REVIEW OF DISTRIBUTION, BIOLOGY AND CONTROL METHODS OF SIX MAJOR INSECT PESTS OF CORN IN THE UNITED STATES

by

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INTRODUCTION

Corn (Zea mays L.) grows over a wider geographical range and over a wider range of environments than any other cereal. Corn ranks second in world cereal production and third in production among the developing countries (Hanson 1974).

The United States is first in corn production in the world. Among the American grain crops, corn ranks at the top in acreage, in tonnage, and in total value of production (Anonymous 1975h; Butz 1973). The latest statical data show a corn yield for grain of 4,651,167,000 bushels, which is equivalent to a current monetary value of $13,716,772,000 (Anonymous 1975g).

Corn is grown throughout the United States. However, the major region is the "Corn Belt" of the North Central Region, centering in Iowa, Illinois, and Indiana, and including adjoining states. For the past 3 years, the leading states in corn grain production have been Iowa, Illinois, Nebraska, Indiana, and Minnesota. These five states produced 62 percent of the total grain in 1974 (Anonymous 1975h).

In Kansas, for many years corn for grain production was largely limited to the northeastern part of the State which comprises the southwest edge of the Corn Belt. But gradually irrigation has increased corn acreage from, for example, a yield of 62,100,000 bushels in 1963 to 131,480,000 bushels in 1974, largely as the result of irrigation in southwestern Kansas (Anonymous 1975g).

The annual reports of the Division of Entomology, Kansas State Board of Agriculture (Anonymous 1975i), lists 13 species of insects on corn with a combined control cost and loss of 4.203% of total crop value in 1974 (Table 1).*

Although more than 225 species of insects have been recorded to feed on corn, relatively few have been shown to cause serious economic damage (Neiswander 1931). The most important insect pests of corn in the United States are: European corn borer Ostrinia nubilalis (Hübner), northern corn rootworm Diabrotica longicornis (Say), western corn rootworm Diabrotica virgifera LeConte, corn earworm Heliothis zea (Boddie), fall armyworm Spodoptera frugiperda (J. E. Smith), and southwestern corn borer Diatraea grandiosella Dyar (Burkhardt 1971).

The objective of this study was twofold. One objective was to study 6 selected, important corn insect pests, with varying life cycles, habits, ecology and control, including both literature and personal observations of work on some of the species being conducted in the laboratories of the Department of Entomology at Kansas State University as well as associated field studies. The second objective was to learn more about insects in an agricultural area where insects, crops and control methods differ from Peru where corn is not a major crop. Much can be gained by examining insect pest studies in unrelated areas because there is a natural tendency for people working on the same crop (corn, beans, potatoes or most any other crops) to exchange ideas with each other, rather than gaining new ideas from other areas of study.

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* See Appendix for Tables.

There follows a *brief outline* of the 6 species studied. The body of this paper then considers each in more detail.

The European corn borer, a foreign pest that was accidentally introduced to this country, has become the most injurious insect enemy of corn in the United States. Today it currently occurs in 40 states and is spreading farther south and west every year (Brindley et al. 1975).

Next are the northern and western corn rootworms, both natives of the United States. Their economic importance varies among geographical areas. Although the northern species was at one time the most serious in the Corn Belt states, it is being replaced rapidly by the western corn rootworm. The western species which was first discovered in Kansas and reported as an economic pest of corn in Colorado in 1909, and is now moving toward all over surrounding areas but mainly eastward into most of the Corn Belt states (Anonymous 1974a, 1974b).

The corn earworm is another native species of America but is widespread in many parts of the world. It has many other hosts; for example in Kansas, it attacks tomatoes (tomato fruit worm) and the young grain heads *of sorghum.* It is not as injurious to field corn, but it is the number one pest of sweet corn. It is currently distributed all over the United States; wherever corn is grown it can be found.

The fall armyworm, a close relative of the corn earworm, is an important pest, particularly in southern states where it commonly has from six to eleven generations annually (Little 1963). It has a wide range of plant hosts, including grasses. However, its northward range is limited by cold winter temperatures. Thus infestations in northern areas are the result of migrations of adult moths from the south. Rose et al. (1975) found that they migrate annually from areas of the Mississippi valley, to as far north as Sault Ste. Marie (Canada).

The southwestern corn borer, originally confined to Mexico, had reached into southwestern areas of the United States about the same time that European corn borer was spreading into the Corn Belt. In past years its northern boundary was determined by the degree of exposure of overwintering larvae to winter temperatures, and by the amount and intensity of corn grown. Today it is expanding rapidly eastward from Arkansas and Missouri to central Alabama, Tennessee and Kentucky, and northward as far as south-central Nebraska. It is now currently found in 15 states.

The above mentioned insects have been investigated by a number of workers under widely different environmental conditions. During the early years, the research was directed largely toward studies on biology and the development of control measures that were cultural, biological, and mechanical as well as chemical. Since most of these control approaches have been shown often to be ineffective, or even harmful on occasion to other living organisms (chemicals), research has changed toward exploring other possible or probable means of control such as host plant resistance, genetic manipulation, pheromonal disruption and use of microbial and other biological control agents. The most consistent and effective control of these insects would be achieved by means of a pest management system, i.e., utilizing all suitable techniques and methods of control to the degree needed, and in the most effective combination, which must be closely associated with environmental factors and the population dynamics of the pests. This primarily requires detailed information about the biology, ecology and behavior, as well as possible control approaches, of the target insect. Because literature on these aspects is so extensive, and published in many different papers, this report brings together the most important findings from the past and up to date, in regard to biology and methods used to control these 6 major insect pests of corn.

LITERATURE REVIEW

European Corn Borer

Distribution and Abundance in the U.S.A.

The European corn borer, the most destructive pest of corn in the U.S.A., was first found in 1917 by Vinal (Sparks et al. 1967) on sweet corn near Boston, Massachusetts.

The possible source of entry into the U.S.A. was investigated by Smith (Brindley and Dicke 1963) who concluded that the most probable carrier was broom corn from Hungary or Italy between 1909 and 1914.

In 1919 the borer was observed in areas near Schenectady, and Silver Creek, New York (Everett et al. 1958). By 1924 it had spread throughout the New England area including eastern Massachusetts, New Hampshire, southern Maine, most of Rhode Island and Connecticut (Caffrey and Worthley 1927). While the spread westward was gradual, in 1921 it was reported in Ohio and southern Michigan, and in 1938 the borer reached Wisconsin (Everett et al. 1958).

During the early infestation period the insect had one generation each year (Baker and Bradley 1948), but in the late thirties a two-generation corn borer appeared and it became predominant in the infested areas (Anonymous 1972).

After establishing two generations per year, the insect spread rapidly across the United States east of the Rocky Mountains, presently its western limit. It also spread northward into North Dakota and southward into Missouri and Arkansas and reached as far as the Gulf States of Mississippi. Alabama and Georgia (Anonymous 1972; Brindley and Dicke 1963; Burkhardt 1971). Recently Brindley et al. (1975) indicated its probable presence in Florida.

Chiang (1972) studied in detail the dispersion of the borer in Minnesota and in South Dakota from 1945 to 1970 and suggested that after the initial invasion in 1943, two distinctly different populations could have invaded Minnesota, one in 1952 and the other in 1966. Chiang and Hodson (1972) reported that populations in a certain area of Minnesota could be kept at relatively low levels by environmental factors, but that with favorable temperature the borer population could return to an economically significant level.

Details of its distribution and abundance were reported by Anonymous (1972), Brindley and Dicke (1963), and Everett et al. (1958).

Taxonomic Status

In 1876 Hübner (Caffrey and Worthley 1927) originally described the European corn borer and named separately the male and female moths as Pyralis nubilalis and Pyralis silacealis, respectively. Subsequently, the synonymy was subject to a series of changes (Caffrey and Worthley 1927). A great number of publications appeared between 1917 and 1960 under the name of Pyrausta nubilalis (Hübner) (Brindley and Dicke 1963). Marion (Brindley and Dicke 1963) reviewed the taxonomic status of the European corn borer and placed nubilalis in the genus Ostrinia. This change has been accepted and adopted in recent literature. Thus the current scientific name of the European corn borer is Ostrinia nubilalis (Hübner). It belongs to subfamily Pyraustinae, family Pyralidae, and order Lepidoptera (Borror and DeLong 1971; Sparks et al. 1967).

Biology, Ecology and Behavior

General Description of the Insect. The adult female moths are a pale yellowish brown with irregular, darker bands running in wavy lines across the wings. They have a robust body and a wing spread of about 32 mm. The males are distinctly darker, having the wing heavily marked with olive brown. They are slightly smaller and more slender bodied than the females (Anonymous 1967; Burkhardt 1971; Little 1963).

Eggs are round, nearly flat and about 1 mm in diameter. They are white when first laid but prior to hatching they become dark. Eggs are usually found in masses overlapping, much like small fish scales (Baker and Bradley 1948; Metcalf and Flint 1962; Peairs and Davidson 1961).

Newly hatched larvae are about 1.60 mm long, and have a black head and a white to pale yellow body bearing several rows of small brown or black spots. The full-grown larvae are about 25 mm long, gray to light brown or pink, and faintly spotted on the dorsal surface (Anonymous 1967; Burkhardt 1971; Caffrey and Worthley 1927).

Pupae are yellowish brown to dark reddish brown. The average length of the male pupae is 13 to 14 mm, and female pupae 16 to 17 mm (Caffrey and Worthley 1927; Metcalf and Flint 1962).

Life History. The life history is so well known that little may need be said in this paper. However, an attempt will be made to outline briefly the more important facts.

It spends the winter as full-grown larvae in old corn stalks, corn cobs, stubble, or other hostplant remnants (Baker and Bradley 1948). When temperatures warm, that is, exceeding 10°C, overwintering larvae resume development in late April or early May in southern states and in late May in northern states (Anonymous 1967, 1972; Fry 1972). Pupation takes place at the end of May and emergence occurs in about 10 to 15 days (Metcalf and Flint 1962). Soon afterwards the females begin to lay eggs, usually during the warm and calm evenings (Baker and Bradley 1948).

Moths prefer the tallest or most advanced corn plants for oviposition (Frye 1972; Patch 1942). The eggs, in clusters of 15 or 30 overlapping like fish scales, are normally deposited near the midribs on the underside of corn leaves (Anonymous 1972; Little 1963). Female moths may live from 6 to 24 days during which time each individual may lay up to 1900 eggs, the average about 400 (Burkhardt 1971). The eggs may hatch in 3 to 7 days depending on weather conditions (Anonymous 1967).

Obviously, the biological relationships between the insect and the corn plant are not the same for all generations (Guthrie 1974). During the oviposition period of the first generation, most field corn in the Corn Belt states is in the whorl stage of plant development. Thus the newly hatched larvae move into whorl and feed on the spirally rolled leaves where they cause a characteristic "pinholing" injury. The 1st and 2nd instar larvae are usually found in the whorl (Chiang and Hodson 1953; Everett et al. 1958; Guthrie et al. 1960). As the plant grows out of the whorl stage, the larvae develop to the 3rd and 4th instars, and feed primarily on sheath and collar tissue. The 5th and 6th instars bore extensively in the stalk (Burkhardt 1971; Guthrie et al. 1960). Larvae of the second generation appear when the corn plants have tasseled and completed the pollen-shedding stage. The 1st four instar larvae feed on pollen accumulation at the axils of the leaves as well as on sheath, collar, earshoots, husk, and silk tissue (Dicke 1950; Everett et al. 1958; Guthrie et al. 1970), whereas the 5th and 6th instar larvae bore into the stalks, shanks, or ears (Burkhardt 1971).

Upon completion of feeding, the majority of the larvae of the first generation may change to pupae during summer; the rest of them may either die or eventually go into diapause. Whereas many larvae of the 2nd generation change into diapause before cold weather, others may die or also pupate (Burkhardt 1971; Metcalf and Flint 1962). Diapause stage of larvae will be discussed in a following topic.

Pupation generally occurs in the stalk, or ear, or even on the leaves (Anonymous 1967).

The number of generations of the European corn borer per year varies with climatic conditions from one geographic location to another. In North Dakota and Minnesota, generally a single, complete generation occurs, and individuals of the 2nd generation are often killed by low temperatures (Chiang and Hodson 1959; Frye 1972). According to Guthrie (1974), two complete generations occur in the Corn Belt states, although in Iowa a partial 3rd generation has been reported by Showers and Reed (1971).

In the eastern and southern states, more than two generations occur a year. According to Baker and Bradley (19 8), in Virginia the corn borer has 3 generations annually. Also three complete generations occur in Alabama, Georgia (Eden 1956), and in Missouri (Jackson and Peters 1961). and recently 4 generations of the European corn borer has been reported in South Carolina (Durant 1969).

Mating and Pheromone Studies. Mating by the European corn borer moths takes place within the 24 hours after emergence. It usually occurs at dusk, a period when these insects are most active (Burkhardt 1971). The mechanism of copulation of the species has been reported by Pesho (1961), Poos (1927), Showers et al. (1974b) and Sparks (1963).

Several factors have been reported to affect mating behavior of the European corn borer. Sparks (1963) recorded the interaction of temperature and mating when he observed that copulation was achieved by exposing adults to a falling temperature in phase with a light-dark 14:10-hr photoperiod. Loughner and Brindley (Brindley et al. 1975) studied in detail the effects of photoperiod, thermoperiod, and other environmental factors on mating behavior of the borer. Further, Showers et al. (1974 found that temperature plateaus (constant temperatures) for more than 2 hr per night with RH 70-96% significantly increased the mating activity in the species.

Observations of mating behavior of the European corn borer (Sparks 1963) led to investigations of sex attractants in this species. Klun (1968) was first in showing the existence of a sex pheromone in the female moths. Klun and Brindley (1970) identified it as Cis-11-tetradecenyl acetate (Z-11-tda), which was a strong electron captor, soluble in polar organic solvents and a nonsaponifiable compound. Further, showers et al (1974a) reported that Cis-11-tetradecenyl acetate (Z-11-tda) enabled females to detect and seek out the males from considerable distances. In contrast, Klun and Robinson (1971) showed that the opposite geometrical isomers, trans-11-tetradecenyl acetate (E-11-tda), and 11-tetradecenyl acetate (11-tdya) both inhibited the sex attraction of the European corn borer. Nevertheless, subsequent experiments showed elicitation of a sex attraction response by a combination of geometrical isomers (Z-11-tda, and E-11-tda) (Klun and Robinson 1972). Also, males at different geographic sites in the United States were found to respond to opposite isomeric blends of 11-tda. Roelofs et al. (1972) reported that the male European corn borers in New York were attracted to E-11-tda that contained only traces of the Z isomer. Whereas, Klun et al. (1973) indicated that males in Iowa were attracted to Z-11-tda that contained only traces of the E isomer. Recently Kochansky et al. (1975) found that the sex pheromone of the European corn borer population from New York was an isomeric blend of 96 and 4 per cent of E-11-tda and Z-11-tda, respectively. Elsewhere, Klun and cooperators (1975b) r orted that male corn borers at most locations in the United States were most attracted to the 97:3 Z:E blend of 11-tda, while males from the northeastern area were most attracted to 3:97 Z:E, and those males from Pennsylvania and New Jersey exhibited extensive heterogeneity in their responsiveness to the isomer formulations. However, Carde et al. (1975) reported that males in Pennsylvania were attracted maximally to isomeric blends of 97:3 and 2:98 of Cis and trans-11-tetradecenyl acetates. Thus, they suggested the coexistence of 2 distinct populations of this species in the locality.

Attempts of population suppression of the European corn borer by disruption of the sex attraction behavior have been recently reported in the literature. Klun et al. (1975a) showed that microencapsulated (E)-11-tetradecenyl acetate or 11-tetradecenyl acetate, distributed in the field, significantly suppressed the sex attraction of the European corn borer. In addition, they indicated that both compounds were almost equivalently effective. However, these chemicals only disrupted distance communication of the corn borer and had no suppressive influence on the release of male precopulatory behavior (Klun and Robinson 1971).

Diapause Studies. The European corn borer (*Ostrinia nubilalis* (Hübner) has a facultative diapause and enters it as a full-grown larvae (Burkhardt 1971). Diapause has been found to be enforced in the species by endocrinological failure of the neurosecretory cells of the brain (Clautier 1964).

Several ecological factors are involved in regulating the development of diapause of the corn borer. Beck and Hanec (1960) studied diapause under controlled dietary, photoperiod and temperature conditions. They found three prominent characteristics; namely, arrested gonadal development, failure to pupate shortly after cessation of larval feeding, and reduction of oxygen consumption in mature larvae entering diapause. Sparks et al. (1966a) studied 3 populations (Minnesota, Iowa and Missouri) of the European corn borer, and found that diapause of the species was governed by a multigenetic makeup which responded to temperature and photoperiod. Showers et al. (1975) investigated the influence of the interaction between photoperiod and temperature on the diapause response in different locations of the United States. The authors found that in the south, increasing temperature overrode photoperiod (shorter photophase, longer scotophase) and diapause borer was reduced. Whereas, in the north, photoperiod (longer photophase, shorter scotophase) overrode decreasing temperature, but again the result was a reduction in diapause. In addition, they indicated that the highest percentage diapause occurred at the latitude where the photoperiod-temperature interaction was most severe.

Physiological and some biochemical characteristics of diapause larvae have been reported in the literature. Hayes et al. (1972) showed substantial differences in the abilities of diapausing vs nondiapausing larvae to synthesize and incorporate DNA and RNA precursor-type macromolecules. Beck and Alexander (Beck et al. 1965) demonstrated that the ileal epithelium of the borer's anterior intestine secreted a developmental hormone called "proctodone" that may play an important role in diapause development and prepupal morphogenesis. Beck et al. (1965) found that proctodone was photoperiodically sensitive on a rhythmic basis. Moreover, they suggested that proctodone function might be associated with one of the basic elements of the insect's photoperiodic system. Cloutier (1964) reported that termination of diapause in the European corn borer was dependent on reactivation of the endocrine system. When this occurred physiological activity increased at the cell level and resulted in morphogenic changes associated with pupation and emergence.

Ecotypes of the Corn Borer. European corn borer populations have been examined for the presence of geographic strains since the early 1920s. Results of the earlier experiments have been reviewed by Arbuthnot (1944), Brindley and Dicke (1963), and Sparks et al. (1966a). Subsequently, a highly successful cooperative involving several North Central States has demonstrated that the European corn borer can be separated into several biotypes on the basis of differential responses to diapause, survival, and feeding habits (Chiang et al. 1968; Showers et al. 1972; Sparks et al. 1966a, 1966b). Morphometric differences involving five characters (length of Cu_1 of the hind wing, width of scutellum I, length of basisternum II, length of tegula, and length of tibia III) were used by Kim et al. (1967) to separate borers from four locations (Minnesota, Iowa, Missouri, and Ohio) into 4 biotypes. The morphometric relationship showed that the Minnesota biotype was distinctly different from the Missouri and Ohio biotypes, and that the Iowa biotype was intermediate. The results suggested that the biotypes of the European corn borer might have evolved beyond the stage of ecological and physiological differentiation. Chiang et al. (1970) compared 10 morphometric characteristics of the female moths from three localities (Minnesota, Iowa, and Missouri). They were able to show that morphometric characters were affected by ecological conditions under which the insect developed. The effects were more pronounced with characters on the legs and wings than those on the thorax. Thus, the authors suggested the use of characters on the thorax for comparison over time and space of the insect biotypes.

Recently, the European corn borer populations in North America have been separated into 3 ecotypes (Northern, Central, and Southern) based on diapause response to photoperiod and temperature. The northern ecotype is represented by the Minnesota and Quebec (Canada) populations; the central one represented by the Iowa, Nebraska, Ohio and (Frederick Co.) Maryland populations; and the southern one represented by the Alabama, Georgia, Missouri, and (Somerset Co.) Maryland populations (Showers et al. 1975).

Showers et al. (1974), Klun and cooperators (1975), and Kochansky et al. (1975) reported another major difference among European corn borer populations based on sex pheromonal response to different combinations of Z and E isomers of 11-tetradecenyl acetates. However, the pheromone strains (predominantly Z versus predominantly E) did not coincide with, but did transcend, the diapause ecotypes of the species.

Host Range. The European corn borer has been found to attack more than 200 kinds of plants (Burkhardt 1971; Metcalf and Flint 1962). Corn is recognized as the preferred host of the borer, but it also feeds extensively on potatoes, soybeans, millet, sorghum, beets, oats, barley, beans, cotton, many vegetable crops, and large-stemmed flowers as well as many weeds (Baker and Bradley 1948; Caffrey and Worthley 1927; Poos 1927).

)amage and Losses

European corn borer causes damage to corn in several ways. Under ;evere first-generation infestation, several leaves may be almost com-)letely girdled around the collar; this injury plus leaf blade lesions, :aused by the larvae feeding in the whorl of the plant, reduce surface ırea needed for carbohydrate production necessary for high yields (Everett et al. 1958). The stalk tunneling interferes with translocation)f phytosynthetic products throughout the plant and offers sites of entry 'or disease organisms of the corn plant (Everett 1958; Sparks et al. 1967). 'unneling also structurally weakens the plant and thus causes stalk)reakage and ear dropping which makes harvesting more difficult and :xpensive (Anonymous 1967; Chiang and Hodson 1950).

Where two generations of the European corn borer occur, the first jeneration larvae cause the greater reduction in yield, whereas the ;econd generation borers may not reduce the yield seriously (Burkhardt 971).

Corn yield losses due to European corn borer damage have been :stimated by using various methods. Patch et al. (1942) and Sparks :t al. (1967), using the number of larvae per plant as an index, showed :hat corn suffered a 3 per cent yield loss due to one mature first gener- ıtion larva per plant. Everett et al. (1958) found an inverse relation- ;hip between leaf lesions resulting from first-generation infestation ınd yield, but concluded that the best index of yield loss was the ıumber of cavities or larvae per plant at the time of midseason lissections. Jarvis et al. (1961) found that first-generation infes- :ation resulted in greater yield losses than did infestations by the second generation, that greater reductions per unit of damage occurred in late rather than in early planting, and that cavities and leaf lesions were a better index of damage than larvae. Chiang et al. (1960) reported less than 2 per cent yield loss due to one mature second generation larva per plant. However, losses in late planting or late maturing corn approximated losses due to larvae of the first generation.

Yield losses in susceptible and resistant corn hybrids were investigated by Penny and Dicke (1959) who found a 19 per cent yield reduction by the first generation feeding of European corn borers. Scott et al. (1965) reported that corn borer leaf feeding caused a 16 per cent reduction in yield on susceptible hybrids. Scott et al. (1967) found a 12 per cent reduction in yield due to second-generation borer damage on susceptible hybrids.

Estimates of financial losses caused by the European corn borer during the 10-year period 1953-1962 in the U.S.A. ranged from 65,044,000 to 191,614,000 bushels of corn and represented a cash income loss averaging $127,702,700 per year (Sparks et al. 1967).

Control Measures

Biological. Parasitoids. In an attempt of controlling European corn borer in the United States, 24 species of parasitoids were imported from Europe and Asia and released over most of the heavily infested areas (Sailer 1972). However, only six of these parasitoid species became established and proved of some value in reducing borer populations (Brindley et al. 1975). A tachinid fly, *Lydella thompsoni* (=*grisescens*) Herting, that looks much like the common house fly, was reported to be the most effective and widely established exotic parasitoid (Burkhardt 1971). Parasitization as high as 75 per cent was recorded by Rolston et al. (Brindley and Dicke 1963). However, Lydella thompsoni apparently disappeared from various localities of the Corn Belt states (Hill et al. 1973).

Another widely established parasitoid was found to be a tiny eulophid wasp, Sympiesis vividula (Thompson) but it actually may not be important in controlling the European corn borer (Showers and Reed 1969). In the Eastern States, three other parasitoid wasps, Horogenes punctorius (Roman), Macrocentrus gifuensis, and Chelonus annulipensis, can occasionally attack the corn borer (Baker and Bradley 1948).

Predators. Insect predators may also play an important role in the natural biological control of the European corn borer. Frye (1971) reported that predaceous insects including various species of lady beetles and larvae of lacewings could significantly reduce corn borer populations in North Dakota. Dicke and Jarvis (1962) reported that predation by Orius insidiosus peaked during early larval development in first-generation larvae of the European corn borer and was a significant factor in control. However, there was only a little predation by the species on early-instar larvae of second generation corn borers. Sparks et al. (1966c) concluded that insect predators played an important part in fluctuation of European corn borer populations in some locations during some years in the North Central States, but they could not be depended upon year after year or in a given year to alter significantly the borer populations at any specific location.

Birds have been observed feeding on the overwintering European corn borers. Wall and Whitcomb (1964) in Arkansas, and Frye (1972b) in North Dakota, found that downy woodpecker, Dendropos pubescens (Swainson) to be the most important predaceous bird.

Pathogens. Several pathogens have been tested against the European corn borer due to the appearance of insect resistance to chemical insecticides and an increasing awareness of the hazards of insecticide residues (Heimpel 1974). McConnell and Cutkomp (1954) conducted laboratory tests with Bacillus thuringiensis Berliner and showed that mortality of the larvae increased as the spore count increased. Field tests, however, indicated that the bacterium would not constitute a practical means of control. Raun (1963) also reported variable laboratory and field results with strains of the Bacillus thuringiensis. Raun and Jackson (1966) evaluated the capsule formulations of Bacillus thuringiensis var. thuringiensis Berliner under field conditions and obtained good corn borer control.

A microsporidian, Perezia pyraustae Paillot (=Nosema pyraustae) has been reported to be another pathogen of the European corn borer. Zimmack and Brindley (1957) reported that the microsporidian was transmitted through the eggs, and that diseased moths laid fewer eggs than uninfested moths. Van Denburgh and Burbutis (1962) concluded that Nosema pyraustae was an important biotic factor in the regulation of the European corn borer population in Delaware. Frye (1973) reported high infestations of corn borers by the microsporidian in the southeast area of North Dakota.

According to Brindley et al. (1975), no biological agents are today consistently operative at a sufficient level to control the European corn borer in North America. However, Bacillus thuringiensis and Nosema pyraustae have been indicated as potential agents of corn borer control.

Host Plant Resistance. Painter (1968) and Brindley and Dicke (1963) reviewed the early studies of resistance of corn to European corn borers in the United States. Brindley et al. (1975) wrote a comprehensive review of recent developments of varietal resistance to the species.

Resistance of corn to European corn borer was found to be expressed at various stages of plant development. At the seedling stage, most strains of corn were resistant to the borer (Klun 1974). At the whorl stage, some varieties lost their resistance and others retained it; this resistance was called 1st-generation or leaf feeding borer resistance (Guthrie et al. 1960), whereas the resistance that recurred at the pollen-shedding stage of plant development was termed 2nd-generation or sheath feeding borer resistance (Klun and Robinson 1969).

The first-generation borer resistance in corn has been attributed to 2,4-dihydroxy-7-methoxy(2H)-1,4-benzoxazin-3-(4H)-one (DIMBOA), an aglucone that suppresses larval development and increases larval mortality (Klun et al. 1967, 1970). DIMBOA has been shown to be a feeding deterrent and repellent (Klun et al. 1967; Reed et al. 1972). Thus, 1st-generation resistance has been explained by the nonpreference mechanism (Klun 1974). However, Scriber et al. (1975) found that resistance of two tropical genotypes of corn (I.D.R.N. Cornell 6008, and I.D.R.N. Cornell 6006) to leaf feeding borers was mediated by factors other than DIMBOA.

The chemical basis of the 2nd-generation borer resistance is still unknown (Klun 1974), but Klun and Robinson (1969) established that this resistance was due to factors other than DIMBOA. Inbred lines with high DIMBOA and good 1st-generation resistance often have poor 2nd-generation resistance (Guthrie et al. 1970). Oh43 has been found to be resistant to a 2nd-generation infestation (Guthrie et al. 1970). In contrast, inbred B52, which has relatively low DIMBOA concentration, has been highly resistant to a 2nd-generation infestation, but intermediate in resistance to a first generation infestation (Guthrie et al. 1970; Klun and Brindley 1966).

Resistance to both first- and second-generations of European corn borer has been a desired goal for corn hybrids. Russell et al. (1974), working with 200 F_3 lines from B52 x Oh43, obtained 1F_6 inbred line slightly better than Oh43 for first-generation resistance and equal to B52 for 2nd-generation resistance. Sullivan et al. (1974) found various exotic corn varieties to be highly resistant to both first- and second-generation borers. These exotic varieties contained lower DIMBOA concentrations than a susceptible hybrid. Thus the authors concluded that DIMBOA was not the active agent in resistance.

Cultural Practices. A number of cultural practices and special operations have been suggested for reducing corn borer infestations. Burkhardt (1971) stated that planting corn at a given time in an area may keep the injurious effects of borers at minimum. In most of the North Central States early-planted corn may produce the highest yield and also support the highest first-generation borer populations. For agronomic reasons planting corn as early as possible is encouraged in most of the Corn Belt states (Anonymous 1972).

Ensiling, stalk-chopping, disking and clean plowing of corn fields may also help in destroying large numbers of overwintering larvae of the European corn borer (Anonymous 1967; Baker and Brindley 1948).

Mechanical and Physical. Light traps. Light traps of various types and with different light sources have been tested for possible effects of reducing European corn borer infestations. Ficht and Heinton (1941) found that moths were greatly attracted to ultraviolet band of the spectrum. In addition, they were able to increase attraction by placing traps over corn attractive for oviposition. Barret et al. (1971) evaluated the effect of black light traps on sweet corn for corn borer control, and found no significant differences in damaged plants between lighted and unlighted plots.

Sterile-male technique. Walker and Brindley (1963) attempted to control European corn borers by using x-rays to irradiate adult moths and pupae. They found that about 32,000 R were required to induce sterility. Subsequently, Guthrie et al. (1965) suggested that male sterilization of the European corn borer could be obtained by irradiating (1) 3rd- and early 4th-instar larvae to affect only spermatogonia; (2) late 4th-instar larvae to affect spermatogonia and early spermatocytes; (3) half- to full-grown 5th instar larvae and early pupae to affect spermatocytes, spermatids, and mature spermatozoa; and (4) adults to affect spermatozoa. Raun et al. (1967) found that severe somatic damage of nondiapausing larvae occurred after irradiation with gamma rays from a cobalt^{60} source, but diapausing larvae showed little evidence of somatic damage. Further, irradiation of diapausing larvae affected the motility and viability of the sperm but did not induce lethal gene mutations.

Use of Chemicals. DDT, a chlorinated compound, was the most effective and widely used chemical for European corn borer control (Baker and Bradley 1948; Jackson 1963). However, its registration has been cancelled, and other chlorinated insecticides such as Endrin and toxaphene have been restricted (Burkhardt 1971). In recent years several new compounds have been shown to be effective in borer control. Harding et al. (1968) sprayed liquid insecticides over the rows and found Bux, carbaryl, phorate, diazinon, and carbofuran reduced the number of 1st-generation corn borer cavities compared with the untreated plots. Phorate, diazinon, and carbofuran gave the best results. Berry et al. (1972) showed that granular formulations of diazinon, carbaryl, malathion, carbofuran, and EPN were effective in corn borer control. Wedderburn et al. (1973) compared the effectiveness of six insecticides (carbofuran, phorate, carbaryl, diazinon, Dasanit, and Bux) in controlling infestations of 1st-generation borer and found that all insecticides significantly reduced corn borer populations as measured by the number of tunnels found per plant. Plots treated with carbofuran showed the lowest number of tunnels per plant. Berry et al. (1974) tested several new formulations against the European corn borer and showed that granule formulations gave better control of both 1st- and 2nd-generations than spray formulations. In addition, various of the new compounds (Fonophos, Trichlorfon, chlorpyrifos, Acephate, carbofuran and monocrotophos) were found to be promising insecticides.

Various field experiments have shown the possibility of controlling the 1st-generation European corn borer and corn root worms with a single application of granular insecticides. Postplanting applications resulted in most effective control of both pests (Hills et al. 1972; Munson et al. 1970).

Proper timing of chemical applications has been reported to be a critical factor in achieving adequate borer control (Brindley and Dicke 1963; Burkhardt 1971). Various criteria of determining correct timing have been suggested or recommended by different workers. Cox and Brindley (1958) evaluated the following criteria to determine proper timing on field corn for 1st-generation borer control: (1) 1100 borer degree days; (2) tassel-bud ratio of 30 to 50; (3) corn plant extended height of 35 inches; (4) 50 to 100 accumulated egg masses per 100 plants; (5) 87% moth emergence; (6) 75% of plants with leaf-feeding damage; and (7) first egg hatching. After a five-year study the authors found that the one criterion based on 75 per cent leaf feeding in whorls was the most rapid and simple to use. Timing of application differs from one area to another in which corn is grown. For example, in Wisconsin (Doersh et al. 1975) insecticide for borer control is suggested only when 75 per cent or more of the plants have egg masses; and on sweet corn, when 25 per cent or more of the plants show leaf feeding or have egg masses. In South Dakota (Kantack and Berndt 1975), application on corn field for 1st-generation borer is determined by either 50% of leaf injury criterion, or corn plant extended height of 35 inches. Treatment for 2nd-generation borer may seldom be needed except on seed-producing fields. In Kansas (Brooks and Gates 1975), 1st-generation control is justified when 50 to 75% of the plants show leaf-feeding injury; and there is no adequate criterion for 2nd-generation borer control.

Western and Northern Corn Rootworms

Distribution and Abundance in the U.S.A.

The geographic distribution of both species, northern corn rootworm, *Diabrotica longicornis* (Say), and western corn rootworm, *Diabrotica virgifera* LeConte, was reported by Chiang (1973) and Luckmann (1974).

According to Chiang (1973) the northern corn rootworm (NCR) was first recorded in Colorado in 1824. Subsequently it expanded eastward throughout the north-central region reaching as far as Maryland and Connecticut. It also spread southward and southeastward but only in scattered and isolated areas of Texas, Alabama and South Carolina. Luckmann et al. (1974) pointed out that most abundant populations of the NCR can be found in an area roughly extending from latitude 37° to 45° N and longitude 80° to 100° W. In addition, they recorded both WCR and NCR to be native species from North America.

The western corn rootworm (WCR) was first recorded in Kansas in 1868 (Chiang 1973), but the first economic importance was reported in 1909 by Gillette (Musick and Fairchild 1971) in sweet corn in Colorado. Since then it had moved in different directions but mainly eastward and northward; it reached southwest Nebraska by 1929-30 (Tate and Bare 1946). According to Kantack (1965) the WCR probably extended into South Dakota as early as 1922. Bryson et al. (Burkhardt and Bryson 1955) in 1945 reported corn damage by the WCR in Kansas. Subsequently a survey conducted by Burkhardt and Bryson (1955) showed that the beetle had expanded throughout the northern area of Kansas including 50 counties. In addition, the authors indicated that this species was moving eastward across Kansas at the rate of 30-35 miles/ year. In 1960 the WCR was found in Missouri (Fairchild 1964). By 1953 and 1964 this beetle had extended its range eastward into Iowa and Illinois, respectively (Bigger 1964). In 1965 it was first reported in Wisconsin (Patel and Apple 1966). In recent years corn damage due to WCR attack was currently reported in Indiana (Matthew et al. 1975), Michigan (Ruppel and Kaiser 1973), and Ohio (Anonymous 1974). The northern limit of the western corn rootworm's range had extended into Minnesota in 1961 (Chiang 1965), North Dakota, Wyoming and as far as Montana (Chiang 1973), whereas its range southward was extended only in isolated areas of Arizona, New Mexico, Oklahoma and Texas (Chiang 1973). Further, severe sweet corn damage by WCR was reported in Utah in 1973 and 1974 (Anonymous 1973, 1974b); in Idaho western corn rootworm ranged 30-40 per cent per plant (Anonymous 1974a), which indicates that this species is also moving westward. According to Luckmann et al. (1974) the WCR is currently abundant in an area roughly extending from latitude 40° to 45° N and longitude 85° to 105° W.

Taxonomic Status

The northern corn rootworm and western corn rootworm beetles both belong to the subfamily Galerucinae, family Chrysomelidae, and order Coleoptera (Borror and DeLong 1971).

The northern corn rootworm was first collected and described by Say (Mihm 1972) as Galleruca longicornis. Since Say's specimens were lost, Smith and Lawrence (Chiang 1973) designated a neotype for Diabrotica longicornis. This change has been currently accepted and adopted in the literature.

The western corn rootworm was first described by LeConte (Brooks 1967) as Diabrotica virgifera, which at present remains without changing.

Details on taxonomic status of these species were reported by Chiang (1973).

Biology, Ecology and Behavior

General Description of the Insects. Northern corn rootworm adults are pale green to yellow colored beetles, about 3 to 6 mm long (Peairs and Davidson 1961; Ruppel and Kaiser 1973). Eggs are small, oval and 0.5 mm long. They are white to pale yellow, and sculptured with diagonal pits (Burkhardt 1971). Larvae are slender, white, about 13 mm in length when fully developed and with the skin of the body usually segmented (Peters 1963). They have rounded anterior margin of the darkened area of anal plate and lacking sclerotized ventral band; they also have a dark band along cranial suture but lacking along frontal sutures (Mendoza and Peters 1964). Pupae are white, short and fragile since they do not have a pupal case (Chiang 1973).

The western corn rootworm adults are pale yellowish to brownish in color with three black stripes down their elytra or wing covers (Musick 1974). They are about 6 mm long and slightly larger than northern corn rootworm beetles (Ruppel and Kaiser 1973). Larvae are similar in appearance to those of the northern corn rootworms except the western corn rootworms have a definite notch in darkened area of anterior margin of anal plate. In addition, they have sclerotized band underneath posterior edge of anal plate. Also, a dark band along cranial suture extending 1/3 the length of frontal sutures (Mendoza and Peters 1964). Eggs and pupae resemble those of the northern corn rootworms (Burkhardt 1971; Chiang 1973).

Life History. The northern corn rootworm, *Diabrotica longicornis* (Say), and the western corn rootworm, *Diabrotica virgifera* LeConte, are quite similar in biological characteristics (Luckmann et al. 1975). However, according to Peters (1963) the western corn rootworm adults are much stronger fliers and more voracious leaf and silk feeders than the northerns. The western corn rootworm females would oviposit in ear tips whereas the northern females would not under the same conditions.

In the Corn Belt states both northern corn rootworm (NCR) and western corn rootworm (WCR) have only one generation per year (Kuhlman et al. 1970; Luckmann et al. 1974; Musick 1974). They spend the winter in the egg stage and hatching starts in May to early June in the following year (Burkhardt 1971). Several factors have been found to play a role in regulating the overwintering stage and hatching. Chiang et al. (1972) studied the effect of temperature on egg hatching of both species and found that cold exposure was essential for hatching of the majority of NCR eggs but not WCR eggs. In addition, they were able to show that in both species the greater post-chill hatching occurred after exposure to 5°C rather than to lower temperatures. Chiang (1974) reported similar results in regard to WCR. Further, he indicated that exposure of eggs to winter temperatures would tend to reduce their viability and this adverse effect could be more pronounced with more severe winter temperatures. Patel and Apple (1967) observed egg hatching of the NCR, without chilling, 9 days after deposition. George and Ortman (1965) showed that WCR eggs in diapause hatched after 4 days at 4°C, but the speed of hatching increased as the hatching of diapaused eggs at 4°C was extended to about 4 months. Elsewhere, George (Chiang 1973) found that a two-week period of prechill was required for the embryo of WCR to develop sufficiently to undergo a normal diapause development period, but longer prechill duration did not increase hatching.

The threshold temperature for hatching of eggs of NCR was determined as 52°F (11.1°C) (Apple et al. 1971; Chiang and Sisson 1968) and of the WCR was also found to be 11.1°C (Wilde 1971).

Water requirements affect egg hatching. Mihm et al. (1974) reported that continuous exposure of WCR eggs to moisture resulted in the highest hatching under laboratory conditions. Cunningham and Peters (1964) found similar results for egg hatching of NCR.

Newly hatched larvae are very small and are extremely difficult to find in the soil. They are able to move quickly to the roots where they primarily feed on the root hairs and outer cortical tissue (Sechriest 1969). As larvae become older and food requirements increase they burrow into the cortical parenchyma, the outer ring of cells of the adventicious roots. Channeling also then occurs in the stele of the root (Howe and Britton 1970). The 1st instar larvae of both species may be able to move as far as 102 cm through the soil to reach the corn roots (Short and Luedtke 1970; Suttle et al. 1967).

Kuhlman et al. (1970) studied the development of immature stages of the WCR at varied temperatures and found that the average duration of the first larval stadium at 11.7°C was 39.7 days; none completed the second larval stadium. In addition, at 15.6°C newly hatched larvae reached maturity in 70.8 days; at 22.2°C the average duration was 38.2 days; and at 29.4°C the average number of days as an immature was 26.6. Studies of NCR larval development in relation to temperature were not found in the literature.

Western and northern corn rootworms become full grown in July to August in most of the Corn Belt states and pupate in inconspicuous pupal cells which generally may be observed about 64 cm from the main roots and about 23 cm deep (Chiang 1973). However, Sechriest (1969) in Illinois, observed 90% of larval pupation between 0-5 cm in depth. The duration of the larval plus pupal stages has been reported to be about one month (Luckmann et al. 1974).

Adult western and northern corn rootworms may remain for a considerable time in the field where they emerge, but later they migrate to other fields as the food becomes scarce (Luckmann et al. 1975). Flight behavior and dispersal activity of the adult beetles have been reported by a number of workers. Cinereski and Chiang (1968) studied the movements of adult northern corn rootworms by identifying pollen types in the digestive tracts and concluded that beetles moved among corn and other crops throughout the season. Howe et al. (1963) reported that flight of most NCR beetles in growing corn occurred below the 6-foot level. Witkowski et al. (1975) investigated the flight activity of WCR and found it to be bimodal with flight activity peaks occurring in the 2-3 h periods after sunrise and before sunset. Further, peak flight activity was recorded at temperatures of 22.2 to 27.0°C.

Adult northern corn rootworms feed predominantly on the corn silks, whereas the westerns commonly feed on the leaves and other plant parts including silks (Howe et al. 1963).

Female beetles of the WCR may live from 16 to 84 days, during this time each female can oviposit as many as 1045 eggs. Males have generally shorter life than females (Ball 1957). Hill (1975) has shown similar results in the same species. Eggs are usually concentrated in the rows at the base of the corn plants in unirrigated fields (Patel and Apple 1967), and between rows in fields with irrigation (Lawson 1964). Most eggs of the NCR are deposited in the upper few inches of soil (Patel and Apple 1967), whereas WCR females often deposit their eggs at a greater depth in the soil (Luckmann et al. 1975).

Mating and Pheromone Studies. According to Ball (1957), mating by the WCR beetle may take place shortly after emergence and it may last as long as 3 hours. Hill (1975) studied in detail the mating habits and oviposition pattern of the western corn rootworms. He observed that females copulated only once, and males were able to mate with several females. Ball and Chaudhury (1973) reported the presence of a sex pheromone(s) in adult female of western corn rootworms. They showed that the 5% ether/hexane fraction elicited male attraction under laboratory conditions. However, they were not able to ascertain the effectiveness or potency of these compounds in the field. In recent investigations of the corn rootworm mating behavior, it has been demonstrated that the sex pheromone is produced by the virgin WCR females. The chemical compound has been tested to be highly attractive to WCR males under field conditions. Northern corn rootworm males have also been attracted to traps baited with WCR pheromones. WCR females have been found to be apparently attractive to older males at the time of or shortly after emergence. However, adult males may not respond well under laboratory conditions until 4-6 days after emergence (Anonymous 1975f).

Interspecific Relationship of the Two Species. The interrelationship of the western corn rootworm and northern corn rootworm has been reviewed by Chiang (1973). Since these two species live together an interaction between them exists (Luckmann et al. 1974). Hill (1967) reported an attempt of displacement in distribution of the northern corn rootworms by the western corn rootworms. Chiang (1973) stated that this displacement may occur due to the hybridization of the two species. Hintz and George (1967) obtained the F_1 progeny of crosses under laboratory conditions. The F_1 adults had the phenotype of the western corn rootworm.

Host Range. Corn has been shown to be the most favorable host for development by larvae of the northern and western corn rootworm (Ortman 1974). However, Branson and Ortman (1967, 1970) reported 8 narrow leaf crop species to be additional hosts of the western corn rootworm larvae; namely, wheat, spelt, barley, foxtail, millet, intermediate wheat grass, pubescent wheat grass, tall wheat grass, and slender wheat grass. Chiang (1965) observed rootworm adults of both species on plants other than corn, such as alfalfa, sunflower, chrysanthemum, and squash.

Damage and Losses

Corn damage is caused by larval and adult feeding of both northern and western corn rootworm species. Larvae of the two species generally do the same type of damage to the corn roots (Granados 1967). Root larval feeding and subsequent destruction of tissue cause the lodging of the plants and also provide entries for disease organisms (Apple and Patel 1963; Howe and Britton 1970). Further, the feeding of even a small number of larvae may inhibit the capacity of the infested plants to assimilate water and nutrients from the soil (Musick 1974).

Ludwig and Hill (1975) showed several significant feeding differences between adults of the western and northern corn rootworm. The authors examined gut contents and found greater percentage of corn leaf tissue in guts of the WCR than in those of the northerns. In contrast, the NCR beetles fed more extensively on pollens of other plants in addition to corn than did the WCR beetles.

Since the adult corn rootworms are active in the corn field during silking and pollination period of corn, they can affect yield through interference with pollination (Musick 1974). If populations are sufficiently high and if beetles are present during the critical pollination period, they can keep the silks clipped back to the tip of the ear throughout the pollination period (Peters 1963; Granados

1967). This damage may result in incompletely filled ears, which is often called "scattergrain" or barren stalks (Musick 1974).

Yield losses due to WCR and NCR damage may be estimated by obtaining the percentage of reduction in ear weight of lodged plants, compared with that on standing plants in the same field, and multiplied by the percentage of lodging (Chiang 1973). Yield loss may also be estimated in relation to root damage rating. Hills and Peters (1971) found a yield reduction of 5.8 bu/acre for every adjusted root damage rating unit on a 1 to 6 scale.

Recently, Apple et al. (1975) investigated corn yield losses due to NCR and WCR attack in seven midwestern states. They found that in Nebraska rootworms reduced yields 25.5% during the years 1971-74. During the same years Wisconsin suffered a 7.4% loss; in 1971 and 1972 Missouri had a 21.7% loss, while Ohio trials in 1972 and 1973 indicated an average 6.9% loss. Iowa, in 1974, and Illinois, in 1971, had 3.4 and 5.8% yield reduction, respectively, whereas Minnesota did not have corn yield reduction in three years (1971-1973-1974).

Control Measures

Biological. Control attempts of northern and western corn rootworms by means of biological agents have been reported by a number of workers. Munson and Helms (1970) tested the nematode-bacterium complex (*Neoaplectana carpocapsae* Weiser and *Achromobacter nematophilus* Poinar) called DD-136, in the field for biological control of corn rootworm larvae (*Diabrotica* spp.). They found that the nematodes were not effective in reducing corn rootworm populations.

Chiang (1970) suggested that predaceous mites were important in reducing large numbers of larvae of the corn rootworm. He was able to show that manure applied to corn fields increased predaceous mite populations and thought they caused a 63% reduction of corn rootworms. However, recent experiments have shown that the increase in mortality of the corn rootworms is due to high concentrations of salt in manure instead of predaceous mites (Wilde, personal communication).

Insect parasitoids have been recovered from adult corn rootworms but their occurrence is infrequent (Wilde, personal communication). Predators and disease organisms for corn rootworm population reduction have not been found in the literature as far as it was reviewed.

Host Plant Resistance. The development of resistant varieties of corn has been reported to be a highly desirable means of corn rootworm control (Ortman 1974).

Several methods have been employed for evaluating corn varieties for resistance. Fitzgerald and Ortman (1964) evaluated larval feeding damage by firmness of root anchorage, foliage yellowing or burning, and stunting. In addition, they dug the more resistant lines and rated the roots for type of root system root-feeding damage, and root degeneration. Ortman et al. (1968) used a vertical device to measure the pounds of vertical pull required to remove a plant from the soil. Their study indicated that the pounds of pull was an efficient and useful method of obtaining quantitative data on root-pulling resistance and significant correlations were found between vertical pull and other criteria of root evaluation. Zuber et al. (1971) reported that a method which consisted of comparing root strength between treated and nontreated plots could be as efficient as any other method to evaluate corn strains of resistance and/or tolerance to the corn rootworm.

The majority of rootworm resistance found in corn has been classified as tolerance. That is, some lines are able to develop new roots above the feeding points of the larvae almost as fast as the larvae destroy root tissue (Ortman 1974). Furthermore, tolerance of corn strains to the rootworm damage has been considered to be composed of 4 traits: (1) decreased feeding damage, (2) decreased root lodging, (3) increased root size, and (4) increased secondary root development (Owens et al. 1974). Inbreds showing considerable tolerance or resistance include N38A, Ind. 38-11, HD2187, SD10, C.I. 38B, B55, Oh05, A251, M022, H51, M012, A297, and B57 (Burkhardt 1971).

Also, antibiosis in corn strains to feeding by corn rootworms has been investigated. Ortman and Gerloff (1970) obtained an indication of antibiosis from some exotic germplasm from South and Central America, and the West Indies. Branson (1971) screened near relatives of corn from the tribe Tripsacae as potential sources of antibiosis. He found that a single species, _Tripsacum dactyloides_ had a high degree of antibiosis to feeding by larvae of the corn rootworms. Subsequently, Ortman (1974) reported that a corn hybrid, _T. dactyloides_ x _Z. mays_ containing 3 _Tripsacum_ genomes and one corn genome, caused a marked reduction in adult corn rootworm emergence.

Sifuentes and Painter (1964) reported resistance to adult feeding of the western corn rootworm on 27-day-old corn. They found the type of resistance was monogenic and recessive. Granados (1967) screened

356 corn lines for silk resistance to feeding of adult western, northern, and southern corn rootworms by evaluating corn lines for both silk and ear damage. Twelve of the corn lines were found to be resistant to feeding by the adult rootworms. The corn lines classified as resistant included: K166, K-1859, SD10, and nine exotic lines. Reissig and Wilde (1971) showed varied degrees of suitability to adult WCR feeding on silk and tip kernels of 15 genetic sources of corn. On the basis of attraction of adults to water extracts, 3 lines of corn (Veracrux x Manfredi, K-1859, and Antigua 6D x C.B.C.) were found to be least preferred.

Cultural Practices. Crop rotation is one of the most important cultural practices that helps in reducing corn rootworm populations (Metcalf and Flint 1962). Larvae of the northern and western corn rootworms cannot survive on the roots of broadleaf plants such as soybeans, alfalfa, sweet clover, red clover, sunflower and field bean, thus these plants can be used safely in rotations with corn (Branson and Ortman 1970). In addition, oats and sorghum can also be used in crop rotations since they are not hosts of the corn rootworms (Branson and Ortman 1969; Branson et al. 1969).

Fall plowing of the heavy textured soil may reduce rootworm populations (Chiang 1973). However, according to Calkins and Kirk (1969) neither fall nor spring plowing could be recommended for controlling corn rootworms.

In the no-tillage system of corn production the eggs, which are laid near the base of the old plants, may remain undisturbed throughout their development. Thus planting corn in between the preceding year's rows could reduce populations of rootworm (Chiang et al. 1971). Ohio studies have shown that larval populations were reduced approximately 30-35% for each 10 inches (25.4 cm) the new corn row is from the old row (Musick 1974).

Early planted corn in most Corn Belt states allows the corn plants to become established before larval hatch and to withstand more severe rootworm infestations. However, early planted corn provides more root mass for larval feeding (Chiang 1973; Musick 1974).

Also, applying extra nutrients such as nitrogen to corn may help in overcoming the injury of rootworms (Burkhardt 1971).

Chemical Control. Because of the high cash value of corn, various types of insecticides have been used for controlling corn rootworms. The first chemicals used by the early farmers and researchers were from the group of chlorinated hydrocarbons (Metcalf and Flint 1962). Tests demonstrated (Burkhardt 1954) that aldrin, heptachlor, and lindane applied in band treatments reduced significantly western corn rootworm larvae populations, and plant lodging. Subsequently aldrin, heptachlor, and chlordane were recommended for both northern and western corn rootworm control (Peairs and Davidson 1961). However, by 1959, ineffective control with the recommended insecticides was noted in some areas of Nebraska (Ball and Weekman 1962). In LD_{50} tests, 100 times more aldrin or heptachlor was required to kill the WCR beetles. Thus the development of resistance to these compounds was evident in the species (Ball and Weekman 1963). Meanwhile, the northern corn rootworms were also found to be resistant to chlorinated hydrocarbon insecticides in Ohio (Blair et al. 1963).

The development of resistance to cyclodiene insecticides in both species has resulted in a rapid trend toward replacing these compounds with organophosphorus and carbamate insecticides for soil treatments (Burkhardt and Fairchild 1967). However, the WCR was also reported to be resistant to some organophosphate compounds (Ball 1968).

At present, effective management of corn rootworm population depends largely on the application of a soil insecticide (Musick 1974). Methods of applying insecticides and timing have been reported to be important factors in achieving an accurate and effective control of corn rootworms (Musick 1975). Musick (1974) has described 4 major methods of applications of insecticides including (1) broadcasting, (2) fertilizer-insecticide combinations, (3) basal or cultivation treatments, and (4) banding. Musick (1975) showed good rootworm control by applying liquid or granular formulations of various soil insecticides in a 7-in. (17.8-cm) band in front of the planter presswheel at planting. Mayo (1975) reported that carbofuran 4F was consistently the most effective insecticide in controlling corn rootworms, regardless of the application technique. However, Dyfonate 4E, and Mocap 6E also provided a high level of corn rootworm control.

Many factors may affect chemical control of northern and western corn rootworms in the soil. Moisture content and pH of the soil as well as wind have been reported to play important roles in a successful achievement of control (Peters et al. 1975).

Adult control by chemicals would be suggested only when interference with pollination appears likely, that is, when silk feeding is occurring at 25 to 50% pollen shed (Roselle et al. 1974). Malathion, diazinon, methyl, or ethyl parathion and carbaryl have been recommended for adult corn rootworm control (Brooks and Gates 1975).

Corn Earworm

Distribution and Abundance in the U.S.A.

The corn earworm, *Heliothis zea* (Boddie), is one of the most destructive insect enemies of corn in the United States, since it has a wide geographical distribution (Burkhardt 1971; Metcalf and Flint 1962). It occurs throughout this country wherever corn is grown, but it has been found to be most destructive in the southern states (Peairs and Davidson 1961). Snow and Copeland (1971) indicate that corn earworm is able to progress through continuous generations in the southern portions of Florida and Texas as well as Louisiana, because these areas have only an average of 2 days per year with temperatures below $32^{o}F$ ($0^{o}C$). Further, according to Blanchard and Douglas (1953), corn earworm pupae can survive in the western region, mainly along the Pacific coast, in sandy soils or protected areas from southern California as far north as southern Washington. In northern and northeastern areas of the United States (Metcalf and Flint 1962), the corn earworm pupae may not survive the winter under ordinary conditions, thus infestations in these areas arise from moths flying in from the south. However, a possibility exists that damage to corn and other crops in northern states is the result of local overwintering populations rather than migrations from the south as it has commonly been reported (Blanchard and Douglas 1953; Snow and Copeland 1971).

Taxonomic Status

Corn earworm was first described under various different scientific names, but the most acceptable combination during the last century was Heliothis armigera (Hübner) of the family Phalaeindae (Heinrich 1939).

Boddie (Todd 1955) described various stages of corn earworm and named Heliothis zea. He was also able to recognize that the corn earworm and the cotton bollworm were the larvae of the same species. Todd (1955) reviewed the taxonomic status of corn earworm and found that the name Heliothis armigera was only applicable to Old World species, and that the corn earworm of the Americas was better named Heliothis zea (Boddie) as originally described by Boddie. Thus the current scientific name of corn earworm is Heliothis zea (Boddie). It belongs to the family Noctuidae, order Lepidoptera (Borror and DeLong 1971).

Biology, Ecology and Behavior

General Description of the Insect. Eggs are spherical, prominently ribbed, and flattened in the base. They are about 0.57 mm in width and 0.51 mm in height. They are translucent white to yellowish-white when freshly deposited, but developing a reddish band during incubation, and darkening prior to hatching (Neunzig, 1964).

Newly hatched larvae are about 1.5 mm long, nearly white with shiny black heads and legs (Neunzig 1964). Full grown larvae are 3 to 5 cm long, and they greatly vary in color, ranging from light green or pink to dark brown or nearly black (Burkhardt 1971). They are marked with alternating light and dark stripes running the entire length of the body. These stripes may not always be the same on different individuals, but usually there is a double dark line on the top side running the length of the larva's body (Blanchard and Douglas 1953). The most distinctive characteristics of larvae are the presence of short, sharp microspines with which the skin is covered, except on the dorsal abdominal tubercles (Little 1963).

Pupae are about 19 mm long, first green in color and later they become brown (Burkhardt 1971).

Moths are about 19 mm long and have a wingspread of approximately 38 mm. They vary in color, the average having the front wings of a light brown to tan color, marked with dark-gray irregular lines and with a dark area near the tip of the wings. The hind wings are white with some dark spots or irregular dark markings (Metcalf and Flint 1962).

Life History. Female adult moths of *Heliothis zea* (Boddie), being of predominantly nocturnal habits, may often be observed feeding on nectar of flowers and ovipositing in great numbers during the late afternoon and evening (Hardwick 1965). In Arkansas, Phillips and Whitcomb (1962) recorded oviposition by *Heliothis zea* as being largely confined to the period between 7:00 and 9:30 p.m. In Louisiana, Callahan (1958) recorded a period of oviposition for the same species that extended throughout the night and which was only slightly heavier in the early hours than in the later hours of darkness. In Texas, Nemec (1971) observed that corn earworm moths were highly active only in the dark of the moon, while in moonlight or in artificial light there was little mating or egg laying. Furthermore, he was able to predict corn earworm population buildup with 24 hours accuracy.

Although the number of plant species on which Heliothis zea will oviposit seems almost limitless, the species prefers corn to any other host (Burkhardt 1971). However, the oviposition on a host plant has been reported to be more complex than simple attraction to the plant. Recently, Jones et al. (1973a) found that triacetin and some of its related chemicals could induce the corn earworm oviposition under laboratory conditions. The eggs are laid on the fresh silks or on the upper leaves of the corn plant. Metcalf and Flint (1962) have recorded as many as 500 to 3,000 eggs per female, the average being over 1,000. Eggs hatch in three or four days, the time varying with the temperature (Little 1963).

The newly hatched larvae feed on the empty shells, but soon afterward they begin feeding on leaves, immature tassel, or silk, and then enter the ear (Blanchard and Douglas 1953). Molting five times, they develop to full grown larvae in two to four weeks (Metcalf and Flint 1962; Burkhardt 1971).

Other unusual habits of corn earworm larvae have been reported in the literature. Wildemutch (Hardwick 1965) found corn earworms feeding on the larvae and pupae of the alfalfa caterpillar (Colias eurytheme Boisduval). Blanchard and Douglas (1953) found the evident tendency to cannibalism of larvae. Whenever two earworms come together, they fight until one or both are injured beyond recovery. Thus, usually one full grown worm may be found in a corn ear (Metcalf and Flint 1962).

Upon completion of feeding, the mature larvae may crawl down the stalk or drop to the ground where they burrow into the soil to depths of 2.5 to 23 cm to form their cells, and the emergence tunnel for adults. Subsequently, they become quiescent within the pupal cells and thus transform to pupae (Blanchard and Douglas 1953; Burkhardt 1971). The duration of pupal period of the females, at temperature of 25^{o}C, has been found to be one day shorter than of the males, and the average for the two sexes may be 13.1 days (Hardwick 1965). However, Metcalf and Flint (1962) and Burkhardt (1971) indicate that in summer, pupal period may last from two to three weeks, and it may be prolonged during cold weather. The corn earworms hibernate as pupae, and this stage will be discussed in a subsequent topic.

The emergence of adult moths may usually occur during the hours of darkness. Callahan (1958) showed a period of emergence between 5:00 p.m. and midnight with a peak emergence between 9:00 and 10:00 p.m. In addition, the mean length of life for adult females of the first generation was found to be 17.2 days, and the maximum length of life, 37 days, under laboratory conditions (Callahan 1961). Nevertheless, according to Burkhardt (1971) female moths may live about 12 days.

The number of generations of the corn earworm per year depends mainly on climatic conditions (Snow and Copeland 1971). In a very mild climate, such as that of southern Florida, Texas and California, the corn earworm insects may complete their life cycles in about a month, and may be able to produce as many as seven generations a year (Blanchard and Douglas 1953). However, in the Corn Belt states there may be usually two or three generations a year, and in the northernmost part of the United States it may only be one generation (Burkhardt 1971; Hardwick 1965).

Mating and Pheromone Studies. Mating by the adult corn earworm can only be observed during the night. Hardwick (1965) reported that copulation could not be induced by keeping the moths in total darkness during daylight hours. Callahan (1958) studied the behavior of the imagos and observed copulations to take place between the second complete night after the emergence and the seventh night. Berger et al. (1965) observed that females, when ready to mate, extended their ovipositor and exposed glandular-appearing structures at their basis prior to mating; males attempting to mate with such females often brushed these areas with their antennae. This, the authors concluded, suggested the presence of a sex pheromone in the females. Subsequently, Shorey et al. (1968) found that females of the corn earworm had a relatively high sex pheromone titer by one-half day after emergence. Roelofs et al. (1974) suggested a chemical (Z)-11-hexadecenal, to be one of the compounds of the corn earworm's sex pheromone. Recently, this chemical was demonstrated to be a strong sex attractant inhibitor, secreted by virgin females (Sekul et al. 1975). Furthermore, another chemical called (Z)-9-tetradecen-1-ol formate (Z-9-tdf) was also reported to be a highly disruptive compound of pheromonal communication between male and female corn earworms (Mitchell et al. 1975).

Diapause Studies. The corn earworms enter diapause as pupae (Ditman et al. 1940; Phillips and Newsom 1966). The initiation of diapause in the pupae has been ascribed to several causes. Phillips and Barber (Hardwick 1965) suggested that the nature of the larval food might be implicated if not directly responsible for instigating pupal diapause in the species. Ditman et al. (1940), however, could find no direct relationship between larval food and pupal diapause, but instead they found that cool temperatures during the larval feeding period would induce diapause in corn earworm pupae. Later, Phillips and Newsom (1966) studied pupal diapause under controlled photoperiod and temperature. They were able to find four prominent characteristics related to diapausing pupae; namely, retention of larval eye spots in the postgenal region, arrested gonadal development, cessation of spermatogenesis in the male, and reduced oxygen consumption. In addition, they stated that diapausing pupae could remain for at least 20 months at 18°C. Mangat and Apple (1966) exposed diapausing pupae of a Wisconsin strain of H. zea (F_1 progeny from field-collected adults) to several temperature and photoperiodic regimes and concluded that temperature was important in diapause termination but that photoperiod (increasing day lengths from 11 to 16 hours at 18.3°C) had no detectable effect. They also calculated a total day-degree accumulation of 6.5 above the thermal threshold of 54.7°F (12.7°C). Roach and Adkisson (1971) also found that the time required for diapause termination in a Texas strain of H. zea decreased with an increase of temperature, but that the effect of photoperiod was variable.

Host Range. The favored host plants of the corn earworm are sweet corn and field corn (Burkhardt 1971). Further, it is an important pest of cotton, tomato, and witch, being known on these crops as the cotton bollworm, tomato fruitworm, and witchworm, respectively. Millet, sorghum as well as soybeans and other leguminous crops are also subject to serious annual damage (Little 1963; Metcalf and Flint 1962; Peairs and Davidson 1961).

Damage and Losses

The corn earworm damages corn in a number of ways. The direct damage occurs when the larvae infest the corn plant in the vegetative stage, by feeding on the tender unfolding leaves. This damage is commonly known as budworm or ragworm (Blanchard and Douglas 1953). Such damage may result in slightly reduced yields, although, when larvae reach the terminal meristem, stunting may occur, so the plants will produce little grain (Sifuentes 1964).

The most serious damage occurs on the ears. When ears begin to silk, larvae feed on silks, which results in an important reduction of pollination and failure of some kernels to develop. Soon afterward, they move to feed on kernels. In sweet corn, besides damage to the kernels, quality and appearance of the ears are also adversely affected (Metcalf and Flint 1962; Sifuentes 1964; Hardwick 1965; Burkhardt 1971). Corn earworms cause indirect damage to corn by opening entrances for other insects and disease organisms that also contribute to lower the yield and quality of the grain (Blanchard and Douglas 1953; Sifuentes 1964). Monetary losses in the United States resulting from damage by corn earworm to corn crop have been estimated to be about $75 million to $160 million annually (Burkhardt 1971; Zuber et al. 1971b).

Control Measures

Biological. There are several species of parasitoids, predators, and disease organisms that play an important role in the natural biological control of the corn earworm (Whitcomb 1974; Ignoffo 1974).

The egg parasitoids, *Trichogramma* spp., which attack many species of Lepidoptera, are the most important natural enemies of *Heliothis zea* (Boddie). Very large numbers of these parasitoids have been reared under laboratory conditions to provide supplemental field releases. In a number of experiments, successful egg parasitization was obtained by mass releasing of *Trichogramma* spp. Lingren (1970) and Ridgway et al. (1974) were able to control bollworm and budworm by release of *Trichogramma* sp. According to Ridgway et al. (1974), field releases of *Trichogramma* sp. reared on eggs of the Angoumois grain moth increased parasitism of *Heliothis* eggs in both corn and cotton; rates of parasitism of *Heliothis* eggs as high as 95% were obtained. In addition, they indicated that releases of 100,000 parasitoid individuals per acre at 2-3 day intervals may insure substantial parasitism of *Heliothis* eggs.

Recent studies of the biological relationship between *Trichogramma* sp. and *H. zea* have demonstrated the existence of a kairomone, host-seeking stimulant for *Trichogramma*, in the moth scales. This material has been isolated, and identified as Tricosane by Jones et al. (1973b). Subsequently, it has been tested in field applications to increase the effectiveness of the parasitoid. The results have shown up to 44% increase of parasitism in eggs of Heliothis zea (Nordlund et al. 1974).

A braconid wasp (Microplitis croceipes (Cresson)), an insect distributed throughout most of the United States, is the predominant parasitoid attacking corn earworms at larval stage (Lewis and Brazzel 1968; Roach 1975). Tachinid flies of the genus Winthemia may also parasitize corn earworms (Blanchard and Douglas 1953; Roach 1975).

Many species of predators can reduce considerable populations of earworms by feeding on eggs, larvae, or pupae. The green lacewing Chrysopa carnea (Stephens) is one of the most predatory insect enemies feeding on larvae. Ridgway and Jones (1968) have successfully controlled the bollworm and tobacco budworm on cotton in field cages and in small plots by releasing larvae of the green lacewing. A year later, Ridgway and Jones (1969) were able to determine the number of larvae of C. carnea (Stephens) that might be needed to control Heliothis spp. on cotton. The results of these studies indicated that about 50,000 larvae per acre might be required to reduce corn earworm populations.

Currently, Chrysopa carnea (Stephens) is being commercially mass produced for field releases in California, Texas, Missouri, and other locations (Whitcomb 1974).

The big-eyed bugs, Geocoris spp. and the flower bugs, Orius insidiosus (Say) are important predators. They can routinely destroy large numbers of Heliothis eggs (Tamaki and Weeks 1972; Van Steenwyk et al. 1975).

The lady beetles were also reported to be significant destructors of corn earworms. According to Whitcomb (1974), the population level of three lady beetles, Hippodamia convergens (Guerin-Meneville), Coleomegilla maculata (DeGeer), and Cycloneda sanguinea (Linn) may determine whether there is going to be a Heliothis zea outbreak in thousands of corn and cotton fields in the United States.

Among disease organisms, the most important pathogen for corn earworm control is Bacillus thuringiensis Berliner. This bacterium possesses high virulence and efficient survival mechanisms, but it lacks a high dispersal capacity and, thus, has only a low potential for developing epizootics in population of its hosts (Angus 1974). Bacillus thuringiensis Berliner has been commonly distributed for agricultural use under different types of commercial preparations (Huang 1974). The effect of this pathogen on corn earworm population in the field was tested by a number of research workers. Patti and Carver (1974) evaluated four commercial preparations of Bacillus thuringiensis: Dipel, Thuricide HPC, Biotrol XK, and Bactospeine P.M., for control of Heliothis spp. on cotton. They found Dipel to be as effective as toxaphene + DDT + methyl parathion in killing larvae. Janes (1975) compared the microbial insecticide Dipel with various chemical insecticides including malathion and methyl parathion for control of corn earworm Heliothis zea (Boddie) and fall army worm, Spodoptera frugiperda (J. E. Smith) on sweet corn. He found Dipel to be very effective as well as malathion.

Among protozoan pathogens, a microsporidian, Nosema heliothidis, may be another significant factor in the natural suppression of the corn earworm populations. According to Brooks (1968), this microorganism is transmitted transovarianly, causing reduction in reproductive capacity of the host. Gaugler and Brooks (1975) found that fecundity, longevity and mating performance as well as diapause potential of the corn earworm were significantly affected by this microsporidian under laboratory conditions.

Viruses have also been tested for corn earworm control (Ignoffo et al. 1965). Major emphasis has been placed on experimentation with a nuclear polyhedrosis virus (NPV) of the same species. This type of virus has been found to be quite virulent, but until 1969 it has not proved to be very effective in field experiments due apparently to unfavorable pH and ultraviolet radiation in the environment (Ignoffo et al. 1965; Ignoffo 1968; Falcon 1971). Later, the virus material was conditioned to withstand these adverse effects, and tested successfully. In one experiment, virus conditioned to withstand the adverse effects of both ultraviolet radiation and unfavorable pH produced a significant reduction in bollworm larvae below the untreated control (Falcon 1971). In a series of similar tests conducted in 6 cotton states in 1969, nuclear polyhedrosis virus (NPV) significantly increased yields and gave control of bollworm comparable to the standard insecticide (Ignoffo et al. 1972).

Since 1970, the Heliothis NPV has currently been registered for agricultural use under the name of "Viron H" (Ignoffo 1974).

Host Plant Resistance. The use of resistant corn varieties is one of the most promising methods of controlling corn earworm populations. Corn resistance studies to this species began in the United States when Collins and Kempton (Keaster et al. 1972) investigated various factors relating to resistance. Only husk length indicated positive correlation with damage. Most recent studies have indicated chemicals present in the silks act as a feeding stimulant (Starks et al. 1965), whereas in the kernels, a strong feeding response could be elicited by a complex of simple sugars and amino acids (Jones et al. 1972).

The first corn showing a high degree of earworm resistance was found by Walter (1962) in a line from Mexico, known as Zapalote Chico. Silks from this strain were shown by Bennett et al. (1967) to be resistant to earworm feeding in field test and in laboratory tests. A low concentration of neutral molecules in extracts of Zapalote Chico silks was found to be the main factor associated with resistance (Straub and Fairchild 1970).

Keaster et al. (1972) reported an identification of 8 different corn strains that had a type of resistance rather than morphological. These include Zapalote Chico, C17, Alabama 18, Florida 6, South Carolina 299 MH, Mississippi 426, K4, and Missouri 13. Whereas another 8 different resistant varieties of field corn were listed by Burkhardt (1971), namely, Dixie 18, Dixie 11, Georgia 281, Louisiana 521, Texas 30, Texas 11W, and Coker 811.

The use of resistant plants or plant materials as an adjunct to other control measures has greatly increased efficacy in reducing corn earworm losses in sweet corn. The feeding stimulant has been incorporated with an insecticide and damage was reduced significantly over the insecticide alone. In fact, more than 8 times more insecticide would be required to equal the control achieved with the feeding stimulant plus insecticide (McMillian et al. 1968).

A resistant sweet corn hybrid (471-U6 x 81-1) has been tested in combination with seven applications of an insecticide (Gardona) under artificial and natural infestations, resulting in about 71% more damage-free ears than the susceptible hybrid plus insecticide. Thus, resistant corn hybrids may require less insecticide than susceptible hybrids to achieve an equivalent high level of earworm damage control (McMillian et al. 1972).

Cultural Practices. Cultural practices for the corn earworm control have not been devised as far as the literature is reviewed. However, in field corn damage may be lessened by employing good agronomic practices such as fertilizing, and planting adapted varieties (Blanchard and Douglas 1953). According to Burkhardt (1971) corn planted at the usual time for an area may sustain less injury than either early or late planted corn.

Mechanical and Physical. Light traps. The use of light traps to control corn earworm has been investigated by a number of workers, but effective control by means of light traps has not been reported in the literature. Sparks et al. (1967) evaluated the effects of electric light traps on cotton field for control of the bollworm and tobacco budworm. He found no effect of trapping on infestations of these insects. Graham et al. (1971) tested the effect of black light traps on a semi-isolated corn field at a density of about 1.6 traps per acre for control of earworms. The results of operating the traps over a 2-year period, including three crops of corn, indicated this method did not prevent infestation nor did it protect crop from damage by the corn earworm.

Sterile-male technique. Snow et al. (1971) attempted to eradicate the corn earworm population from Saint Croix, U. S. Virgin Islands, using the sterile-male technique. The experiments were conducted during the summers of 1968 and 1969. The results of these attempts indicated failure in iradicating the species, because the release of sterile males on the island and the subsequent high ratio of sterile to natural males caused the elimination of oviposition rather than the production of sterile eggs; so the program resulted in cycling the natural population. However, in spite of the failure, these attempts showed important biological and ecological data that would be useful for subsequent investigations.

Use of Chemicals. Application of chemical insecticides is currently practiced only on sweet corn. In contrast, field corn has no practical chemical control (Brooks and Gates 1975).

The chemicals widely used for control of the corn earworm on sweet corn were DDT and some other cyclodienes; but soon afterwards, DDT was reported to be ineffective because corn earworm developed resistance (Graves et al. 1963; Harris 1970). Recently the use of cyclodiene insecticides was restricted due to their harmful effect in other living organisms.

Organophosphate and carbamate compounds have replaced the use of cyclodienes, although a number of workers have reported the evidence of developing resistance in earworm to organophosphate compounds. Harris (1972) reported resistance in *Heliothis zea* (Boddie) to methyl parathion and Toxaphene-DDT on cotton in the Mississippi Valley. Thus, he suggested the use of new insecticides and alternate control methods to prevent or delay bollworm outbreak. In Georgia, Canerday (1974) found also that methyl parathion was ineffective for *Heliothis zea* control. The development of resistance to organochlorine, organophosphorus, and carbamate insecticides in *Heliothis zea* (Boddie) was reviewed by Harris et al. (1972). However, carbaryl was shown to be one of the promising chemicals for corn earworm control. Anderson and Reynolds (1960) found that a 5% carbaryl dust applied massively with a paint brush on the ear tips of sweet corn provided good earworm control. DePew (1966) tested several insecticides for corn earworm control on irrigated sweet corn during 1953-63 in western Kansas. His results indicated that carbaryl, endosulfan and Isobenzan as well as DDT were the most effective materials in reducing earworm infestation. Also, Staples et al. (1968) showed carbaryl to be a very effective insecticide for controlling earworms. Harrison (1974) reported that Lorsban and Leptophos could control earworms as well as carbaryl.

Fall Armyworm

Distribution and Abundance in the U.S.A.

According to Snow and Copeland (1969) the fall armyworm (*Spodoptera frugiperda* J. E. Smith) is a unique species that distributes itself throughout the United States of America. However, this insect is not able to survive the winter anywhere in this country except in the Gulf Coast districts, southern portions of Florida, and Texas. Many of the adult moths migrate or disperse northward from these localities (Burkhardt 1952; Little 1963). Migration occurs every year with the advancement of the season, and they can reach as far as Montana, Michigan, New Hampshire and even beyond the Sault Ste. Marie (Canada) (Luginbill 1950; Metcalf and Flint 1962; Rose et al. 1975).

Fall armyworm is so called because it does not reach the more northerly regions until late in the summer or early in the fall (Luginbill 1950).

Only one generation occurs in the Northern States, but in the Gulf States there may be as many as six to eleven generations in one year (Little 1963).

Taxonomic Status

Fall armyworm was formerly named as Laphygma frugiperda (J. E. Smith), and many papers were published under this name. In 1958, Zimmerman (Todd 1964) synonymized the genus Laphygma with Spodoptera. Subsequently, Bayer (Wiseman 1967) reported that genera Laphygma, Prodenia, and Spodoptera should also constitute a single genus. Todd (1964) reviewed the taxonomic status of the species and recommended a combination, Spodoptera frugiperda (J. E. Smith) should be used for identification purposes in future biological and ecological studies. Therefore, Spodoptera frugiperda (J. E. Smith) of the family Noctuidae (Lepidoptera) is currently being used as the correct scientific name of the fall armyworm.

Biology, Ecology and Behavior

General Description of the Insect. The fall armyworm adult moths are 19 mm long and about 38 mm across their outspread wings (Little

1963). They have an ash colored body. The front wings of the males have a dark gray ground color and mottled appearance with usually an irregular white spot near the extreme tip. The front wings of the female are usually much darker than those of the males. The hind wings of both sexes are pearl-white with a brownish margin (Luginbill 1950; Metcalf and Flint 1962). Eggs are very small, light gray colored, and spherical in shape. They are usually found in clusters, partly covered with grayish fuzz from the body of the female moths (Anonymous 1961; Vickery 1929). Newly hatched larvae are white and have a black head. Full grown larvae are about 38 mm long and vary in color from light tan or green to nearly black. They have three yellowish-white hairlines down the back from head to tail. On the sides and next to the yellow lines is a wider dark stripe, and next to it are equally wide, somewhat wavy, yellow stripe splotched with red. Moreover, larvae's body has prominent black tubercles from which body hairs grow; and front of their heads is conspicuously marked with a white inverted Y (Anonymous 1961; Metcalf and Flint 1962). Pupae are reddish brown at first and gradually darken to almost black. They are usually covered with smooth, leathery skin (Luginbill 1950).

Life History. The female moths of Spodoptera frugiperda (J. E. Smith), being of predominantly nocturnal habits, lay eggs usually at night and they have been found on such unusual places as a clothesline (Rose et al. 1975). In the corn plants, eggs are laid in clusters (masses) frequently on the upper surface of the leaves. A mass generally consists of 50 to several hundred eggs deposited in layers which are superimposed upon one another; and each mass is covered with grayish scales from the female moth's body (Luginbill 1950; Vickery 1929). According to Metcalf and Flint (1962), a female moth may oviposit as many as 1,000 eggs, the average being about 150. The length of the egg stage varies with the temperature. Eggs may hatch in 2 to 3 days at temperatures of 29.7°C and 25.6°C, respectively (Vickery 1929).

The newly hatched larvae feed at first on their empty egg shells, but soon they begin feeding gregariously on the lower leaves, or other regions of the host plant where the eggs were deposited. First and second instar larvae are positively phototactic and negatively geotactic, so they move up into plant whorls, whereas the later instars do not show this response (Greene and Morrill 1970; Morrill and Greene 1973b). Larvae which feed in whorls may later be found in the tassel and finally in the ears as the plant matures (Morrill and Greene 1973a; Young and Hamm 1966).

Larvae molt 6 times and become fully grown in 12 days to more than a month, the time varying with the climatic conditions (Little 1963; Vickery 1929).

Upon completion of feeding, the mature larvae usually crawl down the stalks or drop to the ground where they burrow into the soil to depths of 2.5 or 5 cm to construct their pupal cells within which they transform into pupae (Anonymous 1961). However, larvae of *Spodoptera frugiperda* not only pupate in the soil but also they do in parts of the host plant. Burkhardt (1952) observed many of the larvae pupating in the ears, tassels, and whorls of corn plants. He estimated that approximately one fourth of the larvae population pupated in parts of corn, and not in the soil.

The duration of the pupal stage at summer temperatures may be 10 to 15 days, then the emergence occurs (Luginbill 1950). Adult moths are very active mainly at night. They may be able to fly hundreds of miles away until becoming sexually mature (Metcalf and Flint 1962; Rose et al. 1975). The life span of the adult moths has been recorded to be 10 to 14 days (Little 1963).

The number of generations of the species that annually occur has already been pointed out while discussing its distribution and abundance.

Mating and Sex Attractants. Fall armyworm adults mate under laboratory conditions approximately 2 hours after sundown during a period of about four hours (Sekul and Cox 1965). Mating could be induced by keeping the moths in controlled environmental chamber with temperature, humidity, and light programmed so that "sundown" would occur whenever is desired (Sekul and Cox 1967).

The mechanism of mating of the species has been studied in detail by Snow and Carlysle (1967). They were able to show that virgin male fall armyworms have a light brown to black pigment near the twisted portion of the ductus ejaculatorius. This pigment is incorporated into and transferred with the spermatophore during mating. Thereafter the ductus ejaculatorius simplex is transparent to yellow, which results in an indication of the mating status of the male.

Further studies done on mating habits of the fall armyworm moths showed that virgin females produce a sex pheromone within the last abdominal segment that evokes mating response in the males (Sekul and Cox 1965, 1967). Sekul and Sparks (1967) isolated and identified the sex pheromone as Cis-9-tetradecen-1-ol acetate by combining techniques of saponification, hydrogenation, ozonolysis, ultraviolet and infrared spectroscopy. In addition, they were able to obtain the *synthetic* sex pheromone for the species by reducing methyl myristoleate with lithium aluminum hydrate and acetylating the resulting compound. Elsewhere, Jacobson and Harding (1968) synthesized the same pheromone using the sex attractant of the cabbage looper moth.

The synthetically produced sex pheromone has been tested to suppress wild populations through mass trapping or confusion. Tingle and Mitchell (1975) evaluated pheromone traps of various designs against natural population of the fall armyworm, and found that electric grid trap plus sex pheromone compound, (2)-9-dodecen-1-ol acetate, was the most effective of the traps tested for capturing adult moths. Mitchell et al. (1974) tested 4 synthetic pheromones and an alcohol in field traps as possible sex attractant disruptors for the fall armyworm. Three of the compounds ((Z)-7-dodecen-1-ol acetate, (Z, E) - 9, 12-tetradecadien-1-ol acetate, and (Z)-9-dodecen-1-ol acetate) caused a greater 85% disruption of communication between males and females when they were evaporated into the atmosphere surrounding calling females.

Based on this result, the authors indicated that it might be feasible to use these compounds for a regional suppression program against the fall armyworm.

Host Range. Since the fall armyworm is a polyphagous noctuid, it is usually found as a serious pest of many cereal and forage crops including corn, sorghum, rice, oats, millet, kaffir, alfalfa, clover, and several species of native grasses (Burkhardt 1952; Luginbill 1950). Further, it may also be an important pest of cotton, tobacco, peanuts, potato, cucumber, and cowpeas as well as of some other garden crops (Anonymous 1961; Metcalf and Flint 1962). According to Vickery (1929), however, fall armyworm prefers to feed on coarse grasses, such as corn and sorghum.

Damage and Losses

Fall armyworm is one of the serious pests of corn not only in the United States but also in Mexico, Central and South America (Wiseman 1967).

According to Luginbill (1950), "the most severe general outbreak of this insect ever recorded took place in the summer of 1912, when it swept almost the entire United States east of the Rocky Mountains, destroying corn and millet and severely injuring cotton and truck crops." Since then there have been sporadic outbreaks of the pest almost every year, but these have been confined mostly to the Southern States. Occasionally, however, its destructive action has been reported in some Northern States (Burkhardt 1952; Harrison et al. 1959; Luginbill 1950; Vickery 1929; Wiseman 1967).

The main damage to corn by the fall armyworm occurs in the whorls and furls (leaves surrounding a central roll). Larvae bore into the whorls and feed on leaf tissue giving a ragged appearance to whorls (Straub and Hogan 1974). Young larvae apparently prefer closed leaves of the whorls instead of open leaves. According to Morrill and Greene (1973b), thigmotaxis may explain larval preference of closed areas such as whorls, furls, and regions between stalks and ear shoots. Grown larvae of the fall armyworm may completely destroy young plants or strip older plants of leaves so that only the midribs and stalks remain (Wiseman 1967). However, younger plants have a greater ability to recover from defoliation as pointed out by Kiesselbach and Lyness (Morrill and Greene 1974). Camery and Weber (1953) found that the greatest amount of yield reduction was associated with damage occurring at early-tassel stages, or the period of rapid shoot development, silking, and pollination. Brown et al. (Straub and Hogan 1974), utilizing simulated defoliation, found that crop loss is negligible when defoliation occurs very early in the growth of the plant but becomes progressively greater as the plant matures. Elsewhere, Morrill and Greene (1974) found varying degrees of grain yield reduction in tests utilizing a series of plant maturity-larval infestation level treatments. Within the combinations, however, there were no significant levels of yield loss due to fall armyworm feeding.

Damage also results from ear feeding and stalk boring. Ear damage is usually characterized by shank injury, resulting in dropped ears, rather than by tunneling down through the silk channel as is done by corn earworms. The fall armyworm may simply tunnel straight in through the husk to the kernel area (Wiseman 1967). Painter (1955) recorded damage consisting of injury to the kernels. Burkhardt (1952) reported considerable damage to corn by boring and feeding into the stalks.

According to Harrison et al. (1959) damage to sweet corn by the fall armyworm occurs from the time the plants appear above ground until the ears are ready to harvest. This is one of the most discouraging factors in the production of sweet corn. Blickenstaff (Wiseman 1967) has recorded a similar damage to field corn.

Estimate of monetary losses in the United States resulting from damage by the fall armyworm to corn has not been found, as far as the available literature is reviewed, but probably the corn yield reduction caused by the species rises many millions of dollars annually.

Control Measures

Biological. There are a number of parasitoids and predators that may ordinarily keep the fall armyworm population low and prevent outbreaks, except during years when conditions for the worm are exceptionally favorable (Anonymous 1961; Luginbill 1950).

In the Southern States several species of wasps play an important role in controlling fall armyworm population. A tiny braconid wasp *Chelonus texanus* (Cress) is one of the most effective egg parasitoids of the species (Walton and Luginbill 1936; Vickery 1929), while an eulophid wasp, *Euplectrus* sp., and the ichneumonid wasp, *Campoletis perdistinctus* (Viereck) have been observed parasitizing large numbers of fall armyworm larvae (Lingren and Noble 1972; Luginbill 1950). In addition, tachinid flies Winthemia spp. and Archytas piliventris (V.d.W.) have also been reported to be important parasitoids that might cause considerable reduction of larvae (Metcalf and Flint 1962; Vickery 1929).

In Arkansas, Kirkton (1970) reported a large and dense population of wasps, Polistes spp., preying larvae of fall armyworm.

Soldier bugs, Podisus maculiventris (Say), and ground beetles, Calosoma spp., can occasionally attack caterpillars (Luginbill 1950).

Furthermore, there are various types of disease organisms that have shown significant effects. Bacillus thuringiensis Berliner, which has already been discussed for corn earworm, is an effective pathogen of the fall armyworm and corn earworm (Janes 1973). Elsewhere, Spodoptera nuclear polyhedrosis virus may affect larval populations in sweet corn as pointed out by Young and Hamm (1966). Hamm and Young (1971) reported that a late-whorl or early tassel treatment with a combination of Heliothis and Spodoptera nuclear polyhedrosis viruses could result in an effective control of both fall armyworms and corn earworms.

Host Plant Resistance. Resistance studies with the fall armyworm have been less rewarding than studies involving the European corn borer, and corn earworm. Ditman and Cory (Widstrom et al. 1972) and Brett and Bastida (1963) reported the preliminary studies of resistance in corn to the fall armyworm. Later McMillian and Starks (1966) reported an extensive study of lyophilized plant material extracts for preference by the 3rd and 4th instar larvae of the fall armyworm. They stated that corn kernels obtained 10 days after sib-mating were preferred by the fall armyworms over mature corn seed, four-week-old leaves of corn plants and unpollinated silks. Subsequently, when larvae of the fall armyworm were fed diets of lyophilized plant tissue of 18 corn lines, significant differences in food use were found among corn lines, and plant parts (Starks et al. 1967). Wiseman et al. (1967a, 1967b) showed that fall armyworm larvae highly preferred corn to Tripsacum dactyloides (L.), which is considered a near relative of corn. A corn line "Antigua 2D" was the least preferred of the corns studied by the authors. Wiseman et al. (1973a) found that in an intermediate resistant Antigua corn, both a higher level of resistance and susceptibility could be induced by the use of a complete fertilizer or by individual fertilizer components.

Widstrom et al. (1972), in studies with 8 maize inbreds and their F_1 progeny, found that heterosis contributed substantially to the mean level of resistance among F_1 progenies. In addition, they concluded that a successful selection among these lines and their progeny would depend on the accumulation of additive gene effects for resistance to fall armyworm damage.

Cultural Practices. Since the fall armyworm, Spodoptera frugiperda (J. E. Smith) overwinters only in the south and gradually moves northward during the growing season, early corn planting in the north may be an important factor in control of this species. Corn may mature before this insect can migrate northward and become harmful (Anonymous 1969).

Also, a proper manipulation of host crop nutrition can importantly influence plant responses in regard to insect attack (Leuk et al. 1974). Wiseman et al. (1973b) showed that foliar application of the recommended rate of zinc could produce detrimental effects to the fall armyworm having fed on the treated corn foliage.

Mechanical and Physical. Attempts to eradicate the fall armyworm by the sterile-male technique have been made in the Southern States where these insects are more troublesome than in the North. Noblet et al. (1969) reported the first study of the fall armyworm eradication by gamma irradiation. They were able to establish the sterilizing dosage for male and female fall armyworms at 32.5 and 20 krad, respectively, when treated as 6-day-old pupae. However, treatment of pupae resulted in high mortality and loss of competitiveness. Subsequently, Snow et al. (1972) established the sterilizing dosage for males and females at 35 and 15 krad, respectively, when treated as newly emerged adults. Laboratory and field tests showed that these doses did not alter the lifespan of the adult moths, nor did it affect the ability of the adults to copulate. However, sterilization significantly reduced the oviposition rate of sterile females and the type of quality of sperm transferred by sterile males. Furthermore, the results indicated that sterilized males were approximately 0.46 times as competitive as normal males.

Use of Chemicals. Protection of corn from fall armyworm damage was achieved by several applications of DDT or other cyclodiene insecticides

(Metcalf and Flint 1962; Peairs and Davidson 1961). DDT can no longer be used because of residue problems and increased resistance shown in the species (Harris 1970; Janes and Greene 1969). Since DDT is no longer recommended, several studies have been conducted toward finding insecticides which would adequately replace DDT for preventing fall armyworm damage to sweet corn. Janes and Greene (1969) evaluated 14 different formulations against the fall armyworm and corn earworm in sweet corn. Highest percentage of injury-free ears was recorded in plots treated with Gardona, parathion, methylparathion, carbofuran, Dursban, parathion + lannate, and GC-6506. Cantu and Wolfenbarger (1973) tested 15 compounds, representing 3 new classes of insecticide chemistry, against the fall armyworm and two lepidopteran species. Among the different types of compounds, pyrethroids showed the greatest activity against the three lepidopteran species.

Several other insecticides have been found to be effective in controlling fall armyworm. Janes (1975) reported that Methomyl, chlorpyriphos, leptophos, tetrachlorvinphos, and Bay NTN 9306 gave good worm control when used alone.

According to Brooks and Gates (1975) control of fall armyworm on whorl stage cannot be practical unless 75 per cent of the plants are infested. Control may be justified on silking corn before the larvae have tunneled into the shanks and ears. In addition, they recommend sprays with diazinon, carbaryl, parathion, and mevimphos.

Southwestern Corn Borer

Distribution and Abundance in the U.S.A.

The geographical distribution and abundance of southwestern corn borer (*Diatraea grandiosella* Dyar) in the U.S.A. have been reported in detail by a number of workers including Davis (1933), Wilbur et al. (1950), Rolston (1955), Henderson et al. (1966), Elias (1970), and Chippendale and Reddy (1974a). The insect, originally confined to Mexico, invaded the United States early in this century (Rolston 1955; Clymer 1973). According to Wilbur et al. (1950), southwestern corn borer crossed the Mexican border into Arizona, New Mexico, and Texas in or before 1913; and by 1931 (Davis et al. 1933) it had spread north and eastward reaching central Oklahoma, southeastern Colorado, and southwestern Kansas. This species apparently disappeared from Kansas during 1933 to 1938 when corn did not succeed due to drought, but it noticeably reinvaded the state about 1941 (Wilbur 1950). By 1942, heavy infestations of corn in south-central Kansas were recorded, and by 1943 it spread rapidly through Kansas, reaching as far as the south-central area of Nebraska (Anonymous 1975e; Tate and Bare 1945). However, Chippendale and Reddy (1974a) indicate that the northern limit of the borer's range had receded from Nebraska and northern Kansas due to the cold winter temperatures which prevail in these localities. The eastern limit had extended across Oklahoma into west-central Arkansas by 1950 (Rolston 1955), and southwestern Missouri in 1953 (Chippendale and Reddy 1974a). In 1955, it was first reported in Louisiana (Floyd et al. 1969). In 1958, 1960, and 1962, it reached the states of Mississippi, Tennessee, and Alabama, respectively (Henderson et al. 1966). By 1964, the borer had penetrated the state of Illinois, and subsequently large populations of overwintering larvae were reported in this state (Fairchild 1965; Anonymous 1975). In 1974, infestations probably heavier than since outbreaks of the 1940s and early 1950s were reported in Kansas. During that period the pest caused many corn growers to drop corn production particularly in southern and central areas of the state (Anonymous 1974). In 1975, heavy infestations in late planted corn were currently reported in Kentucky (Anonymous 1975a). Elsewhere, fall survey conducted in southeast areas of Missouri showed an average of 52.8% infested corn (Anonymous 1975c), while up to 100% of corn was infested by the borer in New Mexico (Anonymous 1975b).

Taxonomic Status

According to Rolston (1955) all papers and records in regard to southwestern corn borer were published in the United States under the name of *Diatraea saccharalis* until 1911. In that year Dyar (Elias 1970) reviewed *Diatraea* and described southwestern corn borer as a new species from Mexico. The review, however, was not reliable from the scientific standpoint for the author used only external characteristics of the adult. Subsequently, Dyar and Heinrich (1927) published a complete revision of the genus *Diatraea* using genital characteristics of both sexes in addition to the external morphology of the adult. The original description of the southwestern corn borer remained unchangeable as Diatraea grandiosella Dyar. Later, Box (1956) separated the species from the genus Diatraea to Zeadiatraea, and redescribed it as Zeadiatraea grandiosella based also on genital characteristics of the male and female adults. However, the majority of papers on southwestern corn borer has been published in the United States under the original name, Diatraea grandiosella Dyar, which indicates that presumably a number of workers do not accept the generic name, Zeadiatraea given by Box.

The current scientific name of southwestern corn borer, as far as found in the majority and recent literature, is Diatraea grandiosella Dyar. It belongs to subfamily Crambinae, family Pyralidae, and order Lepidoptera (Anonymous 1975a; Anonymous 1975b; Chippendale 1975; Dyar and Heinrich 1927; Rolston 1955).

Biology, Ecology and Behavior

General Description of the Insect. Adult moths are from 15 mm to 19 mm long with a wingspread of about 32 mm, with males generally smaller than the females (Wilbur et al. 1950; Clymer 1973). Both male and female moths are solid white to pale yellow with lighter hind wings and, when at rest, the wings are folded about the body (Anonymous 1975e).

The eggs are about 1.2 to 1.6 mm in length by 0.8 to 1 mm in width. They are elliptical to oval and flattened with a slightly convex upper surface. Freshly laid eggs are translucent white, but prior to hatching they develop 3 parallel, transverse, pink or orange-red markings with the base yellow, orange-yellow, or reddish brown. Eggs are usually found in chains or groups that overlap much like fish scales (Anonymous 1975e; Rolston 1955).

The newly hatched larvae closely resemble the full grown larvae which are from 25 to 32 mm long and dull white or yellowish white in color. They also have prominent dark brown or black spots over the entire body (Henderson and Davis 1969; Wilbur et al. 1950). Full grown larvae of the overwintering brood generally lose their spots and become creamy yellow color (Anonymous 1975; Clymer 1973).

The pupae range between 13 and 25 mm in length. The newly formed pupae are about the same color as the larvae. They gradually assume a dark brown color (Henderson and Davis 1969).

Life History and Habits. Adult moths of the southwestern corn borer are nocturnal in habit (Walton and Bieberdorf 1948). Females oviposit eggs at night, usually in chains or clusters with the individual eggs overlapping like fish scales (Hensley 1955; Rolston 1955). Oviposition preferences in regard to the stage, and parts of the corn plant have been reported by a number of workers. Hensley (1955) found that 82% of all eggs were deposited on leaves. The remainder were on leaf sheaths and stalk surfaces. Davis et al. (1933) reported that the upper surface of the corn leaf was favored during oviposition, and that the lower surface and stalk were second and third choices, respectively. Stewart and Walton (1964), however, reported no difference between numbers of eggs found on upper and lower leaf surfaces on plants in the field.

Rolston (1955) indicated that moths may be attracted to corn, for oviposition, according to the stage of development and height, or both. Stewart and Walton (1964) suggested that leaf surface rather than factors related to stage or age of the plant determined the number of eggs deposited on a plant. Thus, larger plants received more eggs because of the greater surface area exposed to random contact by moths.

A female moth may oviposit between 150 to 400 eggs (Davis et al. 1933). However, Stewart and Walton recorded 61 to 78 eggs per moth under field conditions. In addition they found females to be more productive the first two days following mating, with egg production diminishing sharply thereafter until they become spent by the fifth day.

The eggs hatch in 3 to 7 days, depending on the temperature (Rolston 1955; Anonymous 1975e). Newly hatched larvae leave the vicinity of the eggs and move into the whorl of the corn plants where they feed for about 10 days on immature leaves (Davis et al. 1972; Clymer 1973). Rolston (1955) observed positive thigmotaxis in larvae of the species but did not observe phototaxis or geotaxis.

Feeding behavioral experiments conducted by Chippendale and Reddy (1974b) showed that compounds such as glucose, fructose, sucrose and dextrins as well as amylopectin were feeding stimulants and permitted optimum growth and development of the southwestern corn borer, whereas pentoses, arabinose, ribose, xylose, galactose, mannose and sorbose inhibited larval growth. In a related study, Chippendale (1975) found that ascorbic acid in a concentration of 0.5% (wet wt.) was an essential nutrient for normal growth, development and fertility of the southwestern corn borer, but it had a neutral effect on larval feeding behavior. In addition, he tested the sensitivity of the six larval stages to ascorbic acid, and showed that the species had a critical dietary requirement during the second and third stages.

After feeding in the whorl, the larvae enter the stalk during the 3rd to 4th instars, and start tunneling (Davis et al. 1933; Rolston 1955). On tassel-stage corn, most young larvae move into the ear and feed between the husk layers and between ears and ear shoots. Later they feed on the kernels, cob and shank (Anonymous 1975e). The larvae then move from the ears and ear shoots to the stalk where they start tunneling up and down (Anonymous 1975d).

Larvae may molt an average of 6 times and become full grown in about 25 days (Clymer 1973; Davis et al. 1933; Rolston 1955).

Upon completion of feeding and before pupation the mature larvae construct a kind of pupal cell. The larval tunnel is extended to the rind of the stalk where an emergence "window" is made and only a thin "pane" is left (Anonymous 1975e). Pupation takes place usually at the lower end of the tunnel, and emergence occurs in about 10 days (Elias 1970).

The overwintering habits of larvae are somewhat different from the summer larvae's habits (Clymer 1973; Davis et al. 1933). Full grown larvae of the last generation become pale yellow when they begin to girdle stalks from inside and to build a small hibernation cavity (Anonymous 1975e). Larvae usually hibernate in the extreme lower tip of the tap root (Anonymous 1975d). Larval diapause will be discussed in detail in a subsequent topic. The overwintering larvae pupate in the spring and soon the emergence of the moths occurs from the tap root (Clymer 1973). The emergence of the adults from the overwintering generation varies according to the locality. Moths emerge about mid-May in Arizona (Davis et al. 1933), during June in Oklahoma and Arkansas (Rolston 1955; Walton and Bieberdorf 1948), during May in Mississippi (Davis et al. 1974), and during early June in Kansas (Wilbur et al. 1950). Moths from the summer (first) generation emerge during June to July in Arizona, Arkansas, and Mississippi (Davis et al. 1933; Davis et al. 1974; Rolston 1950), and by late July to early August in Oklahoma and Kansas (Anonymous 1975e; Walton and Bieberdorf 1948).

Adult moths may live about 2 to 6 days, with females averaging 2 days longer than males (Davis 1933).

A complete generation may occur in 40 to 50 days in Arizona (Davis et al. 1933), 41 days in Arkansas (Rolston 1955), and about 45 days in Kansas (Wilbur et al. 1950).

The number of generations per year varies from state to state and in some cases within the state. According to Fairchild (1965), there may be only two generations in the northern areas of Kansas, while 3 generations generally occur in the southern area of the state. Three generations are very common in Mississippi, Tennessee and other southern states (Arnold et al. 1970; Davis et al. 1974).

Mating Habits and Sex Attractant Studies. Since the southwestern corn borer moths are of nocturnal habits, they usually mate at night (Walton and Bieberdorf 1948). According to Langille and Keaster (1973) males participate in a precopulatory flight, occurring from about 9 p.m. to 12 midnight and 5 to 8 hours after emergence. Thereafter most mating takes place the same night of emergence, between 11 p.m. and 2 a.m. Females may apparently mate only once (Rolston 1955).

Preliminary research to detect the presence of sex attractants in the female moths has been reported in the literature. Davis and Henderson (1967) investigated the possibility of the sex attractancy of the male moths to females for mating. They observed that most females began to attract males on the night of emergence, but attractancy dropped sharply after the fourth day, and was completely absent in 8-day-old females. Subsequently, Langille and Keaster (1973) reported that males of *Diatraea grandiosella* Dyar were attracted to unmated (virgin) females, which in general, were less than 73 hr old; but females were not attracted to males. These findings virtually indicate that virgin females secrete a pheromone responsible for the sexual stimulation of the males.

Diapause Studies. The southwestern corn borer, *Diatraea grandiosella* Dyar, has a facultative diapause and enters it as an immaculate mature larva which is a polymorphic variant of the spotted nondiapause larva (Chippendale and Reddy 1972; Davis et al. 1933). Several ecological and physiological factors are involved in regulating the initiation, development and termination of diapause (Chippendale and Reddy 1972, 1974a; Chippendale and Alexander 1973; Yin and Chippendale 1974). Chippendale and Reddy (1972) reported that mature larval diapause was successfully induced by exposing the immature larval stages to 23^{o}C and a photoperiod of 12L:12D. In addition, they pointed out that polymorphism was of special physiological interest because the transition from the spotted to immaculate larva positively identified the initiation of diapause. Spermatogenesis was found to be arrested and secondary spermatocytes degenerated during the first phase of larval diapause (Alexander and Chippendale 1973), whereas a resumption of spermatogenesis took place during the last phase (Chippendale and Alexander 1973).

A possible nature of hormonal mechanisms regulating diapause induction and development were suggested by Chippendale and Reddy (1972). Later, Yin and Chippendale (1974) showed that the topical application of a juvenile hormone mimic to mature spotted non-diapause larvae effected them to ecdyse into immaculate diapause larvae which were morphologically and physiologically equivalent to normal-diapause larvae. The authors concluded that the larval diapause of the southwestern corn borer is initiated and maintained by the juvenile hormone.

Chippendale and Reddy (1973) studied in detail the effect of temperature and photoperiod on the development of the mature larval diapause of the southwestern corn borer. The results of the study indicated that diapause induction was an extremely temperature-dependent process, but did not require a period of chilling (5°C). The role of the photoperiod in regulating diapause development was found not entirely clear. The authors, however, were able to demonstrate a photoperiod response only at 25°C, when diapause was instituted following larval exposure to daily photophases ranging from 8 to 14 hr. In related experiments the same workers (1974a) determined the supercooling point (-8.5°C) and freezing point (-2°C) of the diapause larvae, and showed that the borers were susceptible to freezing. Also, they were able to demonstrate that borer populations do not survive in localities where the 10-year-mean January temperature falls below -7°C (19.4°F). In other related experiments Reddy and Chippendale (1973) studied the water involvement in diapause. They showed that southwestern corn borer did not require contact water to complete diapause development. In fact, they found that this process occurred more rapidly in larvae held dry than in those continuously provided with water. The availability of water did, however, promote the post-diapause pupal moulting cycle of larvae which had completed diapause development.

Host Range. The host range of the southwestern corn borer has not been reported in detail as far as the literature is reviewed. However, according to various workers, corn is the principal host plant attacked by the borer, but it also feeds upon sorghum, sugar cane, broom corn, sudan grass, johnson grass, and cocklebur (Anonymous 1975d; Clymer 1973; Metcalf and Flint 1962; Rolston 1955; Walton and Bieberdorf 1948).

Damage and Losses

The southwestern corn borer may produce various types of damage to corn. Whorl feeding, "dead heart," stalk tunneling, and stalk girdling have been reported to be the most important types of damage (Arnold et al. 1970; Black et al. 1970a; Clymer 1973; Davis et al. 1972; Douglas 1968; Scott and Davis 1974).

Feeding of the young larvae in the whorls causes a reduction in leaf surface. The whorl feeding damage appears as small glazed areas and as larval feeding continues, holes are cut through the leaves giving a ragged appearance to whorls (Anonymous 1975d; Black et al. 1970a). Several insects can cause this characteristic ragging damage including fall armyworm, and corn earworm (Clymer 1973; Straub and Hogan 1974). This type of damage is normally caused by the first generation larvae, and it may not be economically important (Arnold et al. 1970). However, under heavy infestation of the first generation larvae, they may penetrate into the growing tip of the young plants and feed on the meristimatic tissue causing "dead heart" in the center leaves, which results in either death or severe stunting of the plant (Anonymous 1975e; Black et al. 1970a; Walton and Bieberdorf 1948; Wilbur et al. 1950).

According to Arnold et al. (1970), "the most striking types of damage are tunneling in the lower portion of the stalks, and later in the season, girdling of the stalks just above the ground level." Tunneling is usually caused by late instar larvae which may destroy part of the vascular tissue of the stalks resulting in grain yield reduction (Henderson and Davis 1969; Stanley et al. 1962). Girdling is an unusual type of damage characteristic of the southwestern corn borer (Rolston 1955). Larvae that are preparing to go into diapause, girdle the stalks just above the ground level by cutting a circular groove inside of the stalk (Davis et al. 1974; Walton and Bieberdorf 1948). Both summer and overwintering larvae may girdle corn stalks in

Tennessee (Arnold et al. 1970). Girdling weakens the stalks and greatly increases the amount of lodging. Ears from lodged plants cannot be harvested by mechanical harvesters, and these ears are subject to damage by rodents and disease organisms. Thus, girdling usually causes great yield reductions (Black et al. 1970a; Chada et al. 1965; Davis et al. 1974). According to Mitchell and Young (1975), girdling may result in over 50% of the stalks lodging or falling. Arnold et al. (1970) observed more than 90% of the lodged stalks due to girdling in Tennessee. Douglas (1968) reported the tunneling by the southwestern corn borer reduced the yield of corn in Mississippi by an average of 17.9 bushels per acre. A combination of tunneling and girdling reduced yields by 1917 bushels per acre. Scott and Davis (1974) found significant direct yield losses of 20 and 9% from first- and second-generation damage, respectively. The authors indicated that these amounts did not include possible losses incurred by lodging caused by girdling of the plants.

Control Measures

Biological. Several beneficial insects, including both parasitoids and predators, may play an important part in population reduction of the southwestern corn borer. Davis et al. (1933) listed *Trichogramma minutum* Riley and *Apanteles diatraeae* Muesebeck as parasitoids of eggs and larvae, respectively. Clymer and Daniels (1975) reported that both larvae and adult lady beetles, larvae of the green and brown lacewing, and several members of the assassin bugs as well as large numbers of spiders may prey on larvae of the southwestern corn borer, while flower bugs may destroy eggs. Significant effects of these beneficial arthropods, however, have not been reported in the literature.

A bird, the yellow shafted flicker, Colaptes auratus (Linn.), has been observed feeding on the overwintering larvae (Black et al. 1970b; Floyd et al. 1969; Wall and Whitcomb 1964). Davis et al. (1973a) found the flicker to be the major factor in the mortality of overwintering borers in Mississippi. Also, they indicated that the flicker was highly efficient in finding stalks that contained larvae. Wall and Whitcomb (1964) found that flickers could destroy from 1.7 to 24.6 per cent of the overwintering population in certain areas of Arkansas. Black et al. (1970b) evaluated the extent and value of predation by flickers in Mississippi. The results showed that flickers removed from 63.7 to 81.8 per cent of the overwintering larvae. The authors concluded that the flicker was a key factor in the reduction of overwintering southwestern corn borer populations.

Host Plant Resistance. The preliminary studies on resistance of corn to the southwestern corn borer were reported in Oklahoma (Walton and Bieberdorf 1948) and Kansas (Wilbur et al. 1950). Painter (1968) found that the hybrid K228 x K230 showed lower infestation and a higher percentage of infested plants lodged than the susceptible strains. York and Whitcomb (1963) reported the development of a synthetic variety, Ark SWCB Syn., with a high degree of resistance to stalk invasion. Subsequently, York and Whitcomb (1966) developed two additional synthetic resistant varieties, namely, Ark SWCB Syn., and Ark leaf feed Res. Syn.

Elias (1970) tested 57 corn varieties, from different countries, for resistance to the stalk borers including southwestern corn borer.

He found 12 corn selections (Antigua gpo. 1, Antigua gpo. 2, Guadeloupe gpo. 1A, Haiti gpo. 1, Haiti gpo. 3, Puerto Rico gpo. 1, Puerto Rico gpo. 2, Puerto Rico gpo. 3, Republica Dominicana gpo. 2, Santa Lucia gpo. 2, San Croix gpo. 1, Tuxpantigua and (T_2 x WF_9) x T_2) were the best sources of resistance to the borers. Davis et al. (1973b) screened corn germplasm for possible resistance to 1st and 2nd broods of the southwestern corn borer in Mississippi. After 4-year study the authors showed that two lines of corn from Antigua Gpo. 2 (Mp68:576, and Mp68:616) had intermediate resistance to 1st brood attack. Several corn lines from southern states and Central America showed some degree of resistance to the attack of 2nd brood.

Additional studies on resistance of corn to the southwestern corn borer are presently underway in Kansas and in different Southern Corn Belt states.

Cultural Practices. Several workers have reported the feasibility of controlling the southwestern corn borer by means of a number of cultural practices (Anonymous 1975d; Arnold et al. 1970; Clymer 1973; Clymer and Daniels 1975; Henderson and Davis 1969; Mitchell and Young 1975).

Area wide stalk destruction through practices, such as double disking and deep breaking, destroy the plant crown which affords overwintering larval destruction (Anonymous 1975d; Clymer and Daniels 1975). Henderson and Davis (1969) reported that fall disking would reduce overwintering larval populations, but it would need to be done over a large geographical area to prevent reinfestation by migrating adult populations. Also, they indicated that deep plowing was not as efficient as disking.

Early planting is another cultural practice that has been reported to be an important factor in control of the southwestern corn borer mainly in northern states (Anonymous 1969). Rolston (1955) reported that loss from "dead heart" and stunting in Arkansas could be reduced by early planting. Also, Chada et al. (1965) in Oklahoma, indicated that corn yield losses due to borer infestation could be reduced by early planting and harvesting. Arnold et al. (1970) in Tennessee, reported that the most consistent advantage of early planting of corn was the reduction in girdling. Further, research data and observational data in southern states indicated that early planted corn was less susceptible to plant lodging caused by the borer (Clymer and Daniels 1975; Mitchell and Young 1975). According to Fairchild (1965), however, early planting may not always be feasible because of variations in environmental and climatic conditions. Likewise, it was indicated (Anonymous 1975e) that no known cultural method has consistently controlled the southwestern corn borer population in the United States.

Use of Chemicals. Studies of insecticidal control have indicated that the southwestern corn borer population can be reduced by using insecticides, most of which are no longer registered for use on corn (Clymer and Daniels 1975; Fairchild 1965; Pless et al. 1972).

Various soil-applied systemic insecticides have been shown to be promising in controlling the pest. Hensley et al. (1964) reported that preplanting treatment of the soil with a granular formulation of AC 47470 gave highly effective control for 62 days after treatment. In a further test of soil-applied systemics for borer control (Whitcomb et al. 1966), Bayer 25141, Bayer 37289, and carbofuran were found to be promising insecticides. Keaster and Fairchild (1968), working with 6 systemic granular insecticides, found that a split application of carbofuran 1.5 lb/acre at planting and 1.5 lb/acre as a sidedress gave the best control. Pless and Duck (1969) obtained variable results in Tennessee with soil applications of carbofuran.

Foliar applications of insecticides may also prevent the borers attack. Henderson and Davis (1967) tested several insecticides as sprays and granules in Mississippi. They found endrin and isobenzan gave good control, with carbaryl, DDT and diazinon reducing infestation and stalk-girdling on corn. Bacillus thuringiensis Berliner was found to be ineffective. Henderson and Davis (1970) evaluated spray formulations of Azodrin and carbofuran, and granular formulations of carbofuran, endosulfan, and endrin. Four applications of Azodrin and carbofuran significantly reduced borer infestations and stalk girdling. Keaster (1972) tested 15 insecticidal compounds over a 3-year period for control of the southwestern corn borer. He showed 6 insecticides as the most effective in controlling the borer; namely, monocrotophos, diazinon, endrin, carbofuran, and gardona. Pless et al. (1972) obtained significant control of the borers with foliar applications of carbofuran, and sevimol. Davis et al. (1974) reported that in-furrow treatments with carbofuran at planting were as effective for control of 2nd generation southwestern corn borers as the foliar applications of carbofuran timed to coincide with moth emergence.

Timing of applications of chemicals has been reported to be critical for control of southwestern corn borers (Henderson and Davis 1969). Clymer and Daniels (1975) stated that little control would be obtained after the borers have entered the plant. Furthermore, they indicated that the need for chemical treatment should be based on field inspections to determine the abundance of egg masses or young larvae. According to Gates and Brooks (1975) in Kansas, chemical applications for southwestern corn borer control could be justified if 25 per cent or more of the plants are infested with live larvae/or egg masses, and if larvae have not started tunneling down into the stalks. In addition, the authors have suggested the use of Furadan 10 G, diazinon 14 G, or Sevinmol 4.

SUMMARY AND CONCLUSIONS

Distribution, biology, ecology, behavior and methods of control of European corn borer, northern corn rootworm, western corn rootworm, corn earworm, fall armyworm, and southwestern corn borer have been reviewed to provide data that may serve as tools for an accurate Pest Management Program to achieve effective control of these six major pests of corn in the United States.

European corn borer, the most important insect pest of corn, is currently causing economic damage in 40 states. Its biology, ecology and behavior has been thoroughly studied, much more extensively than that of the other 5 insects. Populations in North America have been separated into 3 ecotypes (northern, central and southern) on the basis of differential response to diapause and behavior as well as morphological characteristics. In addition, there are two distinctive pheromone strains (predominantly Z vs predominantly E) that have been separated, based on sex pheromonal response to different combinations to Z and E isomers of 11-tetradecenyl acetates. However, these pheromone strains do not coincide with, but do transcend, the diapause ecotypes.

Because northern and western corn rootworms live together, an interaction between them has been shown. A hybrid with phenotype of the western species was obtained in the laboratory. The western species has become a more serious pest than the northern. Investigations on behavior of these species have shown the existence of a sex pheromone in the western, virgin females.

The literature on corn earworm indicates that it is more injurious in sweet corn than in field corn. Adult moths are highly active only in the dark of the moon, thus their reproductive activity could be prevented by artificial lights if moonlight were absent.

The fall armyworm, a close relative of the corn earworm, cannot survive cold winter temperatures in northern states but is able to migrate from the south as far north as Sault Ste. Marie (Canada). Thus, it is much more troublesome in southern than in northern states.

Southwestern corn borer, originally confined to Mexico, had invaded first Arizona and New Mexico by 1913. Today it currently occurs in 15 states. Extensive, recent literature has been published concerning biology and attempted control. Larval diapause has been found to be extremely temperature-dependent. In addition, a juvenile hormone mimic has been shown to effect diapause development.

Biological, cultural, mechanical and physical as well as chemical methods of controlling the six insect pests are reviewed. No biological agents nor mechanical and physical devices have been reported in the literature to be consistently operative at a sufficient level to control these pests. Corn earworm, northern and western corn rootworms have noticeably developed resistance to cyclodiene and some organophosphorus chemicals. By contrast, granular formulations of carbofuran and carbaryl have been shown to be the most effective insecticides particularly for controlling corn earworm, fall armyworm, and corn rootworms.

The development of resistant varieties of corn has been pointed out to be a highly desirable means of control for all of the 6 insects. Resistance to 1st and 2nd generation of the European corn borer is not conditioned by the same genes. A genotype obtained by combining the two types of resistance has not been shown to be significantly resistant to both generations of the European corn borer. Instead, several exotic corn lines, containing very low concentrations of the chemical DIMBOA, have been demonstrated to be promising sources for controlling not only both generations of the European corn borer but also corn earworm, fall armyworm and southwestern corn borer.

Also, attempts to suppress populations of European corn borer, corn earworm and fall armyworm have been made by disrupting their sex attraction behavior. Up to 85 per cent disruption of communication between male and female fall armyworm moths have been achieved by using pheromone traps in the field. Elsewhere, microencapsulated compounds of sex pheromone inhibitors, distributed in field plots, significantly suppressed the sex attraction of the European corn borer. The treatments, however, did not keep the females from depositing egg masses within the treated areas. Furthermore, the pheromone inhibitors affected only distance communication between males and females.

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APPENDIX

Table 1. Estimated losses and production costs attributed to insects and related arthropods attacking corn (for grain) in Kansas during 1974.

Pest or pest complex [a]	Acres needing control	Acres treated	Yield loss for not treating per acre		Yield loss for not treating all acres		Control cost		Combined control cost and loss	
			bu.	$	bu.	$	Per acre $	All acres $	$	% of total crop value
CB	13,150	3,400	3.8	13.11	37,050	127,823	3.50	11,900	139,723	0.0308
CEW & FA (in ears)	-	14,800	-	-	1,235,618[b]	4,262,882[b]	3.50	51,800	4,314,682	0.9512
CEW & FA (in whorls)	31,320	13,520	3.04	10.49	54,112	186,722	3.50	47,320	234,042	0.05160
CLA	-	32,550	-	-	-	-	3.00	97,650	97,650	0.02153
CR (adults)	138,900	128,255	3.04	10.49	32,361	111,666	3.00	384,765	496,431	0.10944
CR (larvae)	589,000	1,038,000	12.16[c] 1.0[d]	41.95[c] 3.45[d]	821,200[c] 519,000[d]	2,936,640[c] 1,790,550[d]	4.00	4,152,000	8,879,190	1.95747
Cws	9,500	870	3.8	13.11	32,794	113,139	4.00	3,480	116,619	0.02571
ECB	-	5,000	-	-	-	-	3.50	17,500	17,500	0.00386
FB	-	10,800	-	-	-	-	3.50	37,800	37,800	0.00833
SWCB	102,500	10,000	7.6	26.22	703,000	2,425,350	4.00	40,000	2,465,350	0.5435
SpM	-	549,469	-	-	-	-	4.00	2,197,876	2,197,876	0.48453
T	-	2,300	-	-	-	-	3.50	8,050	8,050	0.00177
WBC	-	6,282	-	-	-	-	3.50	21,987	21,987	0.00485
YsAW	5,300	100	2,28	7.87	11,856	40,924	3.50	350	41,274	0.00910
TOTALS (all insects)								7,017,178	19,068,174	4.2037

[a] Pest legend:
CB - Chinch Bug
CEW - Corn Earworm
CLA - Corn Leaf Aphid
CR - Corn Rootworms
Cws - Cutworms
ECB - European Corn Borer
FA - Fall Armyworm
FB - Flea Beetles
SWCB - Southwestern Corn Borer
SpM - Spider Mites
T - Thrips
WBC - Western Bean Cutworm
YsAW - Yellowstriped armyworm

[b] Loss based on statewide fall loss survey; not related to whether corn was or was not treated.

[c] Loss on acreage not treated that needed treatment (70,000 A).

[d] Loss on treated acreage due to poor control in some cases.

1974 PRODUCTION STATISTICS FROM KANSAS CROP REPORTING SERVICE: Total acres harvested, 1,730,000; total bushels produced, 131,480,000; 1974 avg. price/bu., $3.45; total value of crop, $453,606,000.

Table 2. English and metric equivalents.

1 pound per acre	=	1.120 kilograms per hectare
1 acre	=	0.4047 hectare
1 pound	=	0.4536 kilograms
1 bushel (most grains)	=	56.0 pounds or 25.4016 kilograms
1 gallon	=	3.785 liters
1 inch	=	2.540 centimeters or 25.40 millimeters
1 foot	=	30.4799 centimeters

REVIEW OF DISTRIBUTION, BIOLOGY AND CONTROL METHODS OF SIX MAJOR INSECT PESTS OF CORN IN THE UNITED STATES

by

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The European corn borer, Ostrinia nubilalis (Hübner), northern corn rootworm, Diabrotica longicornis (Say), western corn rootworm, Diabrotica virgifera LeConte, corn earworm, Heliothis zea (Boddie), fall armyworm, Spodoptera frugiperda (J. E. Smith), and southwestern corn borer, Diatraea grandiosella Dyar, are the major damaging pests of corn in the United States. Recent data on distribution and abundance of these species in this country as well as the most important findings in biological and behavioral investigations from the past, to date, are reviewed. The differentiation in at least three ecotypes of the European corn borer, based on diapause response, and their relationship with the two pheromone strains are discussed. The evidence of the existence of a sex pheromone in virgin females of western corn rootworm is included.

Biological, cultural, mechanical, physical, and chemical control measures are presented. No biological agents nor physical and mechanical devices have been reported to be consistently operative at a sufficient level to control these pests. Corn earworm, northern and western corn rootworms have noticeably developed resistance to cyclodiene and some organophosphorus chemicals. The development of resistant varieties of corn is a highly desirable means of control for all of these 6 pests. Resistance to first and second generation of the European corn borer in corn is not conditioned by the same genes. A genotype obtained by combining the two kinds of resistance has not shown to be significantly resistant to both corn borer generations. Instead, several exotic corn lines containing very low concentrations of the chemical DIMBOA have been demonstrated to be promising sources of controlling not only both generations of European corn borer but also fall armyworm, and corn earworm.

Attempts of population suppression of the European corn borer, corn earworm, and fall armyworm by pheromonal disruption are discussed. Furthermore, recent studies of diapause development and the role of temperature in regulating the population dynamics of the southwestern corn borer are thoroughly reviewed.