican corn rootworm adults captured in emergence traps placed over sorghum plants was 3% of that captured in emergence traps placed over corn plants ($F = 59.81$; df = 1, 29; $P < 0.05$) (Table 3.4). The number of eggs in sorghum fields, however, did not differ significantly from that in corn fields ($F = 0.75$; df = 1, 18; $P > 0.1$). Because so few Mexican corn rootworm adults emerged from sorghum fields, these findings suggest that eggs in sorghum fields were from adults immigrating from corn.

In 1997, significantly more Mexican corn rootworm adults were captured in emergence traps placed over corn than in emergence traps placed over sorghum, cotton, soybean, or Texas panicum ($F = 64.48$; df = 4, 68; $P < 0.05$) (Table 3.5). Significantly more Mexican corn rootworm adults were captured in emergence traps placed over sorghum than in traps placed over cotton, soybean, or Texas panicum. The number of adults captured in emergence traps placed over sorghum, cotton, soybean, and Texas panicum was 11.2, 2.0, 1.6, and 0.5%, respectively, of that from corn. The head capsule widths of adults emerging from corn did not differ significantly from those of adults emerging from sorghum ($F = 0.43$; df = 2, 460; $P > 0.10$) (Table 3.6). However, the

Table 3.4. Mean total numbers of Mexican corn rootworm adults (± standard deviation) captured in emergence traps and eggs found per 1-liter soil sample in corn and sorghum fields, Bell County, TX, 1996

Crop	*n*	Mean number of adults captured per trap[a]	*n*	Mean number of eggs per 1 liter of soil
Corn	30	44.5 ± 62.6 a	20	1.7 ± 2.9 a
Sorghum	30	1.2 ± 1.9 b	40	1.0 ± 2.4 a

Means followed by the same letter in a column are not significantly different ($P < 0.05$, Tukey's HSD [SAS Institute 1990]).

[a]Trap data were $ln\ (X+1)$ transformed before analysis. However, non-transformed means are presented.

Table 3.5. Mean total numbers of Mexican corn rootworm adults (± standard deviation) captured in emergence traps placed over different species of plants, Bell County, TX, 1997

Crop	*n*	Mean number of adults captured per trap[a]
Corn	18	46.2 ± 35.3 a
Sorghum	18	5.2 ± 6.2 b
Cotton	18	0.9 ± 1.4 c
Soybean	18	0.7 ± 1.4 c
Texas panicum	18	0.2 ± 0.5 c

Means followed by the same letter in a column are not significantly different ($P <$ 0.05, Tukey's HSD [SAS Institute 1990]).
[a]Data were ln (X+1) transformed before analysis. However, non-transformed means are presented.

Table 3.6. Mean head capsule widths and dry weights (± standard deviation) of Mexican corn rootworm adults captured in emergence traps placed over corn and sorghum plants, Bell County, TX, 1997

Crop	*n*	Mean head capsule width (mm)	Mean dry weight (g)
Corn	381	0.998 ± 0.181 a	0.099 ± 0.163 a
Sorghum	82	0.987 ± 0.092 a	0.049 ± 0.087 b

Means followed by the same letter in a column are not significantly different ($P < 0.05$, Tukey's HSD [SAS Institute 1990]).

mean dry weight of adults emerging from corn plots was 51% greater than the mean dry weight of adults emerging from sorghum plots ($F = 5.33$; df = 2, 460; $P < 0.05$). Again, too few Mexican corn rootworm adults were captured in emergence traps placed over cotton, soybean, and Texas panicum to be included in analyses of head capsule width and dry weight. Branson and Ortman (1967a, 1970) obtained results similar to those presented here when western corn rootworm larvae were reared on hosts other than corn. Although Branson and Ortman (1970) did not measure dry weights, they observed western corn rootworm adults had similar head capsule widths when larvae were reared on 5 of 12 potential hosts from the family Poaceae as when reared on corn. However, when larvae were reared on the remaining 7 hosts, head capsule widths of western corn rootworm adults were significantly smaller than when larvae were reared on corn roots. Branson and Ortman (1967a) also reported that western corn rootworm adults reared as larvae on wheat had smaller head capsules and weighed less than adults reared as larvae on corn. It is interesting to note that Branson and Ortman (1970, 1967b) found that larval host did not detrimentally affect adult fecundity.

The results of the present study suggest that compared with corn, sorghum is a host of limited utility for Mexican corn rootworm larvae. Branson and Ortman (1970), however, found that western corn rootworm larvae could not survive for ≥10 d on the roots of sorghum seedlings. In fact, sorghum roots were believed to be toxic to western corn rootworm (Branson et al. 1969). Branson et al. (1969) showed that significantly more western corn rootworm larvae died after 24 h of exposure to roots of sorghum seedlings than after 24 h of starvation. Using homogenized whole sorghum seedlings, Branson et al. (1969) identified the toxin as hydrogen cyanide. Hydrogen cyanide is derived from the cyanogenic glycoside dhurrin found in some tissues of sorghum plants. Both Branson et al. (1969) and Branson and Ortman (1970) used seedlings when they evaluated sorghum as a host for western corn rootworm. However, Branson et al. (1969) found that the hydrogen cyanide content of sorghum plants decreased with increasing plant age and that the number of western corn rootworm larvae surviving after 24 h of exposure to sorghum roots increased when plants were ≥4 wk old. Additionally, Branson et al. (1969) used whole plants to identify the toxin involved in reducing western corn rootworm survival on the roots of sorghum. Halkier and Møller (1989), however, demonstrated that the dhurrin-synthesizing enzyme system is not present in sorghum roots and that the dhurrin content of roots was negligible compared with that of stems and leaves. Furthermore, Starr et al. (1984) found that the lateral roots of sorghum contained only 20% of the amount of dhurrin found in primary roots. Variations in dhurrin content in relation to differences in sorghum phenology and morphology may explain why Branson and Ortman (1970) did not identify sorghum as a host of western corn rootworm, and why Mexican corn rootworm adults emerged from sorghum fields in the present study. Similar to prolonged egg diapause, survival of Mexican corn rootworm larvae on the roots of sorghum plants probably is not a major factor in failure of crop rotation. However, strong selection pressure may select for a biotype of Mexican corn rootworm capable of surviving at higher rates than presently observed on the roots of sorghum.

Although significantly lower than the number of adults captured in emergence traps placed over corn or sorghum, adults captured in emergence traps placed over cotton, soybean, or Texas panicum cannot be ignored. It is possible the observed emergence of Mexican corn rootworm adults from cotton, soybean, and Texas panicum plots indicated an ability of larvae to survive on the roots of these plants. However, because so few adults were captured compared with those from corn and sorghum, it is probable other factors resulted in a basal capture of adults in all emergence traps. It is possible that a few larvae that had almost completed development on surrounding corn roots migrated through the soil into plots of other plants. Laboratory studies showed that 1st-instar western corn rootworm larvae traveled 23.5 cm during a 6-h period and survived ≤144 h without food (Strnad and Bergman 1987, MacDonald and Ellis 1990). However, Short and Luedtke (1970) demonstrated in season-long field studies that western corn rootworm larvae did not move >81.3 cm to corn roots. The row spacing of 0.96 m in the present study, and the placement of traps on the 3rd and 4th row in each plot, probably is outside the migratory range of corn rootworm larvae. Although plots were kept free of weeds throughout the season, a few larvae may have completed development on rhizomes of johnsongrass, *Sorghum halepense* (L.) Persoon, in the plots. A 3rd factor that may have led to capture of some Mexican corn rootworm adults in emergence traps is previously emerged adults were captured accidentally through trivial movement. Branson (1986) stated that corn rootworm adults often try, for unknown reasons, to enter emergence traps. Although these factors possibly explain the capture of Mexican corn rootworm adults in emergence traps placed over cotton, soybean, and Texas panicum, only controlled laboratory experiments definitively will determine the ability of Mexican corn rootworm larvae to survive on the roots of these plants.

Western corn rootworm and northern corn rootworm adults feed primarily on pollen and are attracted most to flowering plants (Cinereski and Chiang 1968, Ludwig and Hill 1975, Hill and Mayo 1980). The flowering stages for corn, sorghum, soybean, and Texas panicum in 1997 were from 12-23 June, 16-26 June, 16-30 June, and 30 June to 15 July, respectively. As previously mentioned, plots of cotton in the flowering stage of plant development were destroyed during corn harvest. Cotton began flowering on 11 July 1997, and plots were destroyed on 30 July. Mexican corn rootworm adult abundance in plots of plants at different growth stages is shown in Table 3.7. Because adult abundance in cotton and soybean was assessed by using a sweep net, it was not possible to compare abundance among plant species. Comparisons were made among plant growth stages for each plant species. Significantly more Mexican corn rootworm adults were present in corn ($F = 146.08$; df = 2, 34; $P < 0.05$), sorghum ($F = 213.66$; df = 2, 34; $P < 0.05$), and Texas panicum ($F = 106.48$; df = 2, 34; $P < 0.05$) during the flowering stage of plant growth than during the pre-flowering or post-flowering stage. The numbers of adults found in soybean during the flowering and post-flowering stages of plant growth were significantly greater than that during the pre-flowering stage ($F = 39.27$; df = 2, 34; $P < 0.05$). There were no significant differences among plant growth stages of cotton in mean numbers of Mexican corn rootworm adults ($F = 0.01$; df = 1, 17; $P > 0.10$). A threshold of 1 adult per plant is used to justify treatment with foliar insecticide to control corn rootworm adults (Pruess et al. 1974) and treatment with soil

Table 3.7. Mexican corn rootworm mean adult abundance (± standard deviation) in plots of different plant species during different plant growth stages, Bell County, TX, 1997

Plant species[a]	*n*	Pre-flowering[b]	*n*	Flowering[b]	*n*	Post-flowering[b]
Corn[c]	72	0.59 ± 0.62 b	72	2.70 ± 1.49 a	162	0.48 ± 0.73 b
Sorghum	99	0.12 ± 0.17 c	81	2.98 ± 2.57 a	126	0.59 ± 0.76 b
Cotton	234	2.38 ± 2.70 a	72	2.19 ± 2.57 a	--	--
Soybean	108	0.57 ± 1.28 b	62	3.46 ± 3.52 a	135	3.43 ± 4.47 a
Texas panicum	180	0.03 ± 0.09 b	91	0.23 ± 0.23 a	35	0.03 ± 0.07 b

Means followed by the same letter in a row are not significantly different ($P < 0.05$, Tukey's HSD [SAS Institute 1990]).

[a]Abundance values for corn, sorghum, and Texas panicum are number of Mexican corn rootworm adults per plant. Abundance values for cotton and soybean are number of Mexican corn rootworm adults captured per 30 sweeps per day of a 38-cm-diameter sweep net.

[b]Data were $ln\ (X+1)$ transformed before analysis. However, non-transformed means are presented here.

insecticide to control larvae in the subsequent season (Steffey et al. 1982). Although sampling procedures for soybean and cotton did not allow estimates of number of adults per plant, the greatest abundance observed was 3.5 adults per 30 sweeps in soybean during the flowering growth stage and probably was below the treatment threshold. In corn and sorghum, the treatment threshold was exceeded by ≈3-fold during the flowering growth stage. The treatment threshold was not exceeded during any growth stage of Texas panicum. That relatively few Mexican corn rootworm adults emerged from sorghum compared with corn (Table 3.6), suggests that adults migrated from corn to sorghum. Naranjo (1991) demonstrated that western corn rootworm and northern corn rootworm were active at corn field boundaries more during the pre-flowering and post-flowering stages of plant growth than during the flowering stage. Naranjo (1991) suggested that because pre-flowering and post-flowering corn lacked pollen or silks, movement of corn rootworm adults at corn field boundaries indicated that adults were emigrating from corn to feed in other areas.

Mean numbers of Mexican corn rootworm eggs found in soil near the different plant species are shown in Table 3.8. Significantly more eggs were found in soil near corn than in that near any other plant species except sorghum ($F = 4.32$; df = 4, 68; $P < 0.05$). Mean numbers of eggs found near sorghum and soybean plants were significantly greater than the mean number of eggs found in plots of Texas panicum. Statistically similar numbers of eggs were found in plots of cotton and Texas panicum. The numbers of eggs in plots of sorghum, cotton, soybean, and Texas panicum were 58.1, 17.7, 23.9, and

Table 3.8. Mean number of Mexican corn rootworm eggs per 0.5-liter soil sample (± standard deviation) collected near different species of plants, Bell County, TX, 1997

Plant species	*n*	Mean number of eggs[a]
Corn	36	6.8 ± 11.2 a
Sorghum	36	3.9 ± 6.9 ab
Cotton	36	1.2 ± 1.9 bc
Soybean	36	1.6 ± 2.1 b
Texas panicum	36	0.5 ± 1.2 c

Means followed by the same letter in a column are not significantly different ($P <$ 0.05,Tukey's HSD [SAS Institute1990]).
[a]Data were *ln* (X+1) transformed before analysis. However, non-transformed means are presented here.

7.4% of that in plots corn. These percentage differences are similar to those for abundance of Mexican corn rootworm adults and may suggest that Mexican corn rootworm adults lay eggs in crops where they feed. As previously discussed, western corn rootworm adults also oviposit in crops other than corn if corn is nearby (Siegfried and Mullin 1990, Tonhasca and Stinner 1991, Levine and Oloumi-Sadeghi 1996).

In summary, prolonged diapause of Mexican corn rootworm eggs and survival of Mexican corn rootworm larvae on the roots of sorghum did not appear to contribute significantly to failure of crop rotation using sorghum to prevent damage to corn. Movement of Mexican corn rootworm adults into sorghum fields to feed and oviposit, however, appears to be the primary reason Mexican corn rootworm damage corn in fields where sorghum was grown the previous season. It is suspected that Mexican corn rootworm and western corn rootworm recently evolved behaviors that allowed these species to partially overcome the detrimental effects of crop rotation on their life cycles (Stewart et al. 1995, Sammons et al. 1997). Stewart et al. (1995) noted that rotation of corn with sorghum as a way to manage Mexican corn rootworm in Texas was effective until 1992. Sammons et al. (1997) remarked that rotating corn with soybean was effective in managing western corn rootworm throughout the Midwest until the late 1980's. It seems that both species can circumvent the effects of crop rotation through oviposition outside their normal larval host crop. Western corn rootworm adults typically oviposit near feeding sites and have been observed feeding in crops other than corn (Branson and Krysan 1981, Siegfried and Mullin 1990, Tonhasca and Stinner 1991, Sammons et al. 1997).

Similar to insecticide resistance management, crop rotation must be managed properly to ensure sustainability of this IPM strategy. In areas where crop rotation has not successfully prevented damage by Mexican corn rootworm to corn, cropping practices could be adjusted to enhance the efficacy of crop rotation. Cropping practices that could be manipulated include the use of different crops for annual rotation, 3-yr rotations, sorghum hybrids with shorter flowering periods, or variation in sorghum planting time. Mexican corn rootworm adults oviposited the fewest eggs in cotton and soybean. These crops instead of sorghum could be used for crop rotation to manage Mexican corn rootworm. However, if Mexican corn rootworm did, in fact, evolve to be able to oviposit in sorghum and circumvent the detrimental effects of crop rotation, the same situation could arise from rotation with any crop. Three-year rotations using sorghum or any crop other than corn, however, probably would lessen the evolutionary advantage of oviposition by Mexican corn rootworm in crops other than corn. Use of sorghum hybrids with shorter flowering periods also may reduce the number of Mexican corn rootworm eggs laid in sorghum because these hybrids would be attractive to Mexican corn rootworm adults for a shorter period of time. Finally, planting sorghum so it flowered before Mexican corn rootworm adults emerged from corn also might allow sorghum to escape oviposition by Mexican corn rootworm adults.

CHAPTER IV

EVALUATION OF METHODS FOR MONITORING EMERGENCE AND ABUNDANCE OF MEXICAN CORN ROOTWORM ADULTS

Estimates of insect pest abundance are used in integrated pest management (IPM) to facilitate control decisions based on relationships between pest abundance and crop damage or loss of potential yield (Pedigo 1994). Insect pest seasonal abundance patterns also can be used to properly time pest control applications (Tollefson and Calvin 1994). Similar to western corn rootworm, *Diabrotica virgifera virgifera* LeConte, and northern corn rootworm, *D. barberi* Smith and Lawrence, Mexican corn rootworm, *D. virgifera zeae* Krysan and Smith, typically is managed through the use of soil insecticide (Cocke et al. 1994). Soil insecticide is applied to control corn rootworm larvae that feed on corn, *Zea mays* L, roots, causing plant lodging and yield loss (Krysan 1986). To aide in decisions to apply soil insecticide, sampling methods have been developed to assess abundance of corn rootworm eggs, larvae, and adults. However, sampling methods for eggs and larvae are inefficient, time consuming, and costly (Ruesink 1986, Tollefson 1990). Methods to sample corn rootworm adults, however, are more economical to use and have been used to relate abundance of adults in 1 season to damage by larvae the subsequent season (Steffey et al. 1982, Hein and Tollefson 1985, Stamm et al. 1985, Tollefson 1990, Levine and Gray 1994). Methods to assess abundance of adults include whole plant inspection and use of sticky or non-sticky traps. Efficiency of these methods in predicting damage by corn rootworm has varied greatly (Foster et al. 1986).

Variations in abundance of western corn rootworm and northern corn rootworm adults determined by whole plant inspection 1 season accounted for 16-38% of the variation in damage rating scores for corn roots the following season (Hein and Tollefson 1985, Foster et al. 1986, Tollefson 1990). Stamm et al. (1985) used data obtained by inspecting plants the previous season and a treatment threshold of 1 adult corn rootworm per plant to predict with 80% accuracy the need for soil insecticide. Hein and Tollefson (1985) found that western corn rootworm and northern corn rootworm abundance assessed by using whole plant inspection and a sticky trap, Pherocon AM® trap (Trécé, Salinas, CA), accounted for 27 and 26%, respectively, of the variation in damage rating scores for corn roots the following season. Levine and Gray (1994) used a non-sticky trap consisting of a 60-ml plastic vial containing a cucurbitacin-carbaryl bait to monitor abundance of northern corn rootworm and western corn rootworm adults. Adult female abundance assessed by using the non-sticky vial trap accounted for 77% of the variation in damage rating scores of corn roots the following season (Levine and Gray 1994). Because cucurbitacin is a feeding stimulant and not an attractant, Levine and Gray (1994) captured only adults that randomly entered the vial trap. Hesler and Sutter (1993), however, described a trap that combines a cucurbitacin-carbaryl bait with a non-pheromonal attractant derived from the blossoms of winter squash, *Cucurbita maxima* Duchesne (Andersen and Metcalf 1986). Although attempts have not been made to correlate numbers of corn rootworm adults captured in this kind of trap to subsequent damage by larvae to corn roots, the effectiveness of this trap in capturing large numbers of adults suggests it has potential as a predictor of damage to corn roots.

Corn rootworms also may be managed using foliar insecticides applied for adults (Pruess et al. 1974). Because corn rootworm adults are mobile and capable of reinfesting small areas treated with foliar insecticide, this management strategy is most successful when practiced over large areas. Assessment of adult abundance is used to justify application of foliar insecticide. In addition, application of foliar insecticide must be timed properly to effectively reduce adult abundance and the amount of oviposition by adults. Emergence patterns of corn rootworm adults have been used to time application of foliar insecticide. Traps of various designs have been used to monitor emergence patterns of Mexican corn rootworm, western corn rootworm, and northern corn rootworm (Fisher 1984, Matin et al. 1984, Cocke et al. 1994). However, using 2 monitoring techniques to assess both adult abundance and adult emergence patterns over large areas can be excessively labor intensive. Using a single monitoring technique to assess both parameters is a more feasible approach. Matin et al. (1984) found a high correlation, $r = 0.985$, between the number of northern corn rootworm adults captured in emergence traps and that found by inspecting plants. Matin et al. (1984) also found a high correlation, $r = 0.87$, between the number of northern corn rootworm adults captured on yellow sticky traps and that found by inspecting plants. A positive correlation, $r = 0.59$, also was found between numbers of western corn rootworm adults captured in sticky traps and found by plant inspection (Hein and Tollefson 1984). The objectives of the experiments reported here were to evaluate efficacies of whole plant inspection and emergence traps, sticky traps, and non-sticky traps as indicators of

Mexican corn rootworm adult abundance and to determine the effectiveness of these methods in monitoring emergence patterns of Mexican corn rootworm adults.

Materials and Methods

Evaluations were conducted during 1995 and 1996 on private farms in Bell County, TX. The monitoring methods evaluated were whole plant inspection, emergence trap, sticky trap, and non-sticky trap. Whole plant inspection consisted of counting the numbers of Mexican corn rootworm adults on 5 randomly selected plants. This is considered the standard method to use for estimating adult abundance (Steffey et al. 1982). Emergence traps were modified, conical wire-screen pecan weevil, *Curculio caryae* (Horn), emergence traps (1 m diameter at base) (Raney and Eikenbary 1969). These traps were designated as the standard for monitoring adult emergence. Sticky traps were Pherocon AM® traps. Pherocon AM® traps were replaced approximately every 10 d or as needed to maintain trap effectiveness (Karr and Tollefson 1987). Non-sticky traps were of the design described by Hesler and Sutter (1993). A non-pheromonal attractant for Mexican corn rootworm was used with the non-sticky traps. This attractant was composed of a 1:1:1 mixture of trimethoxybenzene, indole, and cinnamaldehyde (TIC) (Lance et al. 1992). A dental wick impregnated with 100 mg of this mixture was attached weekly to non-sticky traps. To prevent escape of adults from non-sticky traps, a toxic bait, Slam® (Microflo Company, Lakeland, FL), was placed in the top of each non-sticky trap, as described by Hesler and Sutter (1993). Pherocon AM® traps and non-sticky traps were yellow in color. Yellow attracts corn rootworm adults and is thought to enhance trap effectiveness (Karr and Tollefson 1987, Hesler and

Sutter 1993). All traps were deployed when corn was in the 5-7 leaf stage of development. Plants under emergence traps were trimmed to fit under the trap (Fisher 1984). Sticky traps and non-sticky traps were mounted at corn ear height on PVC pipes (2 cm outer diameter by 120 cm long) inserted in the middle of rows.

In 1995, experiments were conducted in 2 commercial corn fields. Corn was planted in rows 96 cm apart, with ≈54,400 plants per hectare in each field. Two rows 50 m apart were selected in each field. Five sites were selected in each row. Sites were 10 m long and 50 m from any other site. All 4 methods were used at each site. Monitoring was initiated on 12 May 1995 and terminated on 26 June. Plants were inspected and Mexican corn rootworm adults removed from traps 3 times weekly.

In 1996, monitoring methods were evaluated in 8 commercial corn fields. Row spacing and plant density in fields were similar to those in 1995. Again, 2 rows 50 m apart were selected in each field. Sites were of the same dimension as in 1995, but were 0, 10, 60, 110, and 160 m from the field border. All 4 monitoring methods were used at each site. Sampling was initiated on 19 May 1996 and terminated on 9 July. Plants were inspected and Mexican corn rootworm adults removed from traps twice weekly. Because observations of adult behavior in 1995 suggested that plant phenology may have influenced accuracy of some of the monitoring methods for detecting abundance of corn rootworm adults, plant phenology was recorded twice weekly in 1996 as pre-flowering, flowering, or post-flowering. Plants were considered to be pre-flowering during vegetative growth, flowering if ≥10% of plants had green silks, and post-flowering if ≥90% had dry silks.

Data for each year were pooled across sites for each field and sample date and subjected to regression analysis using PROC REG (SAS Institute 1990). Data were log transformed before regression analysis to stabilize the variance component. For data from 1995, numbers of adults captured in sticky traps and non-sticky traps were regressed against numbers of adults found by plant inspection and numbers of adults captured in emergence traps. Additionally, numbers of adults found by inspecting plants were regressed against the numbers of adults captured in emergence traps. Similar analyses were conducted for data collected during 1997, except a dummy variable representing corn growth stage was included in the regression models. Relationships among monitoring methods were examined to identify methods that best described abundance and emergence of Mexican corn rootworm adults, where plant inspection was the standard method to assess adult abundance and emergence traps were the standard method to assess adult emergence. In 1995, Slam® was applied on 14 June to control adults in 1 field used in the monitoring experiment. In 1996, Slam® was applied on 22 June to 4 fields used in the monitoring experiment. These applications were made in conjunction with an areawide management program for Mexican corn rootworm in Bell County, TX. Slam® was applied as large droplets (500–700 micron volume median diameter) to the top of the corn canopy (Hoffmann et al. 1996). Application of insecticide decreased the numbers of Mexican corn rootworm adults found by inspecting plants and that were captured in sticky and non-sticky traps. However, because adults captured in emergence traps emerged from the soil and did not come in contact with Slam®, their numbers were not reduced. Therefore, data from treated fields after application of Slam® were excluded from regression analyses. The coefficient of variation, $(s/\bar{x})*100$, was used as an estimate of relative precision for each monitoring method for data collected during 1995 and 1996 (Steffey 1982). In addition to regression analyses, 1996 data were analyzed as a randomized block design with distance from the field border as a treatment factor. Data were *ln* (X+1) transformed to stabilize the variance component and subjected to analysis of variance using the General Linear Models procedure (SAS Institute 1990). Means for each distance from the field border for each of the monitoring methods were separated using Tukey's Honestly Significant Difference test (HSD) to determine the optimal placement of traps from field borders.

Results and Discussion

Regression analyses of 1995 data are shown in Table 4.1. A significant relationship was detected between the numbers of Mexican corn rootworm adults found by plant inspection and the numbers of adults captured in emergence traps ($r^2 = 0.5582$; $P < 0.01$; $n = 22$). All other regression analyses of 1995 data produced non-significant results. In 1996, numbers of adults found by inspecting plants were significantly related to numbers of adults captured in emergence traps ($r^2 = 0.4969$; $P < 0.01$; $n = 75$), sticky traps ($r^2 = 0.2678$; $P < 0.01$; $n = 75$), and non-sticky traps ($r^2 = 0.2968$; $P < 0.01$; $n = 75$) (Table 4.2). Significant relationships also were found between numbers of adults captured in emergence traps and those captured in sticky traps ($r^2 = 0.1613$; $P < 0.01$; $n = 75$) and in non-sticky traps ($r^2 = 0.2069$; $P < 0.01$; $n = 75$). A significant parameter estimate for the dummy variable used to account for the effects of corn growth stage on relationships among

Table 4.1. Regression equations describing relationships between plant inspection counts (*Y*) and trap captures (*X*), and between emergence trap captures (*Y*) and sticky and non-sticky trap captures (*X*), Bell County, TX, 1995[a]

Monitoring method	Linear equation	Probability > *F*	r^2	Probability > |*t*| b_0	Probability > |*t*| b_1
	Plant inspection counts				
Emergence trap	$Y = 0.4417 + 0.6318X_l$	0.0001	0.5582	0.0007	0.0001
Sticky trap	$Y = 0.5371 + 0.1708X_l$	0.1015	0.1226	0.0253	0.1015
Non-sticky trap	$Y = 0.4908 + 0.1396X_l$	0.1237	0.1019	0.0745	0.1237
	Emergence trap captures				
Sticky trap	$Y = 0.7931 - 0.0551X_l$	0.6148	0.0107	0.0020	0.6148
Non-sticky trap	$Y = 0.6745 + 0.0144X_l$	0.8943	0.0008	0.0452	0.8943

[a]Data were *ln* (*X*+1) transformed before analysis.

Table 4.2. Regression equations describing relationships between plant inspection counts (Y) and trap captures (X), and between emergence trap captures (Y) and sticky and non-sticky trap captures (X) using corn growth stage as a dummy variable, Bell County, TX, 1996[a]

				Probability > $\|t\|$		
Monitoring method	Linear equation	Probability > F	r^2	b_0	b_1	b_2
	Plant inspection counts					
Emergence trap	$Y = 0.0973 + 0.6806X_1 + 0.2441X_2$	0.0001	0.4969	0.4193	0.0001	0.0001
Sticky trap	$Y = 0.5736 + 0.3672X_1$	0.0001	0.2678	0.0001	0.0001	NS[b]
Non-sticky trap	$Y = 0.0491 + 0.2051X_1 + 0.1854X_2$	0.0001	0.2968	0.7596	0.0001	0.0104
	Emergence trap captures					
Sticky trap	$Y = 0.7063 + 0.3075X_1 - 0.2647X_2$	0.0016	0.1613	0.0001	0.0008	0.0039
Non-sticky trap	$Y = 0.0494 + 0.1880X_1$	0.0001	0.2069	0.6566	0.0001	NS

[a]Data were *ln* (X+1) transformed before analysis.
[b]Non-significant.

monitoring methods was produced when numbers of adults found by inspecting plants was compared to those captured in emergence traps and non-sticky traps, and when numbers of adults captured in emergence traps were compared to those captured in sticky traps. In both 1995 and 1996, the strongest relationship was between numbers of adults found by plant inspection and those captured in emergence traps. These results are similar to those obtained by Matin et al. (1984) who found numbers of northern corn rootworm adults captured in emergence traps were correlated more closely to the numbers of adults found by plant inspection than to the numbers of adults captured in sticky traps.

Figure 4.1 displays the seasonal abundance and emergence patterns of Mexican corn rootworm adults found by using each of the monitoring methods in 1995 and 1996. This figure also illustrates when the different corn growth stages occurred during 1996. Examination of this figure confirms that numbers of adults found by inspecting plants and those captured in emergence traps were the most closely related. Further examination of Fig 4.1 shows that in 1995 and 1996, abundance peaks for adults captured in sticky and non-sticky traps occurred after those for plant inspection and emergence traps. Seasonal variations in 1996 of Mexican corn rootworm abundance in sticky traps and non-sticky traps seem related to the time of flowering of corn plants. Corn flowering began on 3 June 1996 and was completed by 20 June. During corn flowering, numbers of adults captured in sticky and non-sticky traps were at their lowest, whereas those found in emergence traps and by inspecting plants were at their peak. Non-pheromonal attractants have been shown to be less attractive to corn rootworm

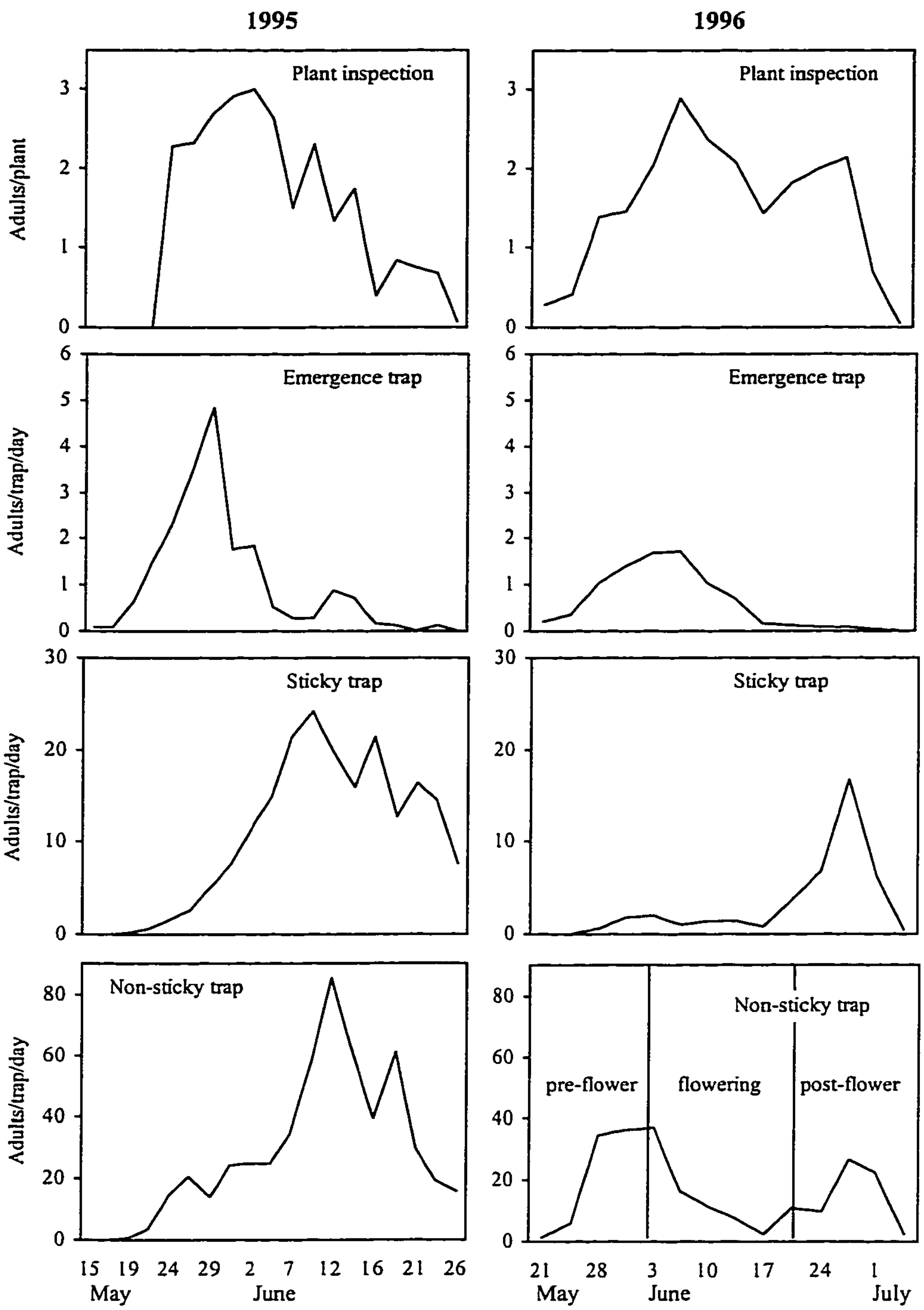

Fig. 4.1. Corn growth stage and seasonal abundance and emergence patterns of Mexican corn rootworm adults monitored by using different sampling methods, Bell County, TX, 1995 and 1996.

adults when corn is silking (Lance and Elliot 1991, Hammack and Hesler 1995). Lance and Elliot (1991) suggested this was a result of competition between the food-based attractants and corn silk, a preferred food of corn rootworm. A similar phenomenon may be influencing the capture of adults in sticky traps. The yellow color of these traps may be relatively more attractive when the food sources for corn rootworms are limited.

Further discussion is warranted by the finding in 1996 that the numbers of adults captured in sticky traps and in non-sticky traps were significantly related to both the numbers of adults found by plant inspection and captured in emergence traps. Improvements in design and composition of the attractant used in non-sticky traps could strengthen these relationships. The non-pheromonal attractant mixture, TIC, used in non-sticky traps in this study was applied at a rate of 100 mg per dental wick. Other studies demonstrated a strong dose-dependent response for western corn rootworm adults and non-pheromonal attractants between the rates of 1 and 100 mg per wick (Andersen and Metcalf 1986, Lampman et al. 1987, Lance 1990). Andersen and Metcalf (1986) found that 30% of 1 TIC component, indole, dissipated from plastic xerographic transparencies within 2 h of application. In the present study, dental wicks impregnated with the non-pheromonal attractant were replaced weekly, which may have been too infrequent to avoid a dose response in Mexican corn rootworm adults. Recent studies identified several compounds from corn that are attractive to western corn rootworm and northern corn rootworm (Hammack 1997, Hibbard et al. 1997). Incorporation of these compounds or sex pheromones into the attractant mixture may increase the strength of the relationships tested here, and the reliability of non-sticky traps in trapping corn rootworm adults. Using such attractants with sticky traps also may improve the accuracy and reliability of these traps for assessing corn rootworm adult abundance and emergence patterns. However, Steffey et al. (1982) found that the cost in human hours was much greater for sticky traps, 13.9, than for plant inspection, 2.3. Cost analyses were not conducted in the present study because the non-sticky trap used was a prototype design, and design alterations probably will enhance the ease of servicing the traps.

The seasonal mean and coefficient of variation (CV) for each monitoring method in 1995 and 1996 are shown in Table 4.3. Lower CV values are indicative of greater precision. The lowest CV values were for plant inspection in 1995 (61.9) and 1996 (62.5). Coefficients of variation for emergence traps varied from 64.8 in 1995 to 153.7 in 1996. Sticky traps had relatively large CV values in 1995 (96.0) and 1996 (133.1). Non-sticky traps produced intermediate CV values in 1995 (84.7) and 1996 (77.1). Seasonal means generally were greatest for adults captured in non-sticky traps and sticky traps and lowest for those found in emergence traps and by plant inspection. The monitoring methods with greater means produced comparatively greater standard deviation values. As a result, methods such as plant inspection, with smaller standard deviation values as compared to their means, were those with the lowest CV values and, therefore, the most reliable monitoring methods. In addition to being the standard method used for assessing adult abundance, the numbers of adults found using plant inspections were closely related to numbers of adults captured in emergence traps. Also, plant inspection was the most reliable method evaluated. As a result, plant inspection

Table 4.3. Seasonal mean (± standard deviation) and mean percent precision for different Mexican corn rootworm adult monitoring methods, Bell County, TX, 1995 and 1996

Monitoring method	*n*	Seasonal mean[a]	Coefficient of variation[b]
		1995	
Plant inspection	20	1.3 ± 0.79	61.9
Emergence trap	20	1.0 ± 0.67	64.8
Non-sticky trap	20	17.6 ± 14.93	84.7
Sticky trap	20	6.3 ± 6.03	96.0
		1996	
Plant inspection	80	1.1 ± 0.71	62.5
Emergence trap	80	0.6 ± 0.95	153.7
Non-sticky trap	80	12.4 ± 9.58	77.1
Sticky trap	80	1.3 ± 1.77	133.1

[a]Plant inspection means expressed as number of Mexican corn rootworm adults per plant. Emergence trap, sticky trap, non-sticky trap means expressed as number of Mexican corn rootworm adults per trap.

[b]Coefficient of variation = $(s/\bar{x}) \times 100$.

seems the best method to use for monitoring both adult abundance and adult emergence. However, cost analyses, as discussed above, will be the determining factor in selecting the optimal method for monitoring Mexican corn rootworm.

Using a single method to assess Mexican corn rootworm adult abundance and emergence patterns can reduce the cost of monitoring to justify and time applications of foliar insecticide. Additionally, monitoring only near field borders could save time when large areas must be monitored. However, distance from the field border had a significant effect on the numbers of Mexican corn rootworm adults recorded by using each of the monitoring methods (Table 4.4). Significantly fewer Mexican corn rootworm adults were captured per trap per day in emergence traps ($F = 11.25$; df = 4, 1,080; $P < 0.01$) and non-sticky traps ($F = 9.25$; df = 4, 1,080; $P < 0.01$) at the field border than at any other distance. Significantly fewer Mexican corn rootworm adults were captured in sticky traps at the field border than at any other distance except at 10 m ($F = 4.95$; df = 4, 1,080; $P < 0.01$). Significantly fewer Mexican corn rootworm adults were found by plant inspection at the field border than at any other distance ($F = 8.59$; df = 4, 1,080; $P < 0.01$). The average numbers of Mexican corn rootworm adults ≥10 m from the field border were 52, 71, 45, and 44% greater than those found at the field border by using plant inspection, emergence trap, sticky trap, and non-sticky trap, respectively. From these findings, any of these methods used to monitor Mexican corn rootworm adult abundance or emergence should be used ≥10 m from the field border.

Table 4.4. Mean number of Mexican corn rootworm adults per plant and per trap per day (± standard deviation) at different distances from the field border, Bell County, TX, 1996

		Monitoring method[a]			
Distance (m)	*n*	Plant inspection	Emergence trap	Sticky trap	Non-sticky trap
0	224	0.6 ± 1.3 b	0.2 ± 0.7 b	0.8 ± 3.2 b	7.7 ± 22.3 b
10	224	1.2 ± 1.8 a	0.7 ± 1.9 a	1.3 ± 4.3 ab	11.9 ± 23.5 a
60	224	1.3 ± 2.0 a	0.9 ± 2.3 a	1.5 ± 5.6 a	13.4 ± 24.4 a
110	224	1.3 ± 1.8 a	0.7 ± 1.7 a	1.6 ± 4.3 a	15.6 ± 30.4 a
160	224	1.2 ± 1.7 a	0.5 ± 1.2 a	1.4 ± 3.9 a	13.8 ± 25.4 a

Means followed by the same letter in a column are not significantly different ($P < 0.05$, Tukey's HSD [SAS Institute 1990]).

[a]Data were *ln* (X+1) transformed before analysis. However, non-transformed means are presented.

CHAPTER V

SUMMARY AND CONCLUSIONS

Using IPM over a large area, or areawide management, was demonstrated to be an effective strategy for reducing abundance of Mexican corn rootworm adults in corn fields. In 1996, the foliar insecticide Slam® was applied to corn and sorghum fields in a 1,366-ha area where Mexican corn rootworm adult abundance exceeded the treatment threshold of 1 adult per plant. Applications were timed according to adult emergence patterns and the presence of gravid females. Mexican corn rootworm adult abundance was reduced by 99.1% in the 1,366-ha area compared with a non-treated area. In the season following application of foliar insecticide, the number of Mexican corn rootworm adults that emerged from the soil was reduced by 93.5% in the area treated with foliar insecticide compared with a non-treated area. Damage caused by Mexican corn rootworm larvae to corn roots also was reduced significantly compared with that in a non-treated area. Soil insecticide reduced by 52.3% the number of Mexican corn rootworm adults that emerged from the soil and reduced damage to corn roots by larvae. Corn root damage rating scores revealed 2-fold less corn root damage in the foliar insecticide-treated area compared with the non-treated area. Corn roots in soil insecticide-treated plots were 1-fold less damaged than those in non-treated plots. These findings agree with the idea that soil insecticide is not an effective long-term solution for Mexican corn rootworm management (Sutter et al. 1991, Gray et al. 1992) and suggest that Mexican corn rootworm is amenable to areawide management using foliar insecticide. However, corn grain yield was similar in the foliar insecticide-treated and non-treated areas in the season following application of insecticide, but was 7.8% greater in soil insecticide-treated plots than in non-treated plots.

Prolonged diapause of Mexican corn rootworm eggs, survival of larvae on roots of plants other than corn, and oviposition by adults near plant species other than corn were investigated as potential factors contributing to the reported failure of crop rotation using sorghum to prevent damage by Mexican corn rootworm to corn (Stewart et al. 1995). Prolonged diapause of eggs was not detected in the Mexican corn rootworm population sampled. The number of adults that emerged from the soil near sorghum plants was 3.0-11.2% of that from the soil near corn plants. However, the number of eggs found in sorghum did not differ significantly from that found in corn. These findings suggest that Mexican corn rootworm adults oviposited in both corn and sorghum, and that adults in sorghum were immigrants from corn. Crops other than sorghum may be useful for rotation with corn to prevent Mexican corn rootworm damage to corn. The numbers of eggs found in soybean and cotton were 17.7 and 23.9% of those found in corn. Because Mexican corn rootworm adults were attracted most to crops in the flowering stage of growth, manipulation of sorghum planting dates or use of hybrids with shorter flowering periods may decrease the amount of Mexican corn rootworm oviposition in sorghum fields.

These findings also have several implications for areawide management of Mexican corn rootworm. First, monitoring both corn and sorghum would increase costs of an areawide management program. Additionally, cost of applying foliar insecticide would increase if sorghum fields required treatment to reduce abundance of Mexican corn rootworm adults. A 3rd implication is that Mexican corn rootworm adults feeding in crops other than corn may be less susceptible to insecticide. Siegfried and Mullin (1989) found that activities of certain enzymes potentially involved in metabolism of insecticides by northern corn rootworm and western corn rootworm adults differed as a result of corn rootworm feeding on squash blossoms and sunflower inflorescences as opposed to on corn. This change in enzyme activity was accompanied by an increase in susceptibility of western corn rootworm to aldrin but no change in susceptibility of northern corn rootworm (Siegfried and Mullin 1989). Other insects exhibited different levels of susceptibility to insecticides when they fed on different crops. For example, Colorado potato beetle, *Leptinotarsa decemlineata* (Say), larvae reared on tomato, *Lycopersicon esculentum* L., were less susceptible to fenvalerate than when reared on eggplant, *Solanum melongena* L. (Ghidiu et al. 1989). Similarly, Thomas and Boethel (1993) found that soybean looper, *Pseudoplusia includens* (Walker), larvae reared on cotton were less susceptible to permethrin than larvae reared on an artificial diet or on soybean.

Perhaps the greatest obstacle in the adoption of a program for areawide management of corn rootworm is the extensive amount of sampling required to justify and time foliar insecticide applications. Knowledge of corn rootworm adult abundance is necessary to identify fields that require treatment. Information about corn rootworm adult emergence patterns is needed to properly time application of foliar insecticide. Different methods for monitoring Mexican corn rootworm adult abundance and emergence were compared to determine if 1 method could be used alone to assess both abundance and emergence. The standard methods for monitoring corn rootworm adult abundance and emergence are by plant inspection and using emergence traps, respectively. In 1995 and 1996, numbers of adults found by using these methods were compared to those captured in non-baited sticky traps and in non-sticky traps baited with food-based lure. In 1995, the number of adults found by plant inspection were significantly related to that captured in emergence traps. All other relationships investigated with regression analysis provided non-significant results. Because observation of Mexican corn rootworm adult behavior in 1995 suggested that corn flowering influenced relationships among numbers of adults captured in traps, stages of corn growth were recorded in 1996. Including this variable in regression analyses resulted in significant relationships among the monitoring methods evaluated. Numbers of adults found by inspecting plants were significantly related to numbers of adults captured in sticky traps. Numbers of adults captured in emergence traps were significantly related to numbers of adults captured in sticky traps and non-sticky traps. The r^2 values for these relationships revealed that the strongest relationship in 1996 was between numbers of adults found by inspecting plants and numbers of adults captured in emergence traps. Non-sticky traps and whole plant inspections were the most reliable monitoring methods examined, based on coefficients of variation. These findings indicate that whole plant inspection may be used alone to assess both adult abundance and emergence in an areawide management program for corn rootworm. Sticky traps and non-sticky traps, however, showed potential for use in monitoring both Mexican corn rootworm adult abundance and emergence. However, significant advancements in trap design and in lure formulation and release rates probably will be necessary before these methods can be used to reliably monitor Mexican corn rootworm.

REFERENCES CITED

Adee, E. A., E. S. Oplinger, and C. R. Grau. 1994. Tillage, rotation sequence, and cultivar influences on brown stem rot and soybean yield. J. Prod. Agric. 7: 341-347.

Andersen, J. F., and R. L. Metcalf. 1986. Identification of a volatile attractant for *Diabrotica* and *Acalymma* spp. from blossoms of *Cucurbita maximu* Duchesne. J. Chem. Ecol. 12: 687-699.

Beardmore, B. W. 1975. Evaluation of western corn rootworm, *Diabrotica virgifera* LeConte, adult control on an individual field basis as an alternative to the use of soil insecticides in eastern Nebraska. M.S. thesis, University of Nebraska, Lincoln.

Bigger, J. H. 1932. Short rotation fails to prevent attack of *Diabrotica longicornis*. J. Econ. Entomol. 25: 196-199.

Boetel, M. A., D. D. Walgenbach, G. L. Hein, B. W. Fuller, and M. E. Gray. 1992. Oviposition site selection of the northern corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 85: 246-249.

Branson, T. F. 1986. Larval feeding behavior and host plant resistance in maize, pp. 159-182. *In* J. L. Krysan and T. A. Miller [eds.], Methods for the study of pest *Diabrotica*. Springer-Verlag, New York.

Branson, T. F., and J. L. Krysan. 1981. Feeding and oviposition behavior and life cycle strategies of *Diabrotica*: an evolutionary view with implications for pest management. Environ. Entomol. 10: 826-831.

Branson, T. F., and E. E. Ortman. 1967a. Host range of larvae of western corn rootworm. J. Econ. Entomol. 60: 201-203.

Branson, T. F., and E. E. Ortman. 1967b. Fertility of western corn rootworm reared as larvae on alternate hosts. J. Econ. Entomol. 60: 595.

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., and E. E. Ortman. 1971. Host range of larvae of the northern corn rootworm: further studies. J. Kansas Entomol. Soc. 44: 50-52.

Branson, T. F., and J. Reyes-R. 1983. The association of *Diabrotica* spp. with *Zea diploperennis*. J. Kansas Entomol. Soc. 56: 97-99.

Branson, T. F., P. L. Guss, and E. E. Ortman. 1969. Toxicity of sorghum roots to larvae of the western corn rootworm. J. Econ. Entomol. 62: 1375-1378.

Branson, T. F., J. J. Jackson, and G. R. Sutter. 1988. Improved method for rearing *Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae). J. Econ. Entomol. 81: 410-414.

Branson, T. F., J. Reyes-R., and H. Valdes-M. 1982. Field biology of Mexican corn rootworm, *Diabrotica virgifera zeae* (Coleoptera: Chrysomelidae), in Central Mexico. Environ. Entomol. 11: 1078-1083.

Brunoehler, R. 1996. Rootworms wrack first-year corn. Crop Protection Manager, Southern Edition 9: 16-19.

Brust, G. E., and L. R. King. 1994. Effects of crop rotation and reduced chemical inputs on pests and predators in maize agroecosystems. Agric. Ecosystems and Environment 48: 77-89.

Chiang, H. C. 1965. Survival of northern corn rootworm eggs through one and two winters. J. Econ. Entomol. 58: 470-472.

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.

Cinereski, J. E., and H. C. Chiang. 1968. The pattern of movements of adults of the northern corn rootworm inside and outside of corn fields. J. Econ. Entomol. 61: 1531-1536.

Coats, S. A., J. J. Tollefson, and J. A. Mutchmor. 1986. Study of migratory flight in the western corn rootworm (Coleoptera: Chrysomelidae). Environ. Entomol. 15: 620-625.

Cocke, J., Jr., J. W. Stewart, M. Morris, and W. Newton. 1994. Emergence patterns of Mexican corn rootworm, *Diabrotica virgifera zeae*, adults in south and central Texas. Southwest. Entomol. 19: 347-354.

Comis, D. 1997. Corn Belt growers give areawide IPM a try. Agric. Research 45: 4-7.

Davis, P. M., and D. Coleman. 1997. Managing corn rootworms (Coleoptera: Chrysomelidae) on dairy farms: the need for a soil insecticide. J. Econ. Entomol. 90: 205-217.

Fisher, J. R. 1984. Comparison of emergence of *Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae) from cut and uncut corn plants in artificial and natural infestations. J. Kans. Entomol. Soc. 57: 405-408.

Foster, R. E., J. J. Tollefson, J. P. Nyrop, and G. L. Hein. 1986. Value of adult corn rootworm (Coleoptera: Chrysomelidae) population estimates in pest management decision making. J. Econ. Entomol. 79: 303-310.

Frisbie, R. E., H. T. Reynolds, P. L. Adkisson, and R. F. Smith. 1994. Cotton insect pest management, pp. 421-468. *In* R. L. Metcalf and W. H. Luckmann [eds.], Introduction to insect pest management. John Wiley & Sons, New York.

Ghidiu, G. M., C. Carter, and C. A. Silcox. 1990. The effect of host plant on Colorado potato beetle (Coleoptera: Chrysomelidae) susceptibility to pyrethroid insecticides. Pestic. Sci. 28: 259-270.

Godfrey, L. D., and F. T. Turpin. 1983. Comparison of western corn rootworm (Coleoptera: Chrysomelidae) adult populations and economic thresholds in first-year and continuous corn fields. J. Econ. Entomol. 76: 1028-1032.

Godfrey, L. D., L. J. Meinke, and R. J. Wright. 1993. Vegetative and reproductive biomass accumulation in field corn: response to root injury by western corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 86: 1557-1573.

Gray, M. E. 1995. Areawide pest management for corn rootworms: fantasy or realistic expectations?, pp. 101-106. *In* Proceedings, 1995 Illinois Agricultural Pesticides Conference, 3-4 January 1995. University of Illinois, Champaign-Urbana.

Gray, M. E., and W. H. Luckmann. 1994. Integrating the cropping system for corn insect pest management, pp. 507-542. *In* R. L. Metcalf and W. H. Luckmann [eds.], Introduction to insect pest management. John Wiley & Sons, New York.

Gray, M. E., A. S. Felsot, K. L. Steffey, and E. Levine. 1992. Planting time application of soil insecticides and western corn rootworm (Coleoptera: Chrysomelidae) injury. J. Econ. Entomol. 85: 544-553.

Gray, M. E., K. L. Steffey, and H. Oloumi-Sadeghi. 1993. Participatory on-farm research in Illinois cornfields: an evaluation of established soil insecticide rates and prevalence of corn rootworm (Coleoptera: Chrysomelidae) injury. J. Econ. Entomol. 85: 544-553.

Gustin, R. D. 1984. Effect of crop cover on oviposition of the northern corn rootworm, *Diabrotica longicornis barberi* Smith and Lawrence. J. Kansas Entomol. Soc. 57: 515-516.

Halkier, B. A., and B. L. Møller. 1989. Biosynthesis of the cyanogenic glucoside dhurrin in seedlings of *Sorghum bicolor* (L.) Moench and partial purification of the enzyme system involved. Plant Physiol. 90: 1552-1559.

Hammack, L. 1997. Attractiveness of synthetic corn volatiles to feral northern and western corn rootworm (Coleoptera: Chrysomelidae). Environ. Entomol. 26: 311-317.

Hammack, L., and L. S. Hesler. 1995. Seasonal response to phenylpropanoid attractants by northern corn rootworm beetles (Coleoptera: Chrysomelidae). J. Kansas Entomol. Soc. 68: 169-177.

Hein, G. L., and J. J. Tollefson. 1984. Comparison of adult corn rootworm (Coleoptera: Chrysomelidae) trapping techniques as population estimators. Environ. Entomol. 13: 266-271.

Hein, G. L., and J. J. Tollefson. 1985. Use of the Pherocon AM trap as a scouting tool for predicting damage by corn rootworm (Coleoptera: Chrysomelidae) larvae. J. Econ. Entomol. 78: 200-203.

Henneberry, T. J., and J. R. Phillips. 1996. Suppression and management of cotton insect populations on an areawide basis, pp. 601-624. *In* E. G. King, J. R. Phillips, and R. J. Coleman [eds.], Cotton insects and mites: characterization and management. Cotton Foundation Publisher, Memphis, TN.

Hesler, L. S., and G. R. Sutter. 1993. Effect of trap color, volatile attractants, and type of toxic bait dispenser on captures of adult corn rootworm beetles (Coleoptera: Chrysomelidae). Environ. Entomol. 22: 743-750.

Hibbard, B. E., T. L. Randolph, E. J. Bernklau, E. M. Abou-Fakhr, and L. B. Bjostad. 1997. Electroantennogram-active components of maize silk for adults of the western corn rootworm (Coleoptera: Chrysomelidae). Environ. Entomol. 26: 285-295.

Hill, R. E., and Z B Mayo. 1980. Distribution and abundance of corn rootworm species as influenced by topography and crop rotation in eastern Nebraska. Environ. Entomol. 9: 122-127.

Hill, R. E., E. Hixson, and M. H. Muma. 1948. Corn rootworm control 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.

Hoffmann, W. C., P. S. Lingren, J. R. Coppedge, and I. W. Kirk. 1996. Aerial application of Slam®: adult corn rootworm control. Ag-Pilot International 19: 18-20.

Jackson, J. J. 1986. Rearing and handling of *Diabrotica virgifera* and *Diabrotica undecimpuntata howardi*, pp. 25-47. *In* J. L. Krysan and T. A. Miller [eds.], Methods for the study of pest *Diabrotica*. Springer-Verlag, New York.

Johnson, T. B., and F. T. Turpin. 1985. Northern and western corn rootworm (Coleoptera: Chrysomelidae) oviposition in corn as influenced by foxtail populations and tillage systems. J. Econ. Entomol. 78: 57-60.

Karr, L. L., and J. J. Tollefson. 1987. Durability of the Pherocon AM trap for adult western and northern corn rootworm (Coleoptera: Chrysomelidae) sampling. J. Econ. Entomol. 80: 891-896.

Kirk, V. M., C. O. Calkins, and F. J. Post. 1968. Oviposition preferences of western corn rootworms for various soil surface conditions. J. Econ. Entomol. 61: 1322-1324.

Knipling, E. F. 1972. Entomology and the management of man's environment. J. Aust. Entomol. Soc. 11: 153-167.

Kogan, M. 1998. Integrated pest management: historical perspectives and contemporary developments. Annu. Rev. Entomol. 43: 243-270.

Krysan, J. L. 1986. Introduction: biology, distribution, and identification of pest *Diabrotica*, pp. 1-24. *In* J. L. Krysan and T. A. Miller [eds.], Methods for the study of pest *Diabrotica*. Springer-Verlag, New York.

Krysan, J. L., and T. F. Branson. 1977. Inheritance of diapause intensity in *Diabrotica virgifera*. J. Heredity 68: 415-417.

Krysan, J. L., T. F. Branson, and G. D. Castro. 1977. Diapause in *Diabrotica virgifera* (Coleoptera: Chrysomelidae): a comparison of eggs from temperate and subtropical climates. Entomol. Exp. Appl. 73: 123-130.

Krysan, J. L., J. J. Jackson, and A. C. Lew. 1984. Field termination of egg diapause in *Diabrotica* with new evidence of extended diapause in *D. barberi* (Coleoptera: Chrysomelidae). Environ. Entomol. 13: 1237-1240.

Krysan, J. L., D. E. Foster, T. F. Branson, K. R. Ostlie, and W. S. Cranshaw. 1986. Two years before the hatch: rootworms adapt to crop rotation. Bull. Entomol. Soc. Am. 32: 250-253.

Lampman, R. L., R. L. Metcalf, and J. F. Andersen. 1987. Semiochemical attractants of *Diabrotica undecimpuntata howardi* Barber, southern corn rootworm, and *Diabrotica virgifera virgifera* Leconte, the western corn rootworm (Coleoptera: Chrysomelidae). J. Chem. Ecol. 13: 959-975.

Lance, D. R. 1990. Factors affecting capture of corn rootworm beetles (Coleoptera: Chrysomelidae) at traps baited with non-pheromonal attractants. Environ. Entomol. 19: 882-889.

Lance, D. R., and N. C. Elliott. 1991. Seasonal responses of corn rootworm beetles (Coleoptera: Chrysomelidae) to non-pheromonal attractants. J. Entomol. Sci. 26: 188-196.

Lance, D. R., and G. R. Sutter. 1990. Field-cage and laboratory evaluations of semiochemical-based baits for managing western corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 83: 1085-1090.

Lance, D. R., and G. R. Sutter. 1992. Field tests of a semiochemical-based toxic bait for suppression of corn rootworm beetles (Coleoptera: Chrysomelidae). J. Econ. Entomol. 85: 967-973.

Lance, D. R., W. Scholtz, J. W. Stewart, and J. K. Fergen. 1992. Non-pheromonal attractants for Mexican corn rootworm beetles, *Diabrotica virgifera zeae* (Coleoptera: Chrysomelidae). J. Kansas Entomol. Soc. 65: 10-15.

Levine, E., and M. E. Gray. 1994. Use of cucurbitacin vial traps to predict corn rootworm (Coleoptera: Chrysomelidae) larval injury in a subsequent crop of corn. J. Entomol. Sci. 29: 590-600.

Levine, E., and M. E. Gray. 1996. First-year corn rootworm injury: East-central Illinois research progress to date and recommendations for 1996, pp. 3-13. *In* Proceedings, 1996 Illinois Agricultural Pesticides Conference, 3-4 January 1996. University of Illinois, Champaign-Urbana.

Levine, E., and H. Oloumi-Sadeghi. 1996. Western corn rootworm (Coleoptera: Chrysomelidae) larval injury to corn grown for seed production following soybeans grown for seed production. J. Econ. Entomol. 89: 1010-1016.

Levine, E., H. Oloumi-Sadeghi, and C. R. Ellis. 1992a. Thermal requirements, hatching patterns, and prolonged diapause in western corn rootworm (Coleoptera: Chrysomelidae) eggs. J. Econ. Entomol. 85: 2425-2432.

Levine, E., H. Oloumi-Sedeghi, and J. R. Fisher. 1992b. Discovery of multiyear diapause in Illinois and South Dakota northern corn rootworm (Coleoptera: Chrysomelidae) eggs and incidence of the prolonged diapause trait in Illinois. J. Econ. Entomol. 85: 262-267.

Lipps, P. E. 1988. Spread of corn anthracnose from surface residues in continuous corn and corn-soybean rotation plots. Phytopath. 78: 756-761.

Ludwig, K. A., and R. E. Hill. 1975. Comparison of gut contents of adult western and northern corn rootworms in Northeast Nebraska. Environ. Entomol. 4: 435-438.

MacDonald, P. J., and C. R. Ellis. 1990. Survival time of unfed, first-instar western corn rootworm (Coleoptera: Chrysomelidae) and the effects of soil type, moisture, and compaction on their mobility in the soil. Environ. Entomol. 19: 666-671.

Matin, M. A., W. N. Yule, and P. Martel. 1984. Comparison of three methods for sampling northern corn rootworm (Coleoptera: Chrysomelidae) adult populations in two Quebec cornfields (*Diabrotica longicornis barberi*). J. Econ. Entomol. 77: 1344-1348.

Metcalf, R. L. 1986a. Coevolutionary adaptations of rootworm beetles (Coleoptera: Chrysomelidae) to cucurbitacins. J. Chem. Ecol. 12: 1109-1124.

Metcalf, R. L. 1986b. Foreword, pp. vii-xv. *In* J. L. Krysan and T. A. Miller [eds.], Methods for the study of pest *Diabrotica*. Springer-Verlag, New York.

Metcalf, R. L., and R. A. Metcalf. 1994. Attractants, repellants, and genetic control in pest management, pp. 315-354. *In* R. L. Metcalf and W. H. Luckmannr [eds.], Introduction to insect pest management. John Wiley & Sons, New York.

Metcalf, R. L., J. E. Ferguson, R. L. Lampman, and J. F. Andersen. 1987. Dry cucurbitacin-containing baits for controlling Diabroticite beetles (Coleoptera: Chrysomelidae) J. Econ. Entomol. 80: 870-875.

Naranjo, S. E. 1991. Movement of corn rootworm beetles, *Diabrotica* spp. (Coleoptera: Chrysomelidae), at cornfield boundaries in relation to sex, reproductive status, and crop phenology. Environ. Entomol. 20: 230-240.

Norton, D. C., J. Tollefson, P. Hinz, and S. H. Thomas. 1978. Corn yield increases relative to non-fumigant chemical control of nematodes. J. Nematol. 10: 160-165.

Ott, L. 1988. An introduction to statistical methods and data analysis, PWS-Kent Publishing Company. Boston, MA.

Pedigo, L. P. 1994. Introduction to sampling arthropod populations, pp. 1-11. *In* L. P. Pedigo and G. D. Buntin [eds.], Handbook of sampling methods for arthropods in agriculture. CRC Press, Boca Raton, FL.

Peterson, T. A., and G. E. Varvel. 1989a. Crop yield as affected by rotation and nitrogen rate. I. Soybean. Agron. J. 81: 727-731.

Peterson, T. A., and G. E. Varvel. 1989b. Crop yield as affected by rotation and nitrogen rate. III. Corn. Agron. J. 81: 735-738.

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.

Raney, H. G., and R. D. Eikenbary. 1969. A simplified trap for collecting adult pecan weevils. J. Econ. Entomol. 62: 722-723.

Ruesink, W. G. 1980. Introduction to sampling theory, pp. 61-78. *In* M. Kogan and D. C. Herzog [eds.], Sampling methods in soybean entomology. Springer-Verlag, New York.

Sammons, A. E., C. R. Edwards, L. W. Bledsoe, P. J. Boeve, and J. J. Stuart. 1997. Behavioral and feeding assays reveal a western corn rootworm (Coleoptera: Chrysomelidae) variant that is attracted to soybean. Environ. Entomol. 26: 1336-1342.

SAS Institute. 1990. SAS/STAT user's guide, Version 6. 4th ed. SAS Institute, Cary, NC.

Shaw, J. T., J. H. Paullus, and W. H. Luckmann. 1978. Corn rootworm oviposition in soybeans. J. Econ. Entomol. 71: 189-191.

Short, D. E., and R. J. Luedtke. 1970. Larval migration of the western corn rootworm. J. Econ. Entomol. 63: 325-326.

Siegfried, B. D., and C. A. Mullin. 1989. Influence of alternative host plant feeding on aldrin susceptibility and detoxification enzymes in western and northern corn rootworms. Pest. Bioch. Physiol. 35: 155-164.

Siegfried, B. D., and C. A. Mullin. 1990. Effects of alternative host plants on longevity, oviposition, and emergence of western and northern corn rootworms (Coleoptera: Chrysomelidae). Environ. Entomol. 19: 474-480.

Smith, R. F. 1978. History and complexity of integrated pest management, pp. 41-53. *In* E. H. Smith and D. Pimentel [eds.], Pest control strategies. Academic Press, New York.

Smolik, J. D. 1978. Influence of previous insecticidal use on ability of carbofuran to control nematode populations in corn and effect on corn yield. Plant Dis. Rep. 62: 95-99.

Spike, B. A., and J. J. Tollefson. 1988. Western corn rootworm (Coleoptera: Chrysomelidae) larval survival and damage potential to corn subjected to nitrogen and plant density treatments. J. Econ. Entomol. 81: 1450-1455.

Spike, B. A., and J. J. Tollefson. 1989a. Relationship of plant phenology to corn yield loss resulting from western corn rootworm (Coleoptera: Chrysomelidae) larval injury, nitrogen deficiency, and high plant density. J. Econ. Entomol. 82: 226-231.

Spike, B. A., and J. J. Tollefson. 1989b. Relationship of root ratings, root size, and root regrowth to yield of corn injured by western corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 82: 1760-1763.

Spike, B. A., and J. J. Tollefson. 1991. Yield response of corn subjected to western corn rootworm (Coleoptera: Chrysomelidae) infestations and lodging. J. Econ. Entomol. 84: 1585-1590.

Stamm, D. E., Z B Mayo, J. B. Campbell, J. F. Witkowski, L. W. Andersen, and R. Kozub. 1985. Western corn rootworm (Coleoptera: Chrysomelidae) beetle counts as a means of making larval control recommendations in Nebraska. J. Econ. Entomol. 78: 794-798.

Starr, J. L., R. J. Newton, and F. R. Miller. 1984. Presence of dhurrin in sorghum root tissue and the effect of pathogenesis on hydrogen cyanide potential. Crop Sci. 24: 739-742.

Steffey, K. L., M. E. Gray, and D. E. Kuhlman. 1992. Extent of corn rootworm (Coleoptera: Chrysomelidae) larval damage in corn after soybeans: search for the expression of the prolonged diapause trait in Illinois. J. Econ. Entomol. 85: 268-275.

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

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

Stewart, J. W., J. Cocke, Jr., J. Taylor, and R. Williams. 1995. Mexican corn rootworm emergence from corn fields where sorghum was grown the previous season. Southwest. Entomol. 20: 229-230.

Strnad, S. P., and M. K. Bergman. 1987. Movement of first-instar western corn rootworms (Coleoptera: Chrysomelidae) in soil. Environ. Entomol. 16: 975-978.

Sutter, G. R., T. F. Branson, J. R. Fisher, and N. C. Elliott. 1991. Effect of insecticides on survival, development, fecundity and sex ratio in controlled infestations of western corn rootworm (Coleoptera: Chrysomelidae). J. Econ. Entomol. 84: 1905-1912.

Sutter, G. R., J. R. Fisher, N. C. Elliott, and T. F. Branson. 1990. Effect of insecticide treatments on root lodging and yields of maize in controlled infestations of western corn rootworms (Coleoptera: Chrysomelidae). J. Econ. Entomol. 83: 2414-2420.

Thomas, J. D., and D. J. Boethel. 1993. Diet influences on permethrin susceptibility and growth of soybean looper larvae (Lepidoptera: Noctuidae). J. Econ. Entomol. 86: 1236-1240.

Tollefson, J. J. 1990. Comparison of adult and egg sampling for predicting subsequent populations of western and northern corn rootworms (Coleoptera: Chrysomelidae). J. Econ. Entomol. 83: 574-579.

Tollefson, J. J., and D. D. Calvin. 1994. Sampling arthropod pests in field corn, pp. 433-473. *In* L. P. Pedigo and G. D. Buntin [eds.], Handbook of sampling methods for arthropods in agriculture. CRC Press, Boca Raton, FL.

Tonhasca, A., Jr., and B. R. Stinner. 1991. Effects of strip intercropping and no-tillage on some pests and beneficial invertebrates of corn in Ohio. Environ. Entomol. 20: 1251-1258.

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: 1615-1619.

Weiss, M. J., K. P. Seevers, and Z B Mayo. 1985. Influence of western corn rootworm larval densities and damage on corn rootworm survival, developmental time, size and sex ratio (Coleoptera: Chrysomelidae). J. Kans. Entomol. Soc. 58: 397-402.

Weissling, T. J., and L. J. Meinke. 1991. Potential of starch encapsulated semiochemical-insecticide formulations for adult corn rootworm (Coleoptera: Chrysomelidae) control. J. Econ. Entomol. 84: 601-609.

Wilson, L. T., P. J. Trichilo, S. Bozkurt, P. K. Tapadiya, D. R. Rummel, S. C. Carroll, J. E. Slosser, T. W. Fuchs, and R. E. Frisbie. 1994. Impact of boll weevil migration on selection of eradication strategies for Texas. Proc. Beltwide Cotton Conf. 2: 975-980.

VITA

Peter Scott Lingren was born in 1971 in Tallahassee, FL. He graduated in 1989 from Atoka High School in Atoka, OK. In 1993, he received a Bachelor of Science Degree in Entomology from Oklahoma State University. Scott was awarded a Master of Science Degree in Entomology from Louisiana State University in 1995. He was married to Kimberly Dawn Dodds in March of 1998 and is currently a candidate for the Doctor of Philosophy Degree in Entomology at Texas A&M University. Scott was employed in May of 1998 by Zeneca Ag Products in Visalia, CA.