

BIOLOGY AND CULTURAL CONTROL OF LESSER CORNSTALK BORER ON
SUGARCANE

By

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To my beloved parents, Mr. Joginder Singh and Mrs. Kulwant Kaur for their perpetual love and support and to my wife, Sandeep Sandhu for encouragement and understanding

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Lesser cornstalk borer, *Elasmopalpus lignosellus* Zeller (Lepidoptera: Pyralidae), is an important sugarcane pest in southern Florida. It feeds on meristematic tissues of young sugarcane shoots and causes dead hearts, symmetrical rows of holes in the leaves, and plant death. Development and survivorship of immature stages, and reproductive, generation and population life table parameters of *E. lignosellus* were studied on sugarcane at nine constant temperatures. Development times were shortest between 27 and 30 °C. Lesser cornstalk borer required 543.5 degree days to complete development ranging from 22.8 ± 0.3 d at 33 °C to 120.7 ± 2.8 d at 13 °C. Pre- and post-oviposition periods decreased and oviposition period increased with increasing temperatures from 13 °C to 33 °C. Mean fecundity, stage-specific survival (l_x), stage-specific fecundity (m_x), intrinsic rate of increase (r), and net reproductive rate were greatest at 30 °C. The relationships between developmental rate and temperature, and between temperature and r , were best fit by the Briere-1 and -2 models, respectively.

A 2-year greenhouse experiment was conducted to document variety and age specific *E. lignosellus* feeding damage and yield effects in sugarcane larvae. Sugarcane response to feeding was recorded as damage symptoms, tiller production,

number of millable stalks, and sugarcane and sucrose yield. Infestation at 3-leaf stage resulted in more dead hearts and dead plants than when infested at 5- and 7-leaf stages. The sugarcane variety CP89-2143 was more sensitive to *E. lignosellus* damage and resulted in reduced sugarcane and sucrose yield compared with CP78-1628 and CP88-1762. All varieties infested at the 3-leaf stage produced more yield than when infested at the 7-leaf stage. Comparison of yield reduction with the *E. lignosellus* lethal damage (dead hearts + dead plants) showed these varieties had equal ability to compensate for feeding damage, but that compensation ability declined with the delay in infestation time.

Field studies were conducted in 2006 to determine the effects of harvest residue from green harvesting versus pre-harvest burning on *E. lignosellus* damage and sugarcane yield. Harvest residue removed from a green harvested field and placed in plots in a plant cane field resulted in significant reduction of *E. lignosellus* damage. Sugarcane (TCA) and sucrose (TSA) yields did not differ between plots with and without harvest residues in plant or ratoon sugarcane. Three post-harvest tillage levels were tested in green and pre-harvest burned fields in 2008 and 2009. Significantly less *E. lignosellus* damage was observed in green versus pre-harvest burned fields in both years. No- and intermediate-tillage significantly reduced damage compared to conventional tillage in green harvested fields only. In both years, greater TCA was produced in intermediate than other tillage levels in green harvested sugarcane, whereas TCA and TSA were greater in conventional than other tillage levels in pre-harvest burned sugarcane.

These studies provide information useful for *E. lignosellus* population prediction and discovered the variety and age specific nature of sugarcane damage by this pest. Field studies showed the positive effects of green harvesting and intermediate tillage for reducing *E. lignosellus* damage and increasing sugarcane yield.

CHAPTER 1 REVIEW OF LITERATURE

Introduction

Sugarcane, *Saccharum officinarum* L. is an important crop grown in many southern temperate through tropical regions of the world. Brazil is the world's leading sugarcane producer followed by India (USDA 2008). Florida, Louisiana, Texas and Hawaii are the main sugarcane producing states in the U.S. Florida is the leading sugarcane producing state in the U.S. with 401,000 acres of sugarcane valued at \$398.9 million dollars in 2008 (USDA 2008). In Florida, sugarcane is mainly grown in the Everglades Agricultural Area around Lake Okeechobee. Due to the lake's warming effect, sugarcane is protected from severe winter and frost conditions.

Sugarcane is a tall-growing monocotyledonous crop plant of the family Poaceae that is cultivated primarily for its ability to store high concentrations of sucrose in the stem internodes. Cox et al. (2000) reported that modern sugarcane varieties cultivated for sugar production are complex interspecific hybrids (*Saccharum* spp.). These hybrids have arisen through intensive selective breeding of species within the *Saccharum* genus, primarily involving crosses between the species *Saccharum officinarum* L. and *S. spontaneum* L. Daniels and Roach (1987) reported that Polynesia was the *S. officinarum* center of origin. The species was probably transported throughout Southeast Asia by humans, leading to a modern center of diversity in Papua, New Guinea and Irian Jaya, Indonesia, where the majority of specimens were collected in the late 1800s.

Commercial sugarcane is propagated vegetatively. Germination refers to the initiation of growth from buds present on the planted sets or on the stems of the stools

that remain in the soil after harvest of the previous crop (Wilcox et al. 2000). Sugarcane varieties differ in their sensitivity to temperature, but in general germination is slow at soil temperatures below 18°C and increases rapidly up to about 35°C. Maturation is associated with the lower rainfall and cooler temperatures of the winter months (Bull 2000).

Insect Pests and Sugarcane

There are several factors that can result in decreased sugarcane yield, including insect damage. Worldwide, sugarcane as an agro-ecosystem is inhabited by many insect species in both above ground (aerial) and below ground (subterranean) habitats (Meagher 1996). He reported the important aerial pest species in the following orders and families: Orthoptera (Acridoidea), Homoptera (Aphididae, Cercopidae, Coccidae, Delphacidae, Diaspididae, Pseudococcidae and Margarodidae), and Lepidoptera (Castniidae, Crambidae, Noctuidae, and Pyralidae). He also reported the subterranean sugarcane insect pests represented by Orthoptera (Gryllidae and Gryllotalpidae), Isoptera (Mastotermitidae, Rhinotermitidae, and Termitidae), Heteroptera (Cicadidae, Cydnidae, Tingidae), Coleoptera (Curculionidae, Elateridae, and Scarabaeidae), Hymenoptera (Formicidae), and Diptera (Stratiomyidae) (Meagher 1996). Common insect pests of sugarcane in Florida are west Indian cane weevil, *Metamasius hemipterus sericeus* (Oliver) (Coleoptera: Curculionidae), white grub, *Ligyris subtropicus* Blatchley (Coleoptera: Scarabaeidae), wireworms *Melanotus communis* (Gyllenhal) (Coleoptera: Elateridae), sugarcane lace bug, *Leptodictya tabida* (Herrich-Schaeffer) (Heteroptera: Tingidae), white sugarcane aphid, *Melanaphis sacchari* (Zehntner) (Homoptera: Aphidae), yellow sugarcane aphid, *Sipha flava* (Forbes)

(Homoptera: Aphidae), sugarcane borer, *Diatraea saccharalis* (Fabricius) (Lepidoptera: Crambidae), and lesser cornstalk borer, *Elasmopalpus lignosellus* (Zeller) (Lepidoptera: Pyralidae) (Nuessly 2006).

Systematics and Distribution of Lesser Cornstalk Borer

The lesser cornstalk borer was first described by Zeller in 1848 as *Pempelia lignosella* from material collected in Brazil and Uruguay, and a single female from “Carolina”, United States. Its seasonal and geographical distribution was recorded by Zeller (1872) from Brazil and Colombia, in South America, and “Carolina” and Texas, in the United States. He also added the description of two varieties, *incautella* and *tartarella*, based on the color variations. Later on in 1881, he placed *incautella* as a synonym of *lignosella* though still retaining *tartarella* as a valid variety.

Blanchard’s 1852 work confused the status of the species by placing it within a new genus, *Elasmopalpus*, and giving it the species name *E. augustellus*. The systematics of lesser cornstalk borer became more complicated in 1888 when it was redescribed as *Dasypyga carbonella* by Hulst (1888) based on specimens collected in Texas, USA. Hulst (1890) later rectified this mistake and placed *D. carbonella* as a synonym of *P. lignosella tartarella*. In the same publication, he redescribed *lignosellus* and placed it in genus *Elasmopalpus* for the first time, giving a bibliography and notes on the distribution and seasonal occurrence. The synonymy, then, stands as follows: *Pempelia lignosella* Zeller, *Elasmopalpus augustellus* Blanchard, *Pempelia lignosella tartarella* Zeller, *Pempelia lignosella incautella* Zeller, *Dasypyga carbonella* Hulst, *Elasmopalpus lignosellus* (Zeller) Hulst, *Elasmopalpus lignosellus incautellus* (Zeller) Hulst, *Elasmopalpus lignosellus tartarellus* (Zeller) Hulst.

The lesser cornstalk borer is widely distributed in the tropical through temperate regions of the New World, including Hawaii and the southern half of the United States from California to the Carolinas, north on the east coast to Massachusetts, and south through Central and South America to Argentina, Chile, and Peru (Heinrich 1956). It is a polyphagous pest attacking large numbers of crops, including corn, peanuts, field peas, beans, soybeans, wheat, barley, oats, rice, cotton, cowpeas, nurseries of forest trees, and sugarcane (Luginbill and Ainslie 1917, Heinrich 1956, Harding 1960, Leuck 1966, Falloon 1974, and Dixon 1982).

Lesser cornstalk borer's first record as an economic pest was in 1878 in the United States (Riley 1882). Outbreaks of lesser cornstalk borer on sugarcane were reported by Plank (1928) in Cuba, Wolcott (1948) in Puerto Rico, and Ingram et al. (1951) in Florida (USA). In Jamaica, it was first reported to attack sugarcane in 1959 and since then it has been recognized as a potentially serious pest of sugarcane (Bennett 1962).

Description and Life Cycle

Lesser cornstalk borer is holometabolous insect. It has well defined egg, larval, pre-pupal, pupal and adult stages. The review of the description and biology of *E. lignosellus* is summarized below by stage.

Eggs

Egg size, color and duration varied among host plants and researchers. Luginbill and Ainslie (1917) reported the egg to be ovate, circular in cross section, 0.67 mm high and 0.46 mm wide. Egg color was greenish white on first deposition, then turned to pinkish and finally crimson with a tinge of yellow near eclosion. Duration of egg stage was 6 to 8 d when larvae were reared on cowpeas. Dupree (1965), working on lesser cornstalk borer on southern peas, reported the same physical description as Luginbill

and Ainslie (1917), but with eggs white to pale yellow initially and then later to deep orange or red. The eggs were 0.5 mm high and 0.4 mm wide. The duration of egg stage was 2.4 d. Leuck (1966) reported on soybean that the eggs were ovate, 0.61 ± 0.01 mm high and 0.37 ± 0.01 mm wide. Egg color was white when first deposited, changed to pink and finally to crimson red. The duration of egg stage was 4 d. Stone (1968) reported the color of sterile eggs was either creamish or red at one end only. He used this distinction to separate the sterile eggs from fertile eggs. Similarly, Simmons and Lynch (1990) reported the first deposited (i.e., sterile) eggs as pale green in color.

The location of egg deposition varied among host plants. Eggs on soybean and southern peas were deposited singly, underside the leaves, on the stem, at the base of the pebbles on soil, and in the exposed sandy soil (Leuck 1966). In sorghum, eggs were deposited in the soil up to the depth of 2 mm and within a 10 cm diameter around the plant (Reynolds et al. 1959). In peanuts, King et al. (1961) reported the majority of eggs in the soil around the plant base with some eggs deposited on the lower stems. Smith et al. (1981) reported that 93.8% of eggs were deposited below the soil surface, 6.1 % on the soil surface, and 0.07% on the peanut plant. Horizontally, 50% eggs were deposited within 5.08 cm radius of the plant and 29% in the next 5.08 cm radius with some deposition as far as 23 cm from plants. Nearly 83.5% of the eggs were laid under the drip line. In corn, Knutson (1976) reported the eggs scattered on the surface of loose, dry soil as compared to compact, wet soil. Eggs were not concentrated near the corn plants. On soybean, eggs were deposited on the top and bottom sides of leaves, all over the stem, and in exposed sandy soil and at the base of the pebbles on the soil. Smith and Ota (2002) reported the eggs were deposited on or near the base of stalks in

sugarcane. On cowpea, Luginbill and Ainslie (1917) reported that eggs were deposited on plant stems, leaf axils and in the soil near the base of plants.

Temperature was found to affect duration of the egg stage and size of the eggs produced by females. Leuck and Dupree (1965) found that the egg stage lasted 428 hr at 18 °C, but only 52 hr at 33 °C. Carbonell (1977), working in Jamaica, West Indies in sugarcane, reported the minimum size of eggs ranged from 0.33 to 0.455 mm (mean of 0.352 mm), and the maximum size ranged from 0.55 to 0.706 mm (mean of 0.593 mm), depending upon the temperature conditions.

Larvae

The head of the larvae is slightly bilobed, flattened, highly polished dark brown, and with a triangular clypeus (Luginbill and Ainslie 1917). The cervical shield is almost straight in front, but much rounded behind. All thoracic and abdominal (except the terminal) segments are slightly swollen.

The number of larval instars, and duration of larval development varies by temperature and food host. *Elasmopalpus lignosellus* passes through four (summer) to six (fall) larval instars, depending upon the temperature (Luginbill and Ainslie 1917). They reported the duration of larval stage on cowpeas ranged from 15.6 to 16.9 d, depending upon the temperature.

Larval coloration and size also was affected by crop host. Length and width for instars I to VI were 1.7 and 0.23 mm, 2.7 and 0.29 mm, 5.7 and 0.44 mm, 6.9 and 0.61 mm, 8.8 and 0.89 mm, 8.8 and 0.89 mm, respectively (Luginbill and Ainslie 1917). Dupree (1965) used fresh foliage and stem sections of seedling southern peas to feed the larvae individually in 15 × 44 mm vials. He reported that larvae were yellowish green, with reddish pigmentation dorsally, and transverse bands that formed in their

early instars. Longitudinal stripes started to develop and became well pronounced instar V. Mature larvae were bluish green, but tended towards reddish brown with fairly distinct yellowish stripes dorsally. The head capsule width for larvae on southern peas was 0.200, 0.307, 0.460, 0.644, 0.883 and 1.300 mm for larval instars I to VI, respectively. Duration of larval instars was 4.2, 2.9, 1.4, 3.1, 2.9, and 8.8 d for instars I, II, III, IV, V and VIth, respectively, with mean larval duration of 33 d. Larval length ranged from 1.8 mm in instar I to 13 mm instar VI. Leuck (1966) placed the cloth cover having eggs on it, between two soybean leaves. Upon emergence, the first instar larvae crawled onto the leaves and fed. Following larval emergence, the larvae and leaves were transferred to a 3.78 L jar with 5 cm layer of fine, white, dry sand at the bottom. He reported the head capsule widths for instars I to VI as 0.19 ± 0.01 , 0.31 ± 0.01 , 0.46 ± 0.01 , 0.65 ± 0.02 , 0.86 ± 0.2 and 1.12 ± 0.01 mm, respectively. The duration of instars I to VI was 2.6 ± 0.2 , 1.8 ± 0.2 , 1.8 ± 0.2 , 2.0 ± 0.3 , 2.8 ± 0.6 and 8.6 ± 0.5 d, respectively, with total larval duration of 13 to 24 d. Mean head capsule width was 0.19 ± 0.01 , 0.31 ± 0.01 , 0.46 ± 0.01 , 0.65 ± 0.02 , 0.86 ± 0.2 and 1.12 ± 0.01 mm respectively for instars I to VI. Chalfant (1975) used modified pinto bean base diet with a fine vermiculite layer over the diet. He poured the diet into 30 ml plastic medicine cups, followed by a 2 to 4 mm layer of autoclaved fine vermiculite. He put five newly emerged larvae in each cup and covered the cup with a polyethylene lid. This diet is considered to be the most effective larval diet available and is used in most of the published research work on lesser cornstalk borer. Carbonell (1977) used young shoots of sugarcane to feed the larvae in a glass jar. He reported the mean length of instars I to VI instars as 1.46, 2.92, 4.95, 7.84, 10.46, 14.36 mm, respectively. Length

and width of head capsule for instars I to VI was 0.240 and 0.190, 0.342 and 0.334, 0.517 and 0.507, 0.786 and 0.724, 0.905 and 0.890, 1.223 and 1.193 mm, respectively. Larvae developed to the pupal stage in 30.33 d feeding on sugarcane.

Pupae

The pupa is pale green, with yellowish abdominal segments initially, later on whole body becomes brown and finally turns to uniform black color (Luginbill and Ainslie 1917). A row of six hooked spines, arranged transversely, is present on the tip of the abdomen. The terminal abdominal segment is round on male pupa and irregular on female pupa. On southern peas, Dupree (1965) reported that pupation occurred below the soil surface encased in a cocoon with a sand coating. On soybean, Leuck (1966) reported pupation in an oval case constructed from sand and silk at the end of one of the larval tunnels beneath the soil.

Size and duration of the pupal stage varied by crop and temperature. On cowpeas, Luginbill and Ainslie (1917) reported the pupa to be 8.1 mm long and 2 mm wide. The length of pupal stage was reported to be variable depending upon the temperature. Pupal development varied from 7 to 11 d in July, 7 to 10 d in August, 8 to 18 d in September through October, and 19 to 21 d in October through November. Dupree (1965) reported that pupae raised on southern peas were 8 mm in length and 2 mm in diameter. The pupal period ranged from 7 to 10 d (mean of 9.0 d) in 1957 and 8 to 10 d (mean of 8.7 d) in 1958. Leuck (1966) reported the duration of pupal stage ranged from 7 to 11 d (mean of 10.0 ± 0.4 d) for males and 9 to 13 d (mean of 10.4 ± 0.4 d) for females raised on soybeans, with an overall pupal duration of 10.2 ± 0.8 d. He also reported the variation in pupal period with change in temperature. Pupal period ranged from 3 to 24 d depending upon the maximum air temperature ranged from 26.5

to 35.7 °C and minimum air temperature ranged from 14.1 to 26.6 °C during this period. Pupal period was more at low temperature and decreased with increase in temperature. Carbonell (1978) reported that the pupal stage lasted an average of 10.96 d on sugarcane in Jamaica, West Indies.

Adults

Adults are linear shaped moths (Luginbill and Ainslie 1917). Their narrow forewings are folded over the dorsal and lateral sides of the body in resting position. Sexes can be easily differentiated from the forewing color. The female has uniformly dark brown or carbon black colored forewings, while males have light brown colored forewings margined with dark brown color. Wing expanse was reported as 17 mm to 25 mm by Luginbill and Ainslie (1917) and 15 to 18 mm by Carbonell (1977).

Leuck (1966) reported that the moths are nocturnal. During daytime they rest under foliage of the host plants (soybean and southern peas) and made short jerky flights when disturbed. Darkness, still air, low humidity and warm temperature were the favorite conditions for adult activity. One-third of females caught in 15 W black light traps were mated and capable of producing eggs. Mating and egg deposition occurred during dark period especially before midnight.

Various solutions have been used to feed adults, including sucrose solution (8% by Chalfant 1975, 2% by Stone 1968), 50% honey with sodium benzoate (Dupree 1965), and 10% honey (Leuck 1966). Mean adult longevity was 11.4 d and 17.9 d for males and 14.5 and 19.5 d for females during the first and second study years, respectively (Dupree 1965). Mean oviposition period was 7.8 d (range 1 to 18 d). Luginbill and Anslie (1917) reported that oviposition period on cowpeas was 10.4 d (range 7 to 14 d) with the majority of eggs deposited before midnight.

Longevity and Reproductive Behavior

More detailed information on longevity and reproductive behavior and output was determined from detailed laboratory studies by Stone (1968). Mated males in laboratory colonies could be distinguished from unmated males by the presence of transparent versus translucent seminal fluid for at least 5 d after mating (Stone 1968). Females had full size eggs in the calyx and lateral or common oviducts within 1 to 2 d after emergence. Stone (1968) reported mating in most of the cases from 0140 to 0640 hr and egg deposition from 1900 to 2100 hr. Average mating time was 102 min with approximately equal mating frequency at all male:female sex ratios from 1:1 to 1:4. Mating was more likely to occur in fed than in unfed moths. Moths mated equally through 1 to 6 d and the pre-oviposition period was approximately 2.8 d. The mean oviposition period was reported to be 11.8 d (range 7 to 19 d). Mean longevity was 24.2 ± 1.5 d in mated males and 18.1 ± 1.7 d in mated females. Longevity of virgin females was roughly twice as long as for mated females. In other studies, the mean oviposition period was reported to be 10.4 d (Luginbill and Ainslei 1917), 11.8 d (Stone 1968), and 6.4 d (Simmons and Lynch 1990) on artificial diet. Dupree (1965) and Leuck (1966) reported a mean oviposition period of 4.1 d (ranging from 1 to 9 d) and 4.7 d, respectively on soybean. After rearing the larvae on artificial diet, Chalfant (1975) reported average longevity of 5 d in females and 8 d in males. He also observed that adults preferred rough surface for oviposition within cages. Blue-colored Handi-Wipes® (disposable paper towel) was found to be the preferred surface for egg laying.

Fecundity

Fecundity varied by host plant and diet. On cowpeas, the fecundity was reported to be 91 to 342 eggs/female with a mean of 192 eggs (Luginbill and Ainslei 1917). King

et al (1961) reported 124 eggs / female on peanuts. On southern peas, Dupree (1965) recorded 11 to 261 eggs / female in 1957 and 5 to 221 eggs / female in 1958. On soybean, 2 to 314 eggs / female with a mean of 125.7 ± 20.5 eggs were reported by Leuck (1966). Stone (1968) reported 293 to 562 eggs / female with a mean of 419.5 ± 14.7 eggs when larvae reared on artificial diet and eggs were laid on cheese cloth. On sugarcane, Carbonell (1978) reported 125.3 eggs / female.

Mack and Backman (1984) reported an increase in fecundity with increase in constant temperature from 17 to 27.5 °C, peaked at 27.5 and 30.5 °C. Fecundity was greatly reduced when adults were kept at a temperature of 17 or 35 °C. They concluded that, this 3-fold increase in number of eggs deposited at 5-fold faster rate might be the reason of outbreaks in hot and dry weather. Mack and Backman (1986) later studied the effect of fluctuating diel temperature on longevity and oviposition. They found that females held in hot day/cool night (8.7 ± 2.2 eggs / day) or very hot day / warm night (13.9 ± 4.3 eggs / day) had significantly higher oviposition rates than females held at cool day/hot night (4.3 ± 1.8 eggs / day) cycles. Simmons and Lynch (1990) studied the performance of lesser cornstalk borer adults feed on eight different diets, including, two honey solution diets, sucrose solution, gatorade, three beer diets and water. Adult's longevity (24.9 d), mean ovipositional period (6.4 d) and fecundity (180 eggs per female) were highest on 8.3% sucrose solution followed by 10% honey solution and yeast. They also pointed out that the adult longevity ranged from 7 to 9 d to 38 to 42 d depending upon the occurrence of mating and fed or not fed. Well fed, unmated adults lived longer than unfed, mated adults.

Generation Time

Life cycle from egg to adult was completed in 38.5 d for the spring generation, and 64.6 d for the fall generation under unspecified laboratory conditions, feeding larvae on cowpeas (Luginbill and Ainslie 1917). Sanchez (1960) reported a life cycle of 24.3 d during August and 46.3 d during September through October by feeding peanut roots to larvae under laboratory conditions. Eggs were exposed to 21.1 to 37.8 °C while larvae were exposed to the following daily minimum and maximum temperatures: August, 26.4 and 34.7 °C; September, 23.3 and 31.7 °C. Pupae were exposed to temperature ranges in August, 18.9 to 38.9 °C; September, 17.8 to 36.7 °C. Dupree (1965) reported a life cycle of 47.8 d and 55 d during June-September in 1957 and 1958, respectively, by feeding larvae on foliage and stem sections of seedling southern peas. Temperature range was 19.2 to 30.2 °C in 1957 and 19.3 to 31.2 °C in 1958. Leuck (1966) recorded a life cycle of 32.8 ± 2.8 d by feeding larvae on soybean or cowpea leaves under laboratory conditions. Monthly mean minimum temperature ranged from 14.1 to 22.6 °C, monthly mean maximum ranged from 26.5 to 35.7 °C. Stone (1968) reported 24 to 28 d generations by feeding the larvae on modified Burger's (wheat germ base) artificial diet. Carbonell (1978) reported that lesser cornstalk borer completed its life cycle in 52.43 d by rearing the larvae on sugarcane.

Number of Generations

The number of generations varies depending on the location, temperature, crops and cropping season. There were four generations per year reported in Colombia, South Carolina, USA (Luginbill and Ainslie 1917). In a normal cropping season of soybeans and cowpeas in southern Georgia, USA (early June through early November), there were three and a partial fourth generation of lesser cornstalk borer (Leuck 1966).

Abiotic Factors Affecting Development

Abiotic factors play important in role development of cold-blooded animals like insects. The temperature and soil moisture are important abiotic factors which affect the development and survival of lesser cornstalk borer. The effects of temperature and soil moisture on lesser cornstalk borer population are discussed below.

Temperature

Overwintering is the phenomenon of passing the colder part of the year by prolonging the growth period when the temperature is too low to hamper the normal development. Larvae or pupae are believed to be the overwintering stages on cowpeas in South Carolina, USA (Luginbill and Ainslie 1917). King et al. (1961) revealed larvae and pupae present in old peanut fields as late as December, but absent from January to April. Prolonged duration of larval and pupal stages due to low temperatures in winter helped the lesser cornstalk borer in overwintering. Leuck (1966) reported the pupae, situated under leafy debris and on the soil surface, was the predominant overwintering stage. Holloway and Smith (1976) indicated that there was a drastic increase in the duration of larval, pre-pupal and pupal stages with a 6 to 7 °C reduction in temperature. They didn't report any diapause development due to alteration in temperature and photoperiod.

Soil Moisture

Soil moisture is one of the primary factor effecting lesser cornstalk infestation and development (King et al. 1961, Leuck 1966, French 1971, Knutson 1976, Mack and Backman 1984, Mack et al. 1988, and Smith and Ota 2002). King et al. (1961) reported that lesser cornstalk borers were more injurious to peanuts during dry years, and larval mortality appeared to be greater during wet seasons. Irrigation seemed to reduce larval

populations in some fields. Leuck (1966) reported an increase in lesser cornstalk borer populations during periods of high summer temperatures, because conditions were optimum for mating and egg deposition. Similarly, Mack and Backman (1984) reported 98% of egg deposition on the soil surface when the soil was dry and 55% when the soil was wet. When the soil was wet, more larvae came out of their silken tunnels and were exposed to predators.

French (1971) reported that major losses occurred due to lesser cornstalk borer on peanuts during years with a moisture deficit for part of or the entire growing season. Knutson (1976) reported more parasitism in plots covered by rain. In laboratory, he reported higher mortality reported in the larvae reared in soil having 100% water holding capacity than dry soil. Mack and Appel (1986) reported that, in hot and dry conditions, the maximal daily temperatures in the soil layer can exceed 48 °C, with soil moisture levels of -5 to -20 bars but lesser cornstalk borer larvae, pupae and adults were adapted to this hot, xeric environment as evidenced by their low cuticular permeabilities and their tolerance of body water losses up to 43%. In continuation with this, Mack et al. (1988) reported high mortality due to body water losses in common predators of lesser cornstalk borer like *Geocoris punctipes* (Say) nymphs (69.4%) and adults (80.6%), *Reduviolus roseipennis* (Reuter) adults (58.1%) and especially *Solenopsis invicta* Buren workers (100%) as compared to lesser cornstalk borer larvae (17%) and pupae and adults (0%). Increased mortality of predators and better survival in hot xeric conditions resulted in the outbreaks of lesser cornstalk borer. In Hawaii, Smith and Ota (2002) reported that prompt irrigation application was the most efficient practice to control lesser cornstalk borer.

Host Plants

Lesser cornstalk borer is a polyphagous pest with very wide host range. Common and scientific names for known plant hosts are provided in Table 1-1. Lesser cornstalk borer larvae feed on both grasses and broad-leaved plants, many of which are weeds that provide alternatives to crop plants within treated fields.

Plant Damage by Lesser Cornstalk Borer

In general, lesser cornstalk borer damages young plants or fruits in contact with (i.e., bean pods) or developing beneath the soil (i.e., peanut). Larvae enter plants at or just below the soil surface. Feeding damage that causes the death of the growing point in grasses results in a condition called dead heart. Larvae form silken tunnels from entrance hole out into the soil in which they rest and molt between feeding. Young leaves in grasses and sedges slightly damaged by larvae below the soil line, but above the growing point, expand from the terminals to display rows of holes.

Peanuts

In peanuts, feeding was mostly restricted to plant parts that were contiguous to soil or no more than 4 cm deep. Any part of the plant which touches the ground is attacked by the larvae which construct silken tunnels in contact with the plant. Larvae bore into small stalks at soil level and tunnel upwards. Attacked plants either dry up quickly in hot dry weather or break in the wind. Fifth and sixth instar *E. lignosellus* are reported to be voracious feeders and caused heavy damage to the crop by quick mining in plants (Dupree 1964). Leuck (1966) reported outbreaks in soybeans and cowpeas associated with field stress, e.g. drought and late planting. Leuck (1967) described two types of lesser cornstalk borer larval feeding damage to 'Early Runner' peanut plants. The first two instars fed on leaves, vegetative bud and flower axils, and slightly scarified ground

level stems. The remaining instars fed on and in pegs and pods. The latter type damage was considered to be potentially the most damaging. Smith et al. (1975) recorded that in Spanish peanuts larvae caused the damage by scarifying the tissue destined to become inflorescences and consuming flower buds concentrated in the crown area. Most of the damage was caused in the plant reproductive stage. Smith and Holloway (1979) recorded the economic injury level for 'Starr' peanuts to be 14,448 larvae/ha while Mack et al. (1988) reported it to be 3.63 to 5.44 larvae per row meter. There was 9.87 kg/ha yield reduction for every 1% increase in infested plants (Berberet et al.1979). Pods in early stages of development (1 to 3 stages) were preferred and severely attacked than the pods in latter stages (4 to 6 stages) of peanuts. Damage to more mature pods was caused by older larvae, but this damage was primarily external scarification (Lynch 1990). Mack et al. (1988) reported more pod and seed damage in \geq R5 stage and at the higher densities of lesser cornstalk borer. Huang and Mack (1989) extracted residues from various plant parts of peanut to see the phagostimulative effect on lesser cornstalk borer larvae. Residues from pods and leaves were found to be more attractive than roots, pegs, lower stems and higher stems. Injury caused by feeding of lesser cornstalk borer on peanut plants resulted in infestation by fungus *Sclerotium rolfsii* Sacc. causing southern stem rot (Wolf et al.1997). Carbondioxide released from underground plant parts of peanuts was reported to be the attractant for lesser cornstalk borer larvae (Huang and Mack 2001).

Corn

Young larvae attacked the plants at collar region or slightly below the soil surface and resulted in a symmetrical pattern of holes on the unfurling leaves. Plants can overcome this damage or they may be partially stunted. Older larvae bored into the

stem of the plant and caused dead hearts (All and Gallaher 1977). The heading above shows that if you have a subheading of a certain level, you must have more than one.

The rationale is that you cannot have a list of only one item.

Sorghum

Larval stages of lesser cornstalk borer were sampled in the upper soil habitat during different growth stages of grain sorghum (Funderburk et al. 1986). Samples revealed that the first generation occurred on vegetative stage while second and third generations were present on reproductive stage of the crop. No other published reports were found on lesser cornstalk borer damage to sorghum.

Soybean

Braxton and Gilreath (1988) reported that the lesser cornstalk borer bored into the plant stem and killed the plants. They recorded 41% damage in young plants compared to only 10% in older plants showing more susceptibility of younger plants to lesser cornstalk borer attack. Soft stem tissues of young plants may be the reason of easy penetration of lesser cornstalk borer which resulted in heavy damage.

Sugarcane

Sugarcane can be harvested either by burning or without burning before harvesting. If sugarcane is not burnt before harvesting, then it leaves sugarcane residue or trash after harvesting and also known as green harvesting. Outbreaks in sugarcane are associated with post-harvest burning (Plank 1928). Wolcott (1948) stated that most severe outbreaks in Puerto Rico occurred in areas where trash had been burned. Trash burnt field had severe damage caused by lesser cornstalk borer. So non-burning of trash was recommended as a preventive measure in Florida sugarcane (Ingram et al. 1951). Bennett (1962) recorded outbreaks in Jamaica,

Barbados, and St. Kitts and concluded that fields burned after harvest generally suffered heavier attacks than those burned before harvest. He also suggested about olfactory stimulus provided by burning attracted gravid moths to the area but the trash blanket provided unfavorable conditions for oviposition. Metcalfe (1966) in Jamaica reported the attraction of moths to bare ground for oviposition within 24 hours of a trash fire. In sugarcane, the larvae bore into the stem of young cane sprouts at or just below the soil surface. The larvae then tunnel upwards in the plant and cause “dead hearts” by feeding on the tissues and killing the growing point. One larva can kill 5 to 7 shoots during its period of development. Generally the peak damage occurred 2 to 3 weeks after harvesting in the stubble cane (Schaaf 1974). Carbonell (1978) observed that *E. lignosellus* attacked the sugarcane during the first 3 months of its growth period and caused dead hearts that were very similar to that caused by *Diatraea saccharalis* (Fabricius) (Lepidoptera: Crambidae). He also reported that all the attacked plants were not killed but there was a recovery of some plants to normal growth. There was 27.84 % recovery in plant canes and 48.06 % recovery in stubble canes. Hence stubble canes had more potential to recover from the damage as compared to plant canes. Delay in growth of the recovered canes was more in stubble canes than plant canes.

Control Strategies

Due to sub-terranean nature and excellent protection by the silken tunnels, its hard to control this pest with a single control strategy. By using a combination of two or more control strategies, the chances to control it will be more. Cultural controls that prevent infestation are more effective than control after infestation of lesser cornstalk borer. Several cultural practices have been evaluated to prevent the infestation and to control this pest.

Cultural Control

Planting Time

Luginbill and Ainslei (1917) recommended late fall or early winter sowing after freeing the fields from all crop residues as the best practice for preventing infestation. Early planting of corn and sorghum was suggested to enable the plants to get a good start before heavy infestation occurs. Early season planting and pre-planting weed control were reported to be the efficient methods to control lesser cornstalk borer (All et al. 1979).

Cultivation

Disking field borders and terraces to stir the ground and break up the winter quarters of the pupae were encouraged by Luginbill and Ainslei (1917). Thorough land preparation was recommended by Isley and Miner (1944) and Cowan and Dempsey (1949). On fall beans, Isley and Miner (1944) suggested that inspection of underground parts of previous crop to determine whether a thorough soil preparation was necessary in order to kill half grown larvae. They believed that larvae from eggs deposited after planting would not have enough time to develop to destructive size before the plants passed the most susceptible stage of growth. Cowan and Dempsey (1949) observed a reduction in lesser cornstalk borer damage to pimiento in thoroughly tilled land compared to conservation tillage. Dupree (1964) reported that fallow land kept for 8-10 weeks before planting resulted in significant reduction of borer damage in peanuts and soybean. Cheshire and All (1979) reported the difference in behavior of larvae on corn in no-tillage and conventional- tillage cultural practices. Greenhouse flats (50 × 35 × 8 cm) with sandy loam soil were used for all treatments. In no-tillage field having wheat and rye residues, the number of attacked plants was only 4 as compared to 22 in

conventional- tillage. They concluded that mulch residues in no- tillage crop provided an alternate food source resulting in reduced damage to the corn.

Irrigation

As hot and dry conditions are favorable for lesser cornstalk borer, irrigation is very important method of control. In case of crops which were planted flat like sorghum, timely flood irrigation gave promising results in lesser cornstalk borer control. In some susceptible crops, sow the crop at the bottom of irrigation furrow and fill the furrow with water during serious infestation. The area between the plant rows may be furrowed out at a later date for irrigation when the plants are larger (Reynolds et al. 1959). Smith and Ota (2002) reported that prompt irrigation application was the most efficient practice to control lesser cornstalk borer. They also pointed out that due to damage in early growth stage, any agronomic practice which can enhance the early growth of sugarcane will enable it to outgrow the susceptible stage quickly. Irrigation reduced the damage by 63.2% in corn (All and Gallaher 1977).

Destruction of Alternate Hosts

Pulling and destroying all infested crop plants was recommended by Watson (1917). Box (1929) recommended eradication of barnyard grass, *Echinochloa crusgalli* from sugarcane fields in Cuba as a method of control. Clean cultivation was recommended by Stahl (1930) in strawberries. Larvae migrating from other plant hosts were the main source of crop infestation in California. Destruction of infested alternate hosts in the field some weeks prior to planting was considered to be an important cultural practice to control lesser cornstalk borer (Reynolds et al. 1959).

Fertilization

Fertilization of sandy areas stimulates growth and makes plants more resistant (Luginbill and Ainslei 1917). Stuckey (1945) reported a two-third reduction of infested cowpea plants when nitrogen, phosphorus, and potassium fertilizers were used, as compared to non-fertilized plots. Similarly Bissell (1946) reported less infestation of lesser cornstalk borer in cowpeas with use of fertilizers.

Green Harvesting

The field of sugarcane which was burnt before harvesting had severe damage caused by lesser cornstalk borer. So non-burning of trash was recommended as a preventive measure in Florida sugarcane (Ingram et al. 1951). Similar observations were taken by Bennett (1962) on sugarcane in Jamaica, West Indies. In sugarcane, Hall (1999) conducted a trial with trash blanket and without trash blanket in stubble cane field. He reported that only 0.5 % shoots were killed by lesser cornstalk borer in the field with trash blanket as compared to 7.0 % shoots killed in fields without trash blanket.

Chemical Control

Many authors have come to the conclusion that the lesser cornstalk borer is difficult to control with insecticides (Arthur and Arant 1956, Reynold et al. 1959, Harding 1960 and Chalfant 1975). Many of these materials are no longer labeled for use on these or any other crops. In nursery-grown Arizona cypress seedlings, Chlorpyrifos 2.5% granules applied at 2.24 kg AI/ha during planting and midseason reported to be most effective (Hyché et al. 1984). Isley and Miner (1944) obtained unsatisfactory control beans with application of calcium arsenate and cryolite to the lower surfaces of the leaves and to the stems of bean plants against migrating larvae in Kansas. Kulash

(1948) reported some control on snap beans with 3% lindane plus 5% DDT dust at the rate of 11.35 kg/ha, and with 60 g of 50% DDT wettable powder in one gallon of water per 15 m of crop row, applied to the base of the plants.

Peanuts

In peanuts, there was no significant increase in yield if DDT, BHC, chlordane, toxaphene or aldrin dusts were applied in the drill prior to planting, but there was significant increase in yield when aldrin, dieldrin (2.27 kg AI/ha) or toxaphene (6.8 kg AI/ha) granules applied to soil surface at the time of pegging (Arthur and Arant 1956). Granular endrin, SD-4402 and parathion at 567 g/ha and DDT at 1134 g/ha were reported to be the most effective insecticides in reducing the larval damage to pegs and nuts. The spray forms of these insecticides at 18.9 to 189.3 L/ha under the pressure of 2110 to 2815 g/cm² obtained were equally effective (Harding 1960). Sanchez (1960) conducted control experiments on peanuts with DDT, endrin, azinophosmethyl, mevinphos, and chlorothion sprays and with dust applications of endrin, dieldrin, heptachlor, DDT, and toxaphene. None of these treatments gave significant control. Mack et al. (1989) reported chlorpyrifos 10G at 2.2 kg AI/ha to be more effective if applied during flowering or pegging than at planting. Hot dry weather during the growing period in Alabama reduced the residues and efficacy of the chemical as compared to in Florida. Length of effectiveness after application was highest with chlorpyrifos (19 to 67 d) followed by fonofos (25 to 28 d) (Mack et al.1991). Mack (1992) evaluated the effect of granular insecticides on secondary pests and predators 'Sunrunner' peanuts. No consistent effect was reported in secondary pests like *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) and *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), but population of predators declined after application

of granular insecticides. Chapin and Thomas (1998) tried an alternate method of application of chlorpyrifos 15G, which was considered to be time consuming and costly. They used chlorpyrifos 4E at 1.13 kg AI/ha as flood treatment which provides 90% control as compared to 94% in case of chlorpyrifos 15G at 2.26 kg AI/ha. This shows that 50% pesticide can be saved in flood treatment with almost same level of control. Chlorpyrifos had also the fungicidal activity against southern stem rot. Cunningham et al. (1959) reported the control of lesser cornstalk borer with spray applications timed with the appearance of the moths of each generation. Effective results were obtained with DDT at 1.71 kg/ha and endrin at 0.47 kg/ha. Reynolds et al. (1959) reported that endrin, aldrin, heptachlor, and dieldrin were more effective as compared to thiodan for lesser cornstalk borer in sorghum. As sowing is followed by irrigation which reduced the strength of insecticides, application of chemicals at the time of plant emergence was preferred over application at planting time.

Corn

In corn, carbofuran at 170.8g/1000 m row reduced the damage to 0% in no-tillage plots. Carbofuran also significantly reduced damage in conventional tillage plots, but the infestation was still more than in untreated no-tillage plots (All and Gallaher 1977). Carbofuran at a lower rate (0.11 kg AI/1000 m row) was effective only if applied in seed furrows during planting in field corn. In banded application at the time of planting, chlorpyrifos and fonofos at 0.22 kg AI/1000 m row were most effective in lesser cornstalk borer control (All et al. 1979). Calvo (1966) reported significant control of lesser cornstalk borer with applications of emulsion forms of Bayer 25141, G.C. 6506, diazinon, endrin, dimethoate, azinphosethyl, heptachlor, disulfoton, and bidrin; trichlorfon and Bayer 39007 as wettable powders and phorate as granules. These

insecticides applied at the rate of 1.13 kg AI/ha after first signs of infestation appeared and directed towards the base of the plants. Endrin and diazinon were found to be the best in both light and heavy soils while Bayer 25141 was effective only in heavy soil.

Sorghum

In sweet sorghum, Henderson et al. (1973) reported Aldrin (10% G) at 2.27 kg AI/ha, carbofuran (10% G) at 4.54 kg AI/ha and diazinon (14% G) at 1.14 kg AI/ha as effective insecticides in reducing lesser cornstalk borer damage. Gardener and All (1982) reported that fonofos and diazinon at moderately high rates (2.24 kg AI/ha) were the most consistent in controlling lesser cornstalk borer while carbofuran was variable in its activity in grain sorghum. Carbofuran reduced the damage significantly at lower rate (0.84 kg AI/ha) but was not as effective at a higher rate (2.24 kg AI/ha).

Cowpeas and Southern Peas

On cowpeas, Wilson and Kelsheimer (1955) and Kelsheimer (1955) reported chlordane as an effective control measure when applied as a 5% dust at a rate of 28.35 kg/ha or as a spray applied at the rate of 1.7 to 2.27 kg/ha on cowpeas. Dupree (1964) reported aldrin, BHC, DDT, heptachlor and toxaphene in the form of granules, dusts and liquids to be the most effective insecticides against lesser cornstalk borer damage in southern peas.

Sugarcane

Bennett (1962) reported the high volume application of endrin at the time of adult abundance in the field, resulted in satisfactory control of lesser cornstalk borer in Florida sugarcane. GY-81 (sodium tetrathiocarbonate) applied at 1600 ppm through drip irrigation system was reported to be the only soil insecticide which was consistently effective in reducing damage (Chang and Ota 1989).

Many of the successful materials are no longer labeled for use on these or any other crops. Most recently, the United States Environmental Protection Agency revoked tolerances for carbofuran which was labeled for multiple insect control in sugarcane, effectively removing the last of the effective products for controlling lesser cornstalk borer larvae protected within plants (EPA 2009)

Biological Control

Due to excellent protection in the silken tunnels and sugarcane habitat, there were very less number of parasitoids and low parasitoidism. Also, with pre-harvest burning of sugarcane, predator population destroyed and in rebuilding stage at the time of high borer population. Three species of larval parasites including *Stomatomyia floridensis* Townsend (Diptera: Tachinidae), *Orgilus sp.* (Hymenoptera: Braconidae) and *Pristomerus pacificus melleus* Cushman (Hymenoptera: Ichneumonidae) caused 34.8% of parasitization of lesser cornstalk borer on soybean and southern peas in Georgia. *S. floridensis* was dominant followed by *Orgilus sp.* and *P. pacificus melleus* (Leuck and Dupree 1965). In Jamaica, Falloon (1974) recorded 1.26% parasitoidism in February to 10.02% in July on sugarcane. Tachinids found to be most successful of the parasitoids followed by *O. elasmopalpi*, *C. elasmopalpi* and the ichneumonid. In Florida, on corn, Knutson (1976) reported that the lesser cornstalk borer in its semi-subterranean habit did not protect itself from parasites having long ovipositor capable of penetrating soil surface and silk tubes. In larval parasites recorded from various crops (corn, peanuts, soybean and grain sorghum) in northern Florida, 98.6% of all larval parasitism was done by braconid, *Orgilus elasmopalpi* Meusebeck, the ichneumonid, *Pristomerus spinator* (F.) and the braconid, *Chelonus elasmopalpi* McComb (Funderburk et al 1984). Schauff (1989) reported a new parasite *Horismenus elineatus*

Schauff (Eulophidae: Entedoninae) from the specimens collected from corn in Texas. This is a gregarious endoparasite of last three instars of lesser cornstalk borer. In predators, *Heteropoda venatoria* L. (Araneae: Sparassidae) was reported as voracious feeders of lesser cornstalk borer on sugarcane in Jamaica (Falloon 1974).

Sampling

As lesser cornstalk borer is difficult to control after the plants show the symptoms of its attack and also significant damage done by that time. So prevention or control at early stage of its infestation known through sampling is beneficial. Pitfall and pheromone traps have been used to detect *E. lignosellus* activity. Pitfall traps were reported to be less time consuming than manual sampling, particularly in wet soil (Jones and Bass 1979). Larger larvae were more accurately sampled than smaller ones by using pitfall traps. Payne and Smith (1975) were the first to report the occurrence of a female produced sex pheromone in the lesser cornstalk borer. They showed that pieplate-type sticky traps baited with lesser cornstalk borer virgin females in the field captured lesser cornstalk borer males and that a diethyl ether extract of female abdomen was electrophysiologically and behaviorally excitatory to males. Lynch et al. (1984) reported 10 compounds from heptane extracts of lesser cornstalk borer female ovipositors. They tried different combinations of these compounds and finally came up with mixture of only four compounds, including 91.6 µg of (Z)-11-HAD, 11.2 µg of (Z)-9-TDOH, 46.4 µg of (Z)-9-TDA and 86.8 µg of (Z)-7-TDA. A mixture of these compounds applied to rubber septa retained activity for 30 d in a field. They also showed that a 92 cm height of trap installed in peanuts at reproductive stage gave the maximum capture of males as compared to other heights and other stages of the peanuts. Funderburk et al. (1985) compared the pheromone-trap captures of lesser cornstalk borer with the

absolute numbers of adults in grain sorghum, soybean, peanut and corn. The relationship between trap captured and flushed adults (actual number) found to be statistically similar. They concluded that the pheromone trap captures can be considered as an important population monitoring tool for lesser cornstalk borer. Funderburk et al. (1987) used pheromone traps to study the seasonal abundance of lesser cornstalk borer in soybean, peanut, corn, sorghum and wheat in northern Florida. Trap captures varied with crop and date of planting in same crop. Results revealed that adults were present in abundance in peanut and sorghum in both vegetative and reproductive stages. In soybean, adult abundance was only in vegetative and early reproductive stages while in wheat it was only in early seedling stages. Only few adults were captured in corn field. Mack and Backman (1988) compared the pheromone trap catches of adults with flush counts in peanut field and reported that they were not similar. They concluded that pheromone traps did not accurately determine the moths when in large number. Pheromone traps were found to be good source of alert for growers against presence of lesser cornstalk borer.

Research Goals

Sugarcane, *Saccharum officinarum* L. is an important crop grown in Everglades Agricultural Area around Lake Okeechobee in Florida. There are several factors that can result in decreased sugarcane yield, including insect damage. Sugarcane as an agro-ecosystem is inhabited by many insect species in both above ground (aerial) and below ground (subterranean) habitats (Nuessly 2006). Lesser cornstalk borer is one of the important below ground pest of sugarcane.

Detailed studies of this pest have been conducted on crops such as peanuts and corn, but only a few studies on sugarcane have been published. Carbonell (1978)

studied the biological parameters of lesser cornstalk borer on sugarcane under natural climatic conditions. Due to uncontrolled temperature conditions, it was difficult to model the development of lesser cornstalk borer based on temperature and to predict its population. Therefore, detailed studies on development of immature stages and reproductive biology need to be conducted on sugarcane at constant temperatures to understand variations in population with temperature.

The quantitative information on the effects of lesser cornstalk borer feeding on sugarcane growth and yield was also not available. This information on variety specific sugarcane response to *E. lignosellus* damage would be useful for the industry in their variety selection program. This information is also important for developing damage thresholds for use in integrated management of this pest in the numerous susceptible grass and vegetable crops grown throughout the southeastern United States.

Also the subterranean feeding habit and excellent protection afforded by silken tunnels makes control of lesser cornstalk borer difficult. Chemical control strategies attempted by many researchers has been ineffective in lesser cornstalk borer control (Kelsheimer 1955, Arthur and Arant 1956, Reynold et al. 1959, Harding 1960, Falloon 1974, Chalfant 1975, Chapin and Thomas 1998). Biological control was also found to be inefficient to control lesser cornstalk borer in sugarcane (Falloon 1974). Several cultural strategies provided effective *E. lignosellus* control in different crops (Ingram et al. 1951, Schaaf 1974, Smith and Ota 2002, Cheshire and All 1979). Therefore, cultural practices against lesser cornstalk borer need to be evaluated in sugarcane.

Due to the importance of lesser cornstalk borer as a pest in Florida sugarcane, lack of knowledge in biology of this pest, effect of its feeding on sugarcane yield, and

having a limited number of available control strategies, studies are needed on various aspects related to lesser cornstalk borer that may lead to improved control. Research objectives proposed to better understand the insect/plant interactions and to develop effective control strategies were the following:

1. To study temperature-dependent immature development of lesser cornstalk borer on sugarcane under laboratory conditions.
2. To study reproductive biology and estimation of life table parameters of lesser cornstalk borer on sugarcane.
3. To determine the effects of lesser cornstalk borer feeding on sugarcane growth and yield.
4. To evaluate cultural control practices against lesser cornstalk borer damage to sugarcane.

Table 1-1. Known host plants of *Elasmopalpus lignosellus* (Zeller)

Common name	Scientific name	Family	References
Garden stock	<i>Matthiola</i> sp.	Brassicaceae	Reynolds et al (1959)
Cultivated radish	<i>Raphanus sativus</i> L.	Brassicaceae	Carbonell (1977)
Black tupelo	<i>Nyssa sylvatica</i> Marsh.	Cornaceae	Dixon (1982)
Flowering dogwood	<i>Cornus florida</i> L.	Cornaceae	Dixon (1982)
Turnips	<i>Brassica napus</i> L.	Crucifereae	Luginbill and Ainslei (1917), Carbonell (1977)
Cabbage	<i>Brassica oleracea</i> L. var. <i>capitata</i> L.	Crucifereae	Guagliumi (1966)
Cantaloupe	<i>Cucumis melo</i> L.	Cucurbitaceae	Sanchez (1960)
Arizona cypress	<i>Cupressus arizonica</i> Greeni	Cupressaceae	Reynolds et al (1959), Dixon (1982)
Southern red Cedar	<i>Juniperus silicicola</i> Bailey	Cupressaceae	Dixon (1982)
Chufa	<i>Cyperus esculentus</i> L. var. <i>sativus</i> Boeckl.	Cyperaceae	Luginbill and Ainslei (1917)
Nutsedge	<i>Cyperus rotundus</i> L.	Cyperaceae	Carbonell (1977), Smith and Ota (2002)
Peanuts	<i>Arachis hypogaea</i> L.	Fabaceae	Cunningham et al. (1959), Harding (1960), Dupree (1964), Carbonell (1977)

Table 1-1 Continued

Common name	Scientific name	Family	References
Soybeans	<i>Glycine max.</i> (L.) Merr.	Fabaceae	Leuck (1966)
Beans	<i>Phaseolus</i> sp.	Fabaceae	Isley and Miner (1944), Bissell (1945), Kelsheimer (1955), Reynolds et al. (1959)
Butter beans	<i>Phaseolus lunatus</i> L.	Fabaceae	Guagliumi (1966), Carbonell (1977)
Mung beans	<i>Phaseolus vulgaris</i> L.	Fabaceae	Carbonell (1977)
Black locust	<i>Robinia pseudoacacia</i> L.	Fabaceae	Dixon (1982)
Chinese beans	<i>Soja hispida</i> Moench.	Fabaceae	Carbonell (1977)
Crimson clover	<i>Trifolium incarnatum</i> L. var. <i>elatius</i> Gibelli and Belli	Fabaceae	Bissell (1945)
Horse beans	<i>Vicia faba</i> L.	Fabaceae	Carbonell (1977)
Hairy cowpeas	<i>Vigna luteola</i> (Jacq.) Benth.	Fabaceae	Carbonell (1977)
Cowpeas	<i>Vigna sinensis</i> (L.) Endl.	Fabaceae	Isley and Miner (1944), Heinrich (1956), Dupree (1964),
Black-eyed peas	<i>Vigna sinensis</i> (L.) Endl.	Fabaceae	Sanchez (1960)
Gladiolus	<i>Gladiolus</i> sp.	Iridaceae	Bissell (1945)
Flax	<i>Linum usitatissimum</i> L.	Linaceae	Heinrich (1956)
Cotton	<i>Hibiscus gossipium</i> L.	Malvaceae	Reynolds et al (1959)

Table 1-1 continued

Common name	Scientific name	Family	References
Sand pine	<i>Pinus clausa</i>	Pinaceae	Dixon (1982)
Slash pine	<i>Pinus elliottii</i>	Pinaceae	Dixon (1982)
Loblolly pine	<i>Pinus taeda</i> L.	Pinaceae	Dixon (1982)
Burnut grass	<i>Aegilops</i> sp.	Poaceae	King et al (1961)
Foxtail	<i>Alopecurus pratensis</i> L.	Poaceae	Isley and Miner (1944)
Oats	<i>Avena sativa</i> L.	Poaceae	Sanchez (1960), Carbonell (1977)
Rhodes grass	<i>Chloris gayana</i> Kunth	Poaceae	Calvo (1966)
Bermuda grass	<i>Cynodon dactylon</i> (L.) pers.	Poaceae	Reynolds et al (1959), Dupree (1964)
Nut grass	<i>Cyperus esculentus</i> L.	Poaceae	Bissell (1945), Reynolds et al (1959)
Water grass	<i>Cyperus</i> sp.	Poaceae	Reynolds et al (1959)
Crab grass	<i>Digitaria sanguinalis</i> (L.) Scop.	Poaceae	Isley and Miner (1944), Reynolds et al (1959), Sanchez (1960), Dupree (1964)
Barnyard grass	<i>Echinochloa crusgalli</i> (L.) Beauv.	Poaceae	Isley and Miner (1944)
Gulf grass	<i>Echinochloa crus-</i> <i>pavonis</i> (Kunth)	Poaceae	Carbonell (1977)
Wire grass	<i>Elausine indica</i> (L.) Gaertn.	Poaceae	Carbonell (1977)
Mexican teosinte	<i>Euchlaena mexicana</i> Schrad.	Poaceae	Guagliumi (1966)
Barley	<i>Hordeum vulgare</i> L.	Poaceae	Reynolds et al.(1959)
Rice	<i>Oryza sativa</i> L.	Poaceae	Guagliumi (1966)

Table 1-1 continued

Common name	Scientific name	Family	References
Johnson grass	<i>Sorghum halepense</i> (L.) pers.	Poaceae	Dupree (1964), Carbonell (1977)
Milo maize	<i>Sorghum</i> <i>subglabrescens</i> (Steud.)A.F.Hill	Poaceae	Luginbill and Ainslei (1917)
Sudan grass	<i>Sorghum Sudanese</i> (Piper) Stapf	Poaceae	Guagliumi (1966)
Kafir corn	<i>Sorghum vulgare</i> Pers. Var. <i>caffrorum</i> (Retz.) Hubbard and Rehder	Poaceae	Guagliumi (1966),
Hegari	<i>Sorghum vulgare</i> Pers.	Poaceae	Sanchez (1960), Guagliumi (1966)
Broom corn	<i>Sorghum vulgare</i> Pers. Var. <i>technicum</i> (Koern.) Fiori and Paoletti	Poaceae	Guagliumi (1966),
Wheat	<i>Triticum aestivum</i> L.	Poaceae	Luginbill and Ainslei (1917), Carbonell (1977)
Corn	<i>Zea mays</i> L.	Poaceae	Luginbill and Ainslei (1917), Isley and Miner (1944), Sanchez 1960), Carbonell (1977)
Common buckwheat	<i>Fagopyrum</i> <i>esculentum</i> Moench	Polygonaceae	Guagliumi (1966)
Strawberries	<i>Fragaria virginiana</i> Duch.	Rosaceae	Stahl (1930), Isley and Miner (1944), Kelsheimer (1955).
Pimento	<i>Capsicum frutescens</i> L.	Solanaceae	Bissell (1945), Wilson and Kelsheimer (1955)

CHAPTER 2
TEMPERATURE-DEPENDENT DEVELOPMENT OF LESSER CORNSTALK BORER,
ELASMOPALPUS LIGNOSELLUS (LEPIDOPTERA: PYRALIDAE) ON SUGARCANE
UNDER LABORATORY CONDITIONS

Introduction

The lesser cornstalk borer is a polyphagous pest attacking many crops including corn (*Zea mays* L.), peanuts (*Arachis hypogaea* L.), field peas (*Pisum sativum* L.), beans (*Phaseolus vulgaris* L.), soybeans [*Glycine max* (L.) Merr.], wheat (*Triticum spp.* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rice (*Oryza sativa* L.), cotton (*Gossypium spp.* L.), cowpeas [*Vigna unguiculata* (L.) Walp.], nurseries of forest trees, and sugarcane (*Saccharum officinarum* L.) (Luginbill and Ainslie 1917, Heinrich 1956, Harding 1960, Leuck 1966, Falloon 1974, and Dixon 1982). It is widely distributed in tropical through temperate regions of the New World, including Hawaii and the southern half of the United States from California to the Carolinas, north on the east coast to Massachusetts, and south through Central and South America to Argentina, Chile, and Peru (Heinrich 1956, Genung and Green 1965, Chang and Ota 1987).

Lesser cornstalk borer is a semi-subterranean pest that attacks sugarcane at or below the soil level. Larvae bore into sugarcane stems below the soil surface and produce a silken tunnel at the entrance hole outward into the soil from which they attack the plants, as well as rest, molt and pupate (Schaaf 1974). Dead heart symptoms are produced when larvae reach the center of the shoot and damage or sever the youngest leaves or apical meristem. Non-lethal damage is caused when larvae only chew a few millimeters into the shoot evidenced by several symmetrical rows of holes revealed as the leaves emerge from the whorl. Larval feeding damage reduces sugarcane photosynthesis, plant vigor, number of millable stalks, and sugar yield (Carbonell 1977).

The first record of lesser cornstalk borer as an economic pest was in 1878 in Georgia and South Carolina on corn (Riley 1882). Outbreaks of lesser cornstalk borer in sugarcane were reported by Plank (1928) in Cuba, Wolcott (1948) in Puerto Rico, and Genung and Green (1965) in Florida. It is a potentially serious pest of sugarcane in Jamaica (Bennett 1962) where it was first reported in 1959. Chang and Ota (1987) reported the lesser cornstalk borer for the first time on Kauai (Hawaii) in 1986 causing 100% dead hearts in ratooned sugarcane fields.

Biological parameters of the lesser cornstalk borer life cycle were studied on cowpea in South Carolina and Florida (Luginbill and Ainslei 1917), peanut in Georgia (Sanchez 1960) and Texas (King et al. 1961), and southern pea (Dupree 1965) and soybean (Leuck 1966) in Georgia. Published studies on *E. lignosellus* development on sugarcane were conducted under uncontrolled, natural climatic conditions (Carbonell 1978). Therefore, it is not possible to determine the relationship between developmental rates and temperature. Understanding the physiological relationship between temperature and development is important for the prediction of population outbreaks and timely management of pests on crops (Jervis and Copland 1996). The objective of this study was to determine the relationships between temperature and development and survivorship of the immature stages of *E. lignosellus* on sugarcane under controlled temperature conditions.

Materials and Methods

Temperature-dependent development of immature stages of lesser cornstalk borer was studied under laboratory conditions. Insects from a laboratory colony were reared on young sugarcane shoots to study developmental rates, temperature thresholds and survivorship.

Insect Colony Maintenance

The laboratory colony was started using larvae, pupae and adult *E. lignosellus* (Fig. 2-1) collected on October through December, 2006 from sugarcane fields at Belle Glade and Moore Haven, Florida. Adults collected from fields were transferred to oviposition cages (17.5 × 17.5 × 17.5 cm) covered with 30 mesh screen and provided with 10% honey solution for feeding. Tubular synthetic stockinette (Independent Medical Co-Op, Inc., Ormond Beach, Florida) was used to line the oviposition cages for egg deposition. Stockinette with eggs was transferred to ziploc bags (S. C. Johnson & Son, Inc., Racine, WI) and maintained for larval emergence in the same environmental conditions as the adults. Newly emerged larvae were transferred to a wheat germ and soy flour base artificial diet (General purpose diet for Lepidoptera, Bio-Serv, Frenchtown, NJ) covered with a thin layer of fine vermiculite (no. 4, Thermo-o-rock, East, Inc., New Eagle, PA) in 32-cell diet trays (43.75 × 20.62 × 2.5 cm, Bio-Serv, Frenchtown, NJ). The artificial diet consisted of 144.0 g/liter dry mix and 19 g/liter agar. Four newly emerged larvae were released in each diet cell and kept under the same environmental conditions as the adults. Larvae were allowed to complete development within the trays. Adults that emerged from pupae within the diet were collected and transferred to oviposition cages. The colony was maintained in a temperature control room at 27 °C, 65-70% RH, and 14:10 (L:D) h photoperiod.

Production of Sugarcane Plants

Mature stalks of sugarcane variety CP 78-1628 were harvested in November, 2006 and 2007 to obtain viable buds for use in producing shoots for examining larval development. Stalks were cut into 10 cm-long seed pieces (i.e., single eye sets) and planted in plastic trays (50 × 36 × 9.5 cm) filled with potting mix to germinate the buds

and produce shoots. Plants were maintained in a greenhouse, fertilized and irrigated as needed. To study larval development on sugarcane, young sugarcane shoots (4-5 leaf stage) were uprooted from trays in the greenhouse and separated from the billets by cutting around the base of the eye, so that a small part of the seed piece remained attached with the shoots and roots. The bases of the shoots were wrapped with moistened paper towel to promote continued rooting and to maintain seedling viability.

Laboratory Temperature Developmental Studies

The effect of temperature on lesser cornstalk borer development was examined at nine temperatures [13, 15, 18, 21, 24, 27, 30, 33 and 36 °C (± 0.05 °C)], at 14:10 (L:D) h and 65-70% RH in temperature control chambers. Relative humidity was maintained by placing plastic containers filled with water in these chambers. Freshly deposited eggs (≤ 12 h old) from the laboratory colony were used to determine the development of egg stage. Eight batches of 50 eggs each were placed in separate Petri plates and observed for the emergence of larvae. The egg developmental period was reported as the time required for emergence $\geq 50\%$ larvae in each batch (Leuck 1966). To observe larval development, sugarcane shoots produced as above were placed horizontally in plastic containers (30 × 15 × 10 cm) fitted with 30 mesh screen at the top for aeration (Fig. 2-2). There was a thin layer of vermiculite covering the base of each shoot, five shoots per container. Fifteen newly emerged larvae were collected from the laboratory colony and placed in each container. Eight containers per replicate were tested at each temperature [13, 15, 18, 21, 24, 27, 30, 33 and 36 °C (± 0.05 °C)]. The experiment was repeated three times at each temperature. The experimental design was a randomized complete block replicated through time. Old shoots were replaced with new ones as

required (i.e., when old ones started desiccating) to provide live shoots throughout larval development.

The number of days from larval emergence to pre-pupal formation was considered as total larval duration. To study the duration of each instar, larvae needed to be closely observed for exuviae and head capsules, which was not possible in the large arenas of the plastic boxes. To solve this problem, the progression of larvae through individual instars was closely observed in glass test tubes set up at the same time and placed in the same temperature control cabinets along with the 15-larvae containers. A single neonate larva was placed on a piece of young sugarcane shoot (4 cm long) in each test tube (15 cm long x 2 cm diam.). Stem pieces were changed daily, and the vials observed for exuviae and head capsules twice daily. Four groups of 40 larvae each were tested at each temperature, and this experiment was replicated three times at each temperature. The change in larval instar was determined by presence of newly cast exuviae. Fully grown larvae stop feeding before pupation and become dirty creamy white in color. This pre-pupal period was measured as the time from cessation of feeding up to the beginning of the pupal stage.

Pupae were collected from each plastic container and placed in plastic Petri dishes with 90 mm diameter and 15 mm height (total eight Petri dishes) lined with moistened paper towel to determine the length of the pupal period. The time taken from the first day of the pupal stage up to adult emergence was defined as the pupal period.

Cohorts of immature *E. lignosellus* were followed from egg deposition through adult emergence to measure survivorship. Percentage survival was calculated using

the formula $N_c \times 100 / N_i$, where N_c was the number of individuals that completed development, and N_i was the total number of individuals that started each stage.

Developmental Rate and Mathematical Models

The results of the development experiments were used to model developmental rate (d^{-1} , reciprocal of developmental time in days) and to estimate developmental thresholds. In all immature stages (eggs, larvae, pre-pupae, and pupae), developmental rate was regressed against temperature using linear and non-linear models (SAS Institute 2008). One linear and six non-linear models (Table 2-1) that have been commonly used to describe temperature-dependent development of insects such as *Ostrinia nubilalis* (Hubner) (Lepidoptera: Pyralidae) (Got et al. 1996), *Plutella xylostella* L. (Lepidoptera: Plutellidae) (Golizadeh et al. 2007), *Cydia pomonella* L. (Lepidoptera: Tortricidae) (Aghdam et al. 2009), and *Halyomorpha halys* (Stal) (Hemiptera: Pentatomidae) (Nielsen et al. 2008), were evaluated to describe the relationship between temperature and developmental rate of lesser cornstalk borer. The parameters of interest were T_0 , T_m , T_{opt} , and K . The lower developmental threshold is the temperature at or below which no measurable development is detected (Howell and Neven 2000). It can be estimated from a linear model as the intercept of the development line with the temperature axis. Some non-linear models (Briere-1, Briere-2, and Taylor model) can also estimate the lower developmental threshold directly from the model equation. The upper developmental threshold is the temperature at or above which development does not occur (Kontodimas et al. 2004). It is better estimated through the non-linear models (Briere-1, Briere-2, Logan-6, and Lactin model), because a linear model is asymptotic to the temperature axis at high temperatures. The

temperature at which the developmental rate is greatest is T_{opt} . In Briere-1 and Briere-2 models, it was calculated by using the equation

$$T_{opt} = (2mT_m + (m + 1)T_0) + \sqrt{4m^2T_m^2 + (m + 1)^2T_0^2 - 4m^2T_m T_0} / 4m + 2$$

where 'm' is an empirical constant which equals two for the Briere-1 model (Briere and Pracos 1998). In Taylor's model, T_{opt} was estimated directly from the mathematical equation [$R_m \times \exp(-.5((T - T_{opt})/T_0)^2)$], where R_m is the maximum developmental rate. In Logan-6 and Lactin models, T_{opt} can be estimated as the parameter value for which their first derivatives equals zero. The thermal constant determines the amount of thermal units (degree days) required by an immature stage to complete its development. It can be estimated directly from the linear equation as the value of K (thermal constant) (Aghdam et al. 2009).

The developmental rate of lesser cornstalk borer was positively correlated with temperature until the upper limit of 33 °C in all developmental stages and total development. In the linear model, the developmental rate at 36 °C was omitted to produce linearity in the data. The omission was important to ensure a better fit of the linear model and to calculate the correct values of the T_0 and K (DeClerq and Degheele 1992). Sigma Plot (Systat Software, Inc., San Jose, CA) was used to plot regressions of the non-linear models.

Performance of a mathematical model is commonly evaluated with the coefficient of determination (r^2), which indicates better fits with higher values, and the residual sum of squares (RSS), which indicates better fits with lower values (Aghdam et al. 2009). In this study we used an additional parameter, Akaike information criterion (AIC), to further estimate the goodness-of-fit for all tested mathematical models. The AIC considers the

number of parameters in the model, and we sought the model with the lowest $AIC = n \ln(SSE/n) + 2p$, where n is the number of treatments, p is the number of parameters in the model, and SSE is the sum of the squared error.

Data Analysis

PROC MIXED (SAS institute 2008) was used to analyze the data due to potential covariance structure associated with taking repeated measures on cohorts through time at each temperature. Temperature, cohorts (plastic containers and Petri dishes), generations (replications through time), and their interactions were modeled in this experiment. Generations were used as the repeated variable and the cohorts were nested under the temperature in the repeated measures statement. Several covariance structures were fitted to the data. The unstructured covariance type fit well and was used for the analysis (Littell et al. 1998). Percentage data were arcsin transformed before analysis and retransformed for presentation purposes. The Tukey's HSD test (SAS Institute 2008) was used for means separation with $\alpha = 0.05$.

Results

Laboratory Temperature Developmental Studies

All immature stages of lesser cornstalk borer completed their development at temperatures between 13 °C and 36 °C. Developmental time decreased with increase in temperature between 13 °C and 33 °C, and then increased at 36 °C in all immature stages and for total development (Table 2-2).

Cohorts ($P \geq 0.93$) and generations ($P \geq 0.88$) did not provide significant sources of variation in the models for the development of eggs, larvae, pre-pupae, pupae or total development of lesser cornstalk borer. None of the modeled interactions ($P \geq 0.98$) were significant sources of variation in the model. Due to the insignificant effects of

cohorts and generations on developmental times, the data for each temperature were pooled across time and containers and analyzed together to determine the effect of temperature. Temperature had a significant effect on development in all immature stages (Table 2-2).

Mean egg developmental time (\pm SEM) ranged from 1.8 ± 0.1 d at 33°C to 17.5 ± 0.1 d at 13°C (Table 2-2). The mean developmental time for larvae ranged from 15.5 ± 0.1 d at 33°C to 65.7 ± 0.4 d at 13°C . Larvae completed six instars before pupating. Temperature had a significant effect on the development of all six instars (Table 2-3). Developmental time was shortest in the first instar and longest in the sixth instar at all temperature treatments (Table 2-3). Mean pre-pupal development ranged from 1.3 ± 0.1 d at 33°C to 10.5 ± 0.1 d at 13°C . Pupal development ranged from a mean of 5.9 ± 0.1 d at 33°C to 29.5 ± 0.2 d at 13°C (Table 2-2). Mean total development ranged from 22.8 ± 0.3 d at 33°C to 120.7 ± 2.8 d at 13°C .

Survivorship of immature stages at each temperature treatment is presented in Table 2-4. Survivorship rose with increasing temperature for all immature stages, peaking at 27°C , and then decreasing with further increases in temperature. At extreme temperatures (13°C and 36°C), percentage survival was quite low with $\leq 50\%$ of eggs, larvae, pupae and pre-pupae surviving at 13°C . Egg and larval survival dropped below 50% at 36°C . Cohorts ($P \geq 0.72$) and generations ($P \geq 0.73$) were not a significant source of variation in the models for the survival of eggs, larvae, pre-pupae, and pupae of lesser cornstalk borer. None of the modeled interactions ($P \geq 0.96$) were significant sources of variation in the model. Due to the insignificant effects of cohorts and generations on survivorship, the data for each temperature were pooled across

time and containers and analyzed together to determine the effect of temperature. Temperature had a significant effect on the survival of all immature stages of *E. lignosellus* (Table 2-4).

Model Evaluation

The fitted coefficients T_0 and K , and model evaluation parameters (r^2 , RSS, and AIC) estimated by the linear regression equation are presented in Table 2-5. The linear model (without the data from 36 °C) provided a good fit to the data in all immature stages with high r^2 (> 0.96) and low RSS (< 0.027) and AIC (< -60.56) values. The linear regression model estimated that lesser cornstalk borer required 543.5 degree days (DD) to complete development from egg deposition to adult emergence on sugarcane with a lower developmental threshold of 9.5 °C. The upper developmental threshold was not estimated by the linear model, because the fitted line did not intersect the x-axis at higher temperature.

The estimates of the fitted coefficients, measurable parameters and evaluation indices for the non-linear models are presented in Table 2-6. Among all non-linear models, the Briere-1 model provided the best fit to the data with high r^2 values, and low RSS and AIC values for each immature developmental stage. The relationship between developmental rate (d^{-1}) of immature stages and temperature (°C) described by Briere-1 equation is presented in figures 2-3 to 2-7. The Briere-1 model provided estimates closer to actual observations for parameters of biological significance (T_0 , T_{opt} and T_m) for all immature stages and for the total immature development than the other non-linear models tested. Furthermore, the Lactin, Logan-6, and the Taylor models recorded low r^2 values and high RSS and AIC values and did not provide good fits to the data. The Taylor model estimated T_{opt} , but due to the absence of T_m in this equation, direct

estimation of T_m was not possible. In polynomial models, first degree ($r^2 = 0.435$), second degree ($r^2 = 0.574$), and third degree ($r^2 = 0.612$) polynomials had poor fit to the data. The fourth degree polynomial model was a good fit ($r^2 = 0.925$) to the data, but due to the greatest number (four) of fitted parameters, AIC value increased, and it decreased the fitness of this model to the data. The Briere-2 model was also a good fit ($r^2 = 0.865$) for the data, but the estimated lower developmental threshold values for larval (-3.5 °C), pupal (0.0 °C), and total development (1.2 °C) were much lower than the observed and estimated values produced by all other tested developmental models.

Discussion

Laboratory Temperature Developmental Studies

Results of this study indicated that developmental time and temperature were closely related in all immature stages of lesser cornstalk borer. Developmental time decreased with increased temperature and increased above the thermal optimum. Previous studies on the life cycle of lesser cornstalk borer were conducted under uncontrolled temperature conditions on most crops; therefore, it is difficult to directly compare the results. The reported egg developmental times of 6-8 d on cowpeas (Luginbill and Ainslei 1917) and 2.4 and 4 d on soybean (Dupree 1965 and Leuck 1966, respectively) all fall within the range of 1.8 d at 33 °C to 17.5 d at 13 °C determined for *E. lignosellus* on sugarcane. Dupree (1965) reported larval developmental times of 4.2, 2.9, 1.4, 3.1, 2.9, and 8.8 d, while Leuck (1966) reported 2.6, 1.8, 1.8, 2.0, 2.8, and 8.6 d for first through sixth instars on soybean, respectively. In both studies, development of the first instar was slower for through fifth instars. In contrast to these reports, first instar larvae on sugarcane completed development rapidly at all temperatures. Sixth instar larvae required more time (approximately three-fold) to complete development

than other instars on both soybean and sugarcane. Mean larval developmental time was reported as 15.6 to 16.9 d on cowpeas (Luginbill and Ainslei 1917), and 30.3 d on sugarcane (Carbonell 1978). These were within the range of our results for mean larval developmental time ranging from 13.8 d at 33 °C to 63.2 d at 13 °C on sugarcane. Pre-pupal development could not be compared with previous studies because other studies did not separate this time segment from the overall larval developmental period. Most of the pupal period developmental rates reported by others fell within the range determined in the present study on sugarcane (i.e., 5.9 d at 33 °C to 29.5 d at 13 °C). Pupal period was reported to be 7-21 d (Luginbill and Ainslei 1917), 7-10 d (Dupree 1965), 3-24 d (Leuck 1966), and 10.9 d (Carbonell 1978) in studies on cowpeas, soybeans, soybeans, and sugarcane respectively.

Model Evaluation

One of the objectives of this study was to select a mathematical model that could best describe the relationship between temperature and lesser cornstalk borer developmental rate on sugarcane. Our results showed that developmental rate increased fairly linearly with an increase in temperature, but decreased at high temperature (36 °C) breaking the linear trend. Similar trends were reported for other insects such as *Nephus includens* (Kirsch) (Coleoptera: Coccinellidae) (Kontodimas et al. 2004) and *P. xylostella* L. (Golizadeh et al. 2007). Linear models were used to determine the lower developmental threshold and thermal constant or degree days (DD) in many temperature-dependent developmental studies (Geier and Briese 1978, Rock and Shaffer 1983, Howell and Neven 2000). However, due to the non-linear relationship between developmental rate and temperature at 36 °C for *E. lignosellus* on sugarcane, the linear equation could only model developmental rate within the

temperature range of 13-33 °C. If we use all the available data over the entire range of tested temperatures, then the slope of the linear model becomes depressed and results in inaccurate simulations of developmental rates and thresholds at both ends of the temperature range (Howell and Neven 2000).

Insect developmental model performance has varied depending on species studied. Good model fits to insect development have been reported for the Logan model on *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) (Coop et al. 1993), the Lactin-2 model on *Sesamia nonagrioides* (Lefebvre) (Lepidoptera: Noctuidae) (Fantinou et al. 2003), the Briere-2 model on *P. xylostella* L. (Golizadeh et al. 2007), and both Briere-1 and Briere-2 models on *C. pomonella* L. (Aghdam et al. 2009). In another pyralid, European corn borer, *O. nubilalis* (Lepidoptera: Pyralidae), the Logan-6 model was reported to be the best fit to the data and T_0 , T_{opt} and T_m were estimated as 10, 34, and 40 °C, respectively (Got et al. 1996). In our study, the Briere-1 model provided the best fit, and the estimated T_0 , T_{opt} and T_m for total development of immature stages were 9.35, 31.39, and 37.90 °C, respectively, which are similar to the estimation for European corn borer. Differing model performance reported in the literature is possibly caused by differences in thermal adaptation of different insects or by differences in the host crop.

This study determined the temperature-dependent development of lesser cornstalk borer on sugarcane under a series of constant temperatures. The developmental rate model derived from this study can be used to estimate the developmental time of this insect under natural conditions of temperatures varying within an appropriate range for the purpose of developing an improved pest management practice. Information on the

life history, developmental thresholds, and thermal requirements can be used to predict the developmental rates under varying temperature conditions. These data are essential in an integrated system to optimize lesser cornstalk borer control.

Table 2-1. Developmental models and their mathematical equations tested to describe the relationship between temperature and development of lesser cornstalk borer on sugarcane.

Model	Equation	References
Linear	$K / (T - T_0)$	Roy et al. (2002)
Briere-1	$aT(T - T_0) \times (\text{sqrt}(T_m - T))$	Briere et al.(1999)
Briere-2	$aT(T - T_0) \times ((T_m - T)^{(1/d)})$	Briere et al.(1999)
Logan-6	$mx(\exp(\rho T) - \exp(\rho T_m - (T_m - T)/\Delta))$	Logan et al. (1976)
Lactin	$\exp(\rho T) - \exp(\rho T_m - ((T_m - T)/ \Delta)) + \lambda$	Lactin et al.(1995)
Taylor	$R_m \times \exp(-.5((T - T_{opt})/T_0)^2)$	Taylor (1981)
Polynomial (fourth order)	$a(T)^4 + b(T)^3 + c(T)^2 + d(T) + e$	Lamb et al. (1984)

K, thermal constant or degree days; T, rearing temperature; T₀, lower temperature threshold; T_m, upper temperature threshold; T_{opt.}, optimum temperature; a, b, c, d, e, empirical constant; mx, growth rate at given base temperature; ρ, developmental rate at optimal temperature; Δ, number of degrees over the base temperature over which thermal inhibition becomes predominant; λ, empirical constant which forces the curve to intercept the y-axis at a value below zero; R_m, is the maximum developmental rate.

Table 2-2. Mean (\pm SEM) developmental times (d) by temperature for egg through pupal stages of lesser cornstalk borer on sugarcane under laboratory conditions.

Temp (°C)	Developmental stages				
	Eggs	Larvae	Pre-pupae	Pupae	Total development
13	17.5 \pm 0.2a	65.7 \pm 0.4a	10.5 \pm 0.2a	29.5 \pm 0.2a	120.7 \pm 2.8a
15	11.4 \pm 0.2b	51.0 \pm 0.4b	7.8 \pm 0.1b	23.4 \pm 0.2b	93.9 \pm 2.4b
18	6.8 \pm 0.1c	35.1 \pm 0.3c	3.6 \pm 0.1c	17.3 \pm 0.2c	69.9 \pm 2.0c
21	4.4 \pm 0.1d	27.4 \pm 0.3d	2.1 \pm 0.1e	11.8 \pm 0.2d	49.8 \pm 1.8d
24	2.8 \pm 0.1f	20.9 \pm 0.2e	1.8 \pm 0.1f	9.9 \pm 0.1f	39.7 \pm 1.3e
27	2.5 \pm 0.1g	17.3 \pm 0.2f	1.6 \pm 0.1g	7.8 \pm 0.1g	29.8 \pm 1.0g
30	2.2 \pm 0.1h	16.7 \pm 0.2g	1.4 \pm 0.1h	6.6 \pm 0.1h	26.1 \pm 0.7h
33	1.8 \pm 0.1i	15.5 \pm 0.2h	1.3 \pm 0.1i	5.9 \pm 0.1i	22.8 \pm 0.3i
36	3.3 \pm 0.1e	20.7 \pm 0.2e	2.2 \pm 0.1d	10.1 \pm 0.1e	37.2 \pm 0.9f
<i>F</i>	26512.3	28661.3	10683.9	37693.9	69445.5
<i>df</i>	8, 897	8, 2099	8, 1834	8, 1722	8, 1542
<i>P</i>	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

F, *df* and *P* values represent ANOVA of temperature treatments within a developmental stage (PROC MIXED, SAS Institute 2008).

Means within a column followed by the same letters are not significantly different (Tukey, *P* > 0.05); ANOVA (PROC GLM, SAS Institute 2008).

Table 2-3. Mean (\pm SEM) developmental time (d) by temperature for lesser cornstalk borer larval instars on sugarcane under laboratory conditions.

Temp (°C)	Larval instar					
	I	II	III	IV	V	VI
13	6.3 \pm 0.1a	7.2 \pm 0.1a	8.9 \pm 0.1a	10.2 \pm 0.1a	10.8 \pm 0.1a	19.8 \pm 0.3a
15	4.2 \pm 0.1b	5.8 \pm 0.1b	7.2 \pm 0.1b	8.3 \pm 0.1b	8.9 \pm 0.1b	16.9 \pm 0.1b
18	3.8 \pm 0.1c	4.9 \pm 0.1c	5.9 \pm 0.1c	6.1 \pm 0.1c	7.2 \pm 0.1c	14.3 \pm 0.1c
21	3.2 \pm 0.1d	3.4 \pm 0.1d	4.2 \pm 0.1d	4.9 \pm 0.1d	5.6 \pm 0.1d	10.2 \pm 0.1d
24	2.8 \pm 0.1e	2.9 \pm 0.1e	3.1 \pm 0.1f	3.4 \pm 0.1f	4.1 \pm 0.1f	8.9 \pm 0.1e
27	2.1 \pm 0.1g	2.4 \pm 0.1gf	2.5 \pm 0.1g	2.5 \pm 0.1g	2.7 \pm 0.1f	5.7 \pm 0.1g
30	2.0 \pm 0.1h	2.0 \pm 0.1g	2.3 \pm 0.1g	2.3 \pm 0.1h	2.2 \pm 0.1f	5.1 \pm 0.1h
33	1.7 \pm 0.1i	1.7 \pm 0.1h	2.0 \pm 0.1g	2.1 \pm 0.1i	2.0 \pm 0.1g	4.3 \pm 0.1i
36	2.3 \pm 0.1f	2.4 \pm 0.1f	2.7 \pm 0.1e	3.4 \pm 0.1e	3.6 \pm 0.1e	7.2 \pm 0.1f
<i>F</i>	1901.7	2326.1	4929.5	6539.5	5645.8	21910.9
<i>df</i>	8, 379	8, 364	8, 339	8, 315	8, 301	8, 277
<i>P</i>	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

F, *df* and *P* values represent ANOVA of temperature treatments within a developmental stage (PROC MIXED, SAS Institute 2008).

Means within a column followed by the same letters are not significantly different (Tukey, $P > 0.05$); ANOVA (PROC GLM, SAS Institute 2008).

Table 2-4. Mean (\pm SEM) percentage survival by temperature of lesser cornstalk borer immature stages under laboratory conditions.

Temp ($^{\circ}$ C)	Developmental stages			
	Eggs	Larvae	Pre-pupae	Pupae
13	50.3 \pm 1.9f	39.9 \pm 1.5g	45.5 \pm 1.6g	51.0 \pm 2.3f
15	67.6 \pm 2.3e	55.5 \pm 2.1f	58.0 \pm 2.1f	65.4 \pm 3.0e
18	75.6 \pm 2.5d	58.0 \pm 2.4e	62.0 \pm 2.1e	74.9 \pm 3.2d
21	77.7 \pm 2.9c	70.4 \pm 2.7c	70.0 \pm 2.3d	81.8 \pm 3.8c
24	85.2 \pm 2.8b	71.7 \pm 2.9cb	86.8 \pm 2.6c	89.3 \pm 3.7b
27	92.7 \pm 3.2a	80.4 \pm 2.9a	92.1 \pm 3.2a	95.0 \pm 3.9a
30	91.2 \pm 3.4a	73.0 \pm 2.4b	90.2 \pm 3.2b	93.7 \pm 3.8a
33	79.1 \pm 2.4c	65.0 \pm 2.3d	88.8 \pm 2.4b	75.0 \pm 2.9d
36	48.4 \pm 1.7f	46.2 \pm 1.8f	61.3 \pm 2.1ef	52.6 \pm 1.7f
<i>F</i>	601.15	435.47	611.44	429.54
df	8, 269	8, 269	8, 269	8, 269
<i>P</i>	<0.0001	<0.0001	<0.0001	<0.0001

F, df and *P* values represent ANOVA of temperature treatments within a developmental stage (PROC MIXED, SAS Institute 2008).

Means within a column followed by the same letters are not significantly different (Tukey, *P* > 0.05); ANOVA (PROC GLM, SAS Institute 2008).

Table 2-5. Parameters from linear regression of developmental rate and temperature for lesser cornstalk borer on sugarcane under laboratory conditions.

Developmental stage	T_0	K	r^2	RSS ($\times 10^{-4}$)	AIC
Eggs	11.341	39.370	0.988	270.010	-78.171
Larvae	9.070	344.832	0.977	73.020	-114.270
Pre-pupae	9.881	27.931	0.967	157.000	-60.563
Pupae	8.902	142.453	0.994	1.031	-110.832
Total development	9.460	543.481	0.992	1.201	-132.331

¹ T_0 , lower developmental threshold; K, thermal constant; r^2 , coefficient of determination; RSS, residual sum of squares; AIC, Akaike information criterion.

Table 2-6. Fitted coefficients and evaluation indices for six non-linear developmental models of lesser cornstalk borer developmental rate on sugarcane.

Model	Parameter	Eggs	Larvae	Pre-pupae	Pupae	Total development
Briere-1	$a(\times 10^{-4})$	3.3	3.0	50.0	9.0	2.0
	T_0	11.79	8.50	10.29	8.90	9.35
	T_m	37.30	38.34	37.16	37.60	37.90
	T_{opt}	31.29	31.65	30.9	31.11	31.39
	r^2	0.953	0.922	0.979	0.942	0.942
	RSS ($\times 10^{-4}$)	30.0	0.5	28.6	0.3	0.1
	AIC	-75.12	-115.89	-75.59	-121.51	-132.16
Briere-2	$a(\times 10^{-4})$	5.6	0.6	5.7	1.4	38.0
	T_0	8.30	-3.50	9.20	0.07	1.20
	T_m	36.00	36.00	36.60	36.00	36.00
	T_{opt}	29.76	28.47	30.36	28.80	28.92
	d	5.90	24.88	2.58	9.59	10.29
	r^2	0.865	0.732	0.861	0.925	0.852
	RSS ($\times 10^{-4}$)	30.0	0.5	28.5	0.3	0.1
Logan-6	AIC	-73.12	-114.06	-73.63	-119.86	-129.20
	mx	0.010	0.005	0.086	0.011	0.003
	ρ	0.08	0.09	0.07	0.09	0.09
	T_m	36.05	37.42	36.03	37.37	37.53
	T_{opt}	32.82	33.12	32.79	31.59	33.19
	Δ	0.15	2.30	0.05	2.67	2.85
	r^2	0.798	0.724	0.712	0.853	0.728
Lactin	RSS ($\times 10^{-4}$)	146.0	1.9	60.2	1.04	0.1
	AIC	-57.29	-53.7	-43.12	-66.7	-69.20
	ρ	0.017	0.003	0.017	0.006	0.002
	T_m	37.58	36.66	36.05	38.07	36.77
	T_{opt}	31.52	32.14	30.59	31.45	32.15
	Δ	0.95	0.19	0.99	0.80	0.19
	λ	-1.20	-1.02	-1.21	-1.05	-1.02
Taylor	r^2	0.911	0.852	0.734	0.852	0.923
	RSS ($\times 10^{-4}$)	30.00	0.68	30.00	0.79	0.12
	AIC	-73.12	-63.89	-47.12	-62.43	-59.79
	R_m	0.479	0.062	0.720	0.146	0.038
	T_{opt}	30.32	31.37	29.50	30.45	30.84
	T_0	7.84	9.68	8.19	9.16	9.16
	r^2	0.792	0.976	0.923	0.872	0.863
	RSS ($\times 10^{-4}$)	180.0	3.2	250.0	17.6	1.05

Table 2-6. continued

Model	Parameter	Eggs	Larvae	Pre-pupae	Pupae	Total development
Polynomial	AIC	-57.19	-67.49	-53.91	-80.45	-102.64
	a($\times 10^{-6}$)	-10.0	-2.1	-10.0	-5.1	-1.2
	b($\times 10^{-3}$)	1.10	18.00	1.03	45.00	11.00
	c	-0.0341	-0.0057	-0.0313	-0.0140	-0.0034
	d	0.466	.077	0.045	0.195	0.047
	e	-2.33	-0.37	-2.49	-0.97	-0.23
	r ²	0.925	0.935	0.964	0.926	0.924
	RSS ($\times 10^{-4}$)	80.00	0.37	130.00	2.82	2.00
	AIC	-61.31	-43.12	-56.45	-72.42	-67.31

K, thermal constant or degree days; T, rearing temperature; T₀, lower temperature threshold; T_m, upper temperature threshold; T_{opt}, optimum temperature; a, b, c, d, e, empirical constants; mx, growth rate at given base temperature; ρ, developmental rate at optimal temperature; Δ, number of degrees over the base temperature over which thermal inhibition becomes predominant; λ, empirical constant which forces the curve to intercept the y-axis at a value below zero; R_m, is the maximum developmental rate.

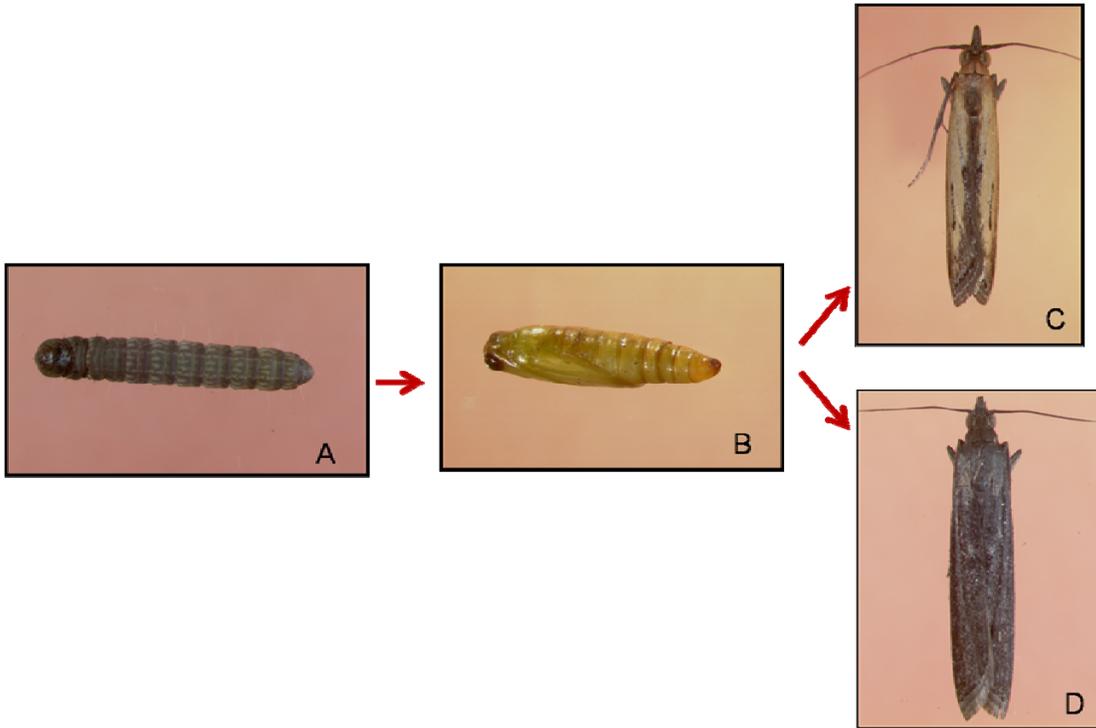


Figure 2-1. Larval, pupal and adult stages of lesser cornstalk borer: A) Larva (sixth instar), B) Pupa, C) Adult male, D) Adult female

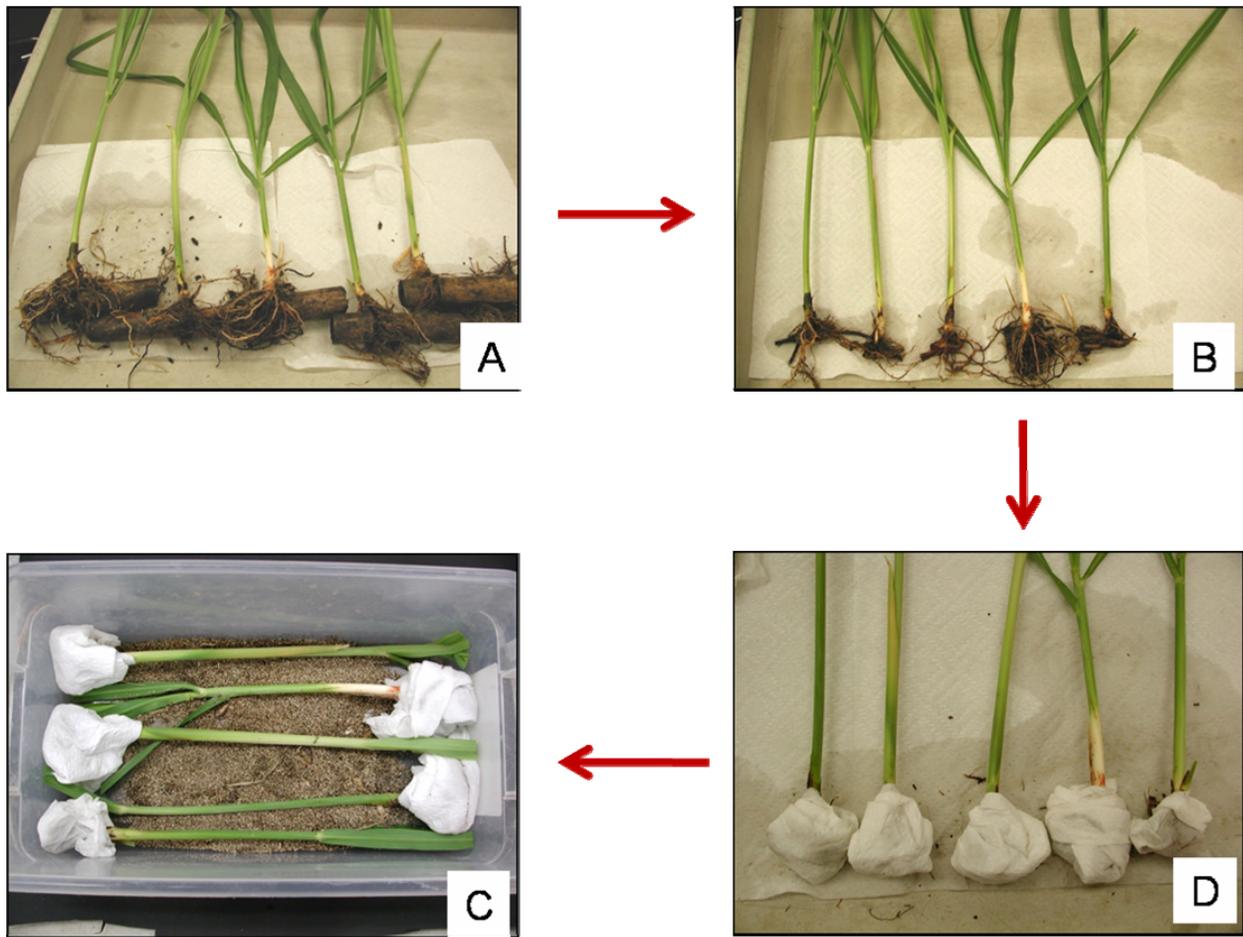


Figure 2-2. Experimental set-up for lesser cornstalk borer larval development on young sugarcane shoots: A) Uprooted sugarcane plants, B) Seed pieces removed, C) Paper towel wrapped around the plant base and kept moist, D) Five shoots placed in each plastic container with a layer of vermiculite underneath.

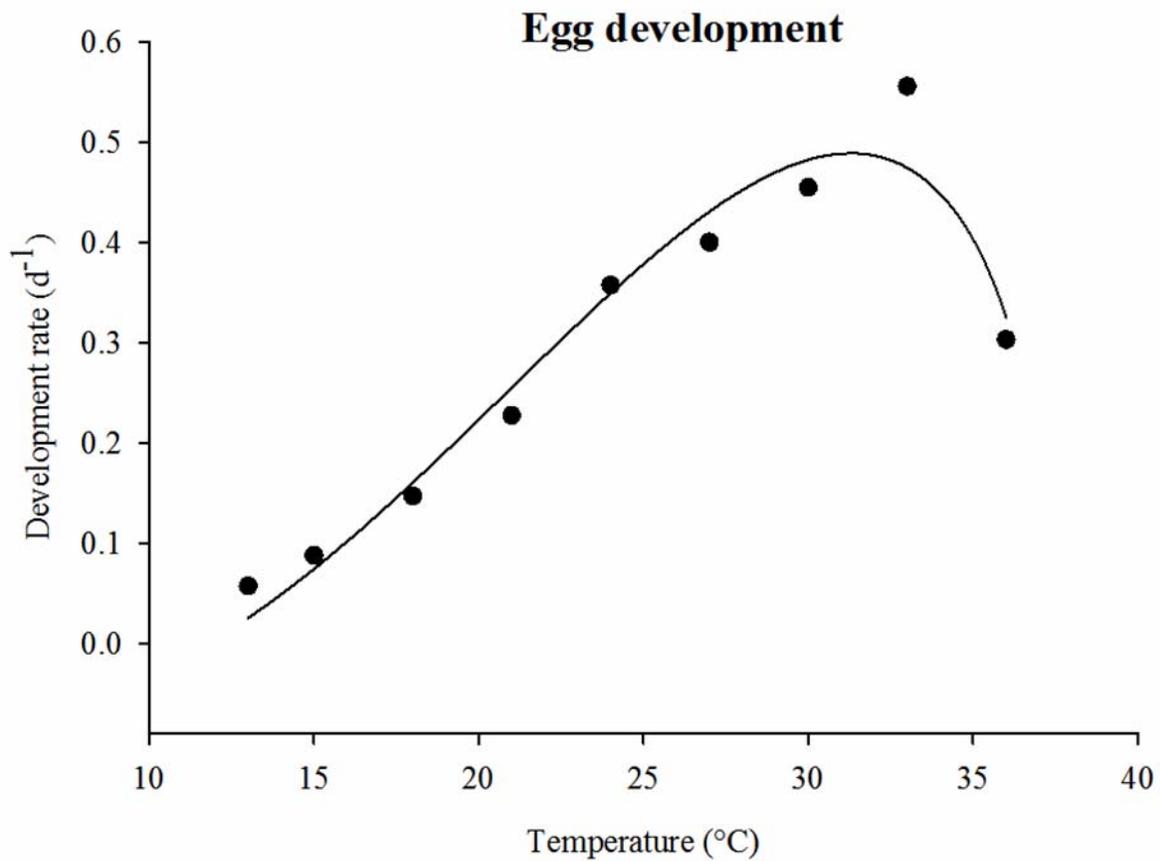


Figure 2-3. Relationship between egg developmental rate (d^{-1}) and temperature ($^{\circ}C$) with mean (\pm SEM) lower (T_0) and upper (T_m) developmental thresholds estimated by Briere-1 model ($aT(T - T_0) \times (\text{sqrt}(T_m - T))$) for lesser cornstalk borer on sugarcane.

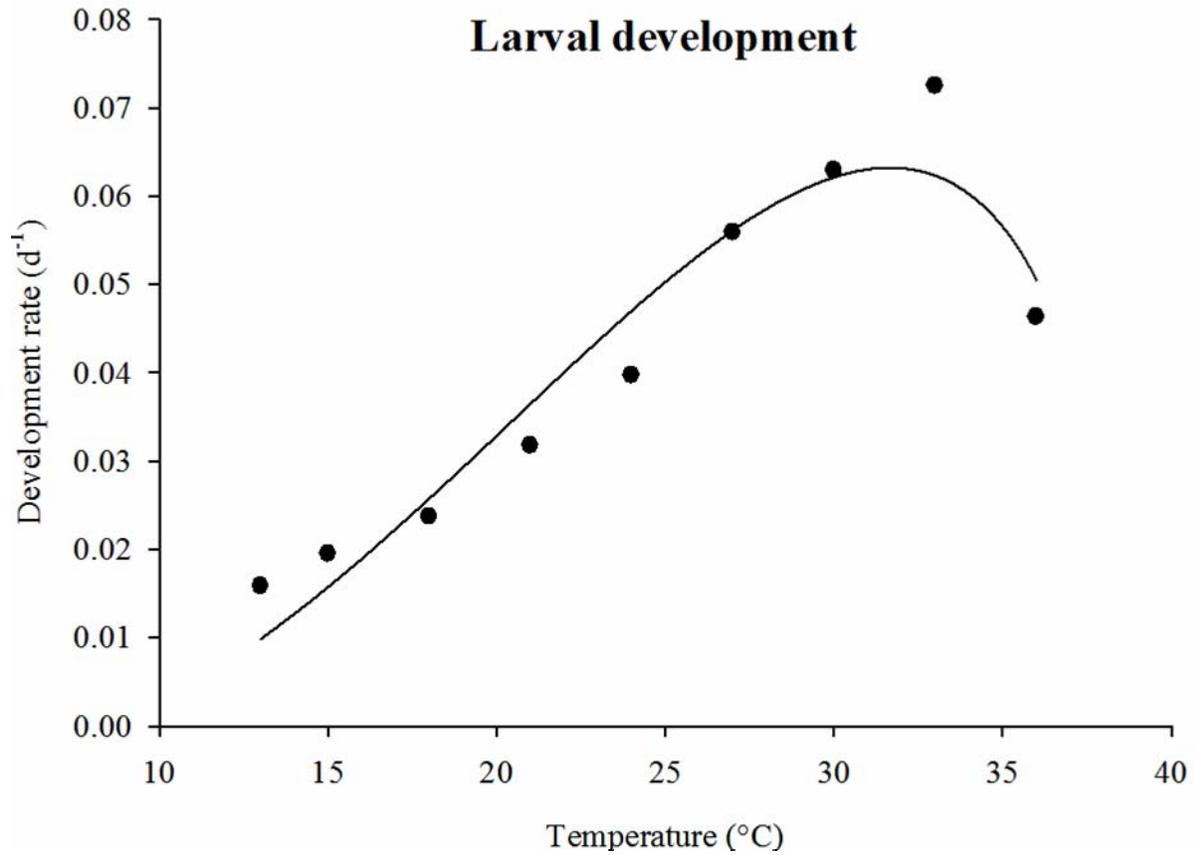


Figure 2-4. Relationship between larval developmental rate (d⁻¹) and temperature (°C) with mean (\pm SEM) lower (T_0) and upper (T_m) developmental thresholds estimated by Briere-1 model ($aT(T - T_0) \times (\text{sqrt}(T_m - T))$) for lesser cornstalk borer on sugarcane.

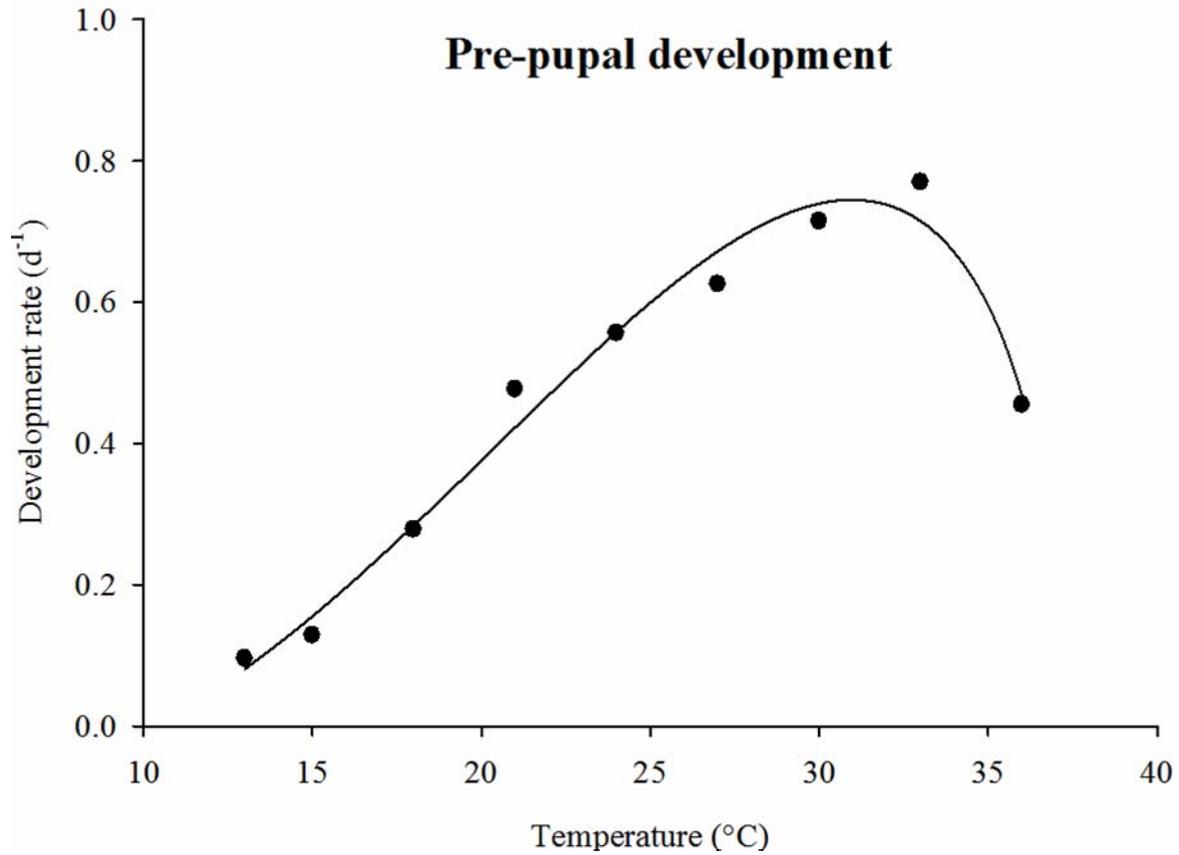


Figure 2-5. Relationship between prepupal developmental rate (d⁻¹) and temperature (°C) with mean (± SEM) lower (T₀) and upper (T_m) developmental thresholds estimated by Briere-1 model ($aT(T - T_0) \times (\text{sqrt}(T_m - T))$) for lesser cornstalk borer on sugarcane.

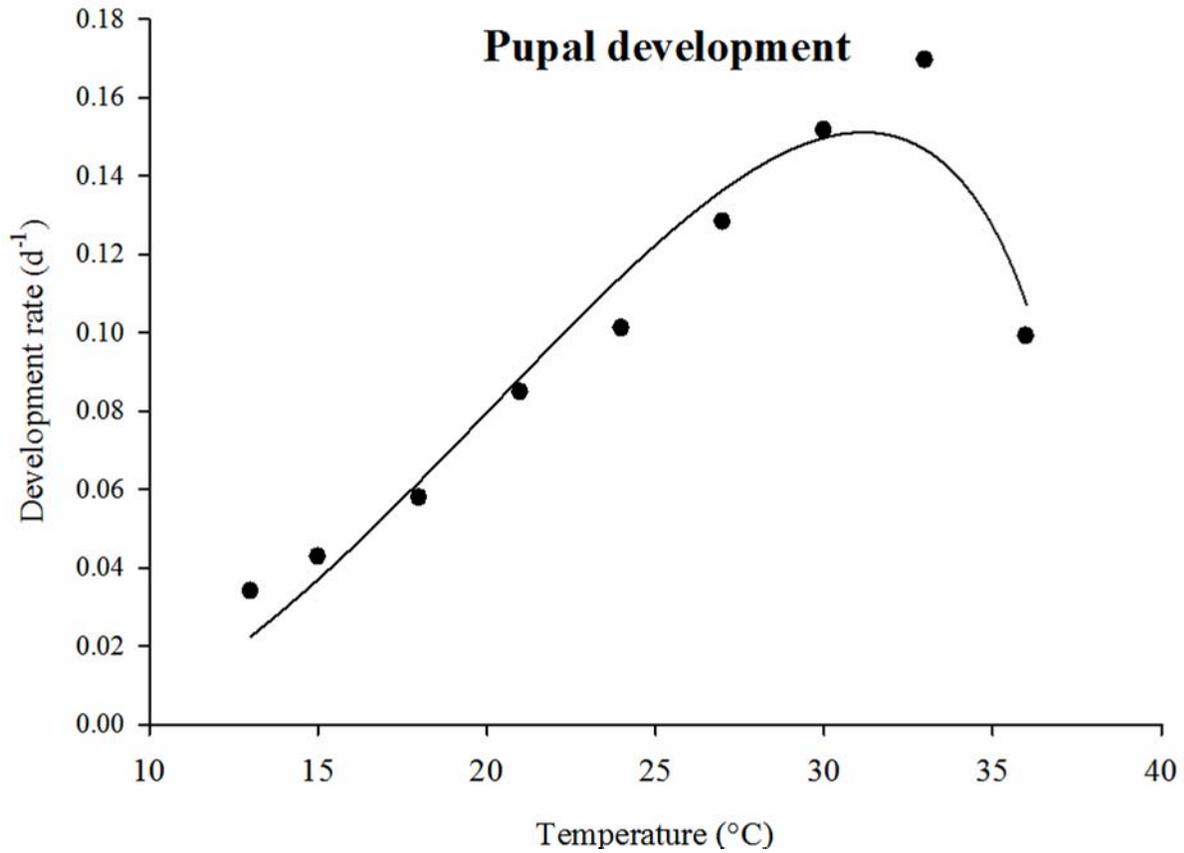


Figure 2- 6. Relationship between pupal developmental rate (d⁻¹) and temperature (°C) with mean (± SEM) lower (T₀) and upper (T_m) developmental thresholds estimated by Briere-1 model ($aT(T - T_0) \times (\text{sqrt}(T_m - T))$) for lesser cornstalk borer on sugarcane.

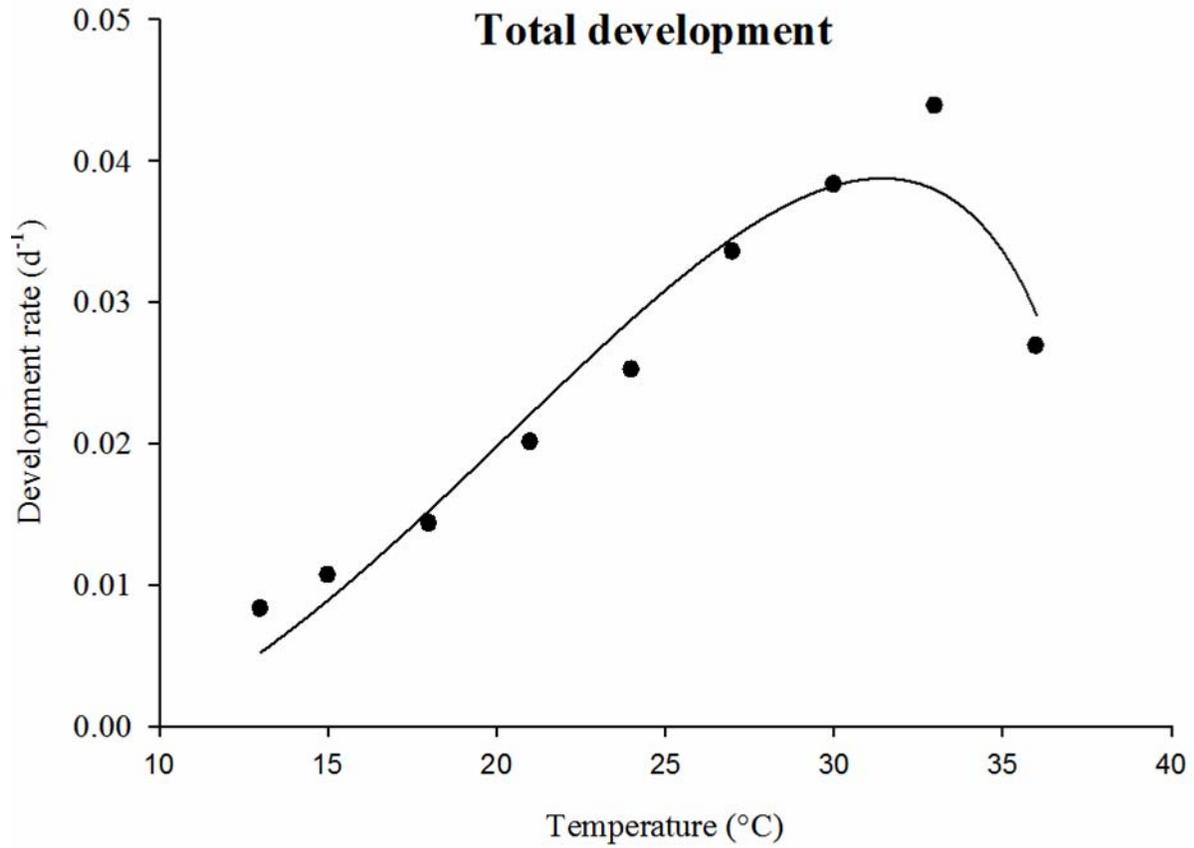


Figure 2-7. Relationship between total (egg deposition to adult emergence) developmental rate (d^{-1}) and temperature ($^{\circ}C$) with mean (\pm SEM) lower (T_0) and upper (T_m) developmental thresholds estimated by Briere-1 model ($aT(T - T_0) \times (\text{sqrt}(T_m - T))$) for lesser cornstalk borer on sugarcane.

CHAPTER 3
LIFE TABLE STUDIES OF LESSER CORNSTALK BORER, *ELASMOPALPUS*
LIGNOSELLUS (LEPIDOPTERA: PYRALIDAE) ON SUGARCANE

Introduction

The lesser cornstalk borer, *Elasmopalpus lignosellus* (Zeller), is a polyphagous pest and widely distributed in United States and Central and South America (Heinrich 1956, Genung and Green 1965, Chang and Ota 1987). It is a semi-subterranean pest that attacks sugarcane at or below the soil level and causes dead hearts or symmetrical rows of holes in emerging leaves. Larval feeding damage reduces sugarcane photosynthesis, plant vigor, number of millable stalks, and sugar yield (Carbonell 1977).

Reproductive studies of lesser cornstalk borer have been conducted on cowpeas (Luginbill and Ainslei 1917), peanuts (King et al. 1961), southern peas (Dupree 1965), soybean (Leuck 1966), and sugarcane (Carbonell 1978) as well as under an artificial diet (Stone 1968) under natural climatic conditions. In all these studies temperature and relative humidity (RH) were not held constant but varied with the climatic conditions. The effects of constant temperature (Mack and Backman 1984) on longevity and oviposition rate of lesser cornstalk borer on artificial diet were reported under controlled environmental conditions. However, quantitative information on life table parameters such as net reproductive rate (R_0), intrinsic rate of increase (r), finite rate of increase (λ), mean generation time (T), and population doubling time (DT) of lesser cornstalk borer was not published in their study.

Life tables are powerful tools for analyzing and understanding the impact of external factors such as temperature on the growth, survival, reproduction, and rate of increase of insect populations (Sankeperumal et al. 1989). The r is used to determine the population increase under optimum conditions, which can vary with the larval host or

diet. It was reported that larval diet had a significant effect on the survival of *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) (Sankeperumal et al. 1989) and the fecundity of *Helicoverpa assulta* Guenee (Lepidoptera: Noctuidae) (Wang et al. 2008). To predict lesser cornstalk borer population on sugarcane, it was important to study its life history on the same host. Due to lack of life table studies of lesser cornstalk borer on sugarcane, we measured the effect of different constant temperature conditions on reproductive parameters (pre-oviposition, oviposition, post-oviposition periods, and fecundity) and life table parameters (r , R_0 , λ , T , and DT) of lesser cornstalk borer reared on sugarcane.

Materials and Methods

Reproductive Parameters

Pre-oviposition, oviposition, post-oviposition periods, and fecundity for lesser cornstalk borer were determined at nine constant temperatures [13, 15, 18, 21, 24, 27, 30, 33, and 36 °C (± 0.05 °C)] at 14:10 (L:D) h and 65-70% RH in temperature controlled chambers to construct time-specific life tables. Ten male:female pairs of newly emerged adults < 12 h old were first released into each of three oviposition cages (17 × 17 × 17 cm) for mating. Adults were obtained from the immatures reared on sugarcane and used for developmental studies at the same temperatures and relative humidity as indicated above in temperature control chambers (Sandhu et al. 2010a). Adults were provided with 10% honey solution for feeding. After 24-h, pairs were moved to transparent plastic cylinders (one pair / cylinder) (11 cm length and 5 cm diameter; Thorton Plastics, Salt Lake City, UT) lined with tubular synthetic stockinette as an oviposition substrate. Thirty pairs from each of three generations were tested over time at each temperature. Adults were observed daily for pre-oviposition, oviposition,

and post-oviposition periods. The stockinette was replaced daily during oviposition periods and the eggs were counted using a hand lens. The orange-colored eggs were easily observed against the white background of the stockinette material. Fecundity was reported as the number of eggs deposited by an individual female during her entire life period. Age-specific female survival (l_x , percentage of females alive at specific age x) and age-specific fecundity (m_x , number of female offsprings produced by a female in a unit of time) were calculated for each day (x) they were alive. The l_x and m_x values were calculated using results from lesser cornstalk borer immature development, survivorship and sex ratio studies conducted concurrently under the same environmental conditions (Sandhu 2010a). Age specific fecundity was calculated as $(f / (m + f)) \times n$, where f = number of females, m = number of males, and n = number of offspring. Mean l_x and m_x were calculated for each cohort of 10 females. Data from pairs of adults in which one or both sexes died before the start of egg deposition were excluded from data analysis. Age-specific survivorship curves were constructed using mean l_x and m_x values for cohorts at each temperature treatment.

Life Table Parameters

The age-specific life table method was used to calculate the life table parameters for lesser cornstalk borer (Birch 1948). The intrinsic rate of increase (r) was calculated using the Euler-Lotka equation ($\sum e^{-rx} l_x m_x = 1$). Mean l_x and m_x values were used to calculate net reproductive rate ($R_0 = \sum l_x m_x$, mean number of female offspring / female), finite rate of increase ($\lambda = \text{antilog}_e r$, the number of times the population multiplies in a unit of time), mean generation time ($T = \sum (x l_x m_x) / \sum (l_x m_x)$, mean age of the mothers in a

cohort at the birth of female offspring), and population doubling time ($DT = \ln(2) / r$, the time required for the population to double).

Model Evaluation

A non-linear distribution was observed when r was plotted against the temperature treatments. PROC NLIN was used to fit six non-linear regression models (Table 3-1) to the data (SAS Institute 2008). Sigma Plot (Systat Software, Inc., San Jose, CA) was used to plot regressions of non-linear models. Models for testing were chosen based on their previous use in insect life table studies. The models were evaluated based on the coefficient of determination (r^2), adjusted coefficient of determination (r^2_{adj} , a modification of r^2 that adjusts for the number of explanatory terms in the model), the residual sum of squares (RSS), and the Akaike Information Criterion (AIC) (Akaike 1974). The r^2 and r^2_{adj} indicate better fits with higher values, whereas RSS and AIC indicate better fits with lower values. The value of AIC was calculated using the formula $AIC = n \ln(SSE/n) + 2p$, where n is the number of treatments, p is the number of parameters in the model, and SSE is the sum of the squared error.

Data Analysis

PROC MIXED (SAS Institute 2008) was used to analyze the variance due to potential covariance structure associated with taking repeated measures over time at each temperature. Normality of the data was tested with Shapiro-Wilk normality test (Shapiro and Wilk 1965). The oviposition cages were treated as cohorts and replications through time were treated as generations for data analysis. Temperatures, cohorts, generations, and their interactions were used in the analysis of variance models. Generations were used as the repeated variable and the cohorts were nested under temperature in the repeated measures statement. Several covariance structures

were fitted to the data. The unstructured covariance type fit well and was used for the analysis (Littell et al. 1998). Data for each pair of adults were used for analysis of effects of temperature, cohort, and generation for pre-oviposition, oviposition and post-oviposition periods and fecundity. Mean daily values by cohort were used for analysis of effects of temperature and generation on l_x and m_x . The percentage of females alive at age x (l_x) was arcsin square root transformed for normality purpose before analysis and retransformed for presentation purposes. The Tukey's HSD test (SAS Institute 2008) was used for means separation with $\alpha = 0.05$.

Results

Reproduction

Temperature had a significant effect on the lengths of the pre-oviposition, oviposition, and post-oviposition periods of lesser cornstalk borer (Table 3-2). Cohorts, generations and the modeled interactions were not significant sources of variation in the models for any of these periods. Therefore, data were pooled across cohorts and generations to calculate means for these periods. Mean pre-oviposition period decreased with increase in temperature from 9.7 d at 13 °C to 2.3 d at 33 °C (Table 3-3). Mean oviposition period was longest (5.6 d) at 27 °C and decreased with increase or decrease from 27 °C. However, the post-oviposition period was shortest at 27 °C (2.6 d) and increased with increase or decrease from 27 °C.

Fecundity was also significantly affected by temperature (Table 3-2). Cohort, generation and modeled interactions were not significant sources of variation in the fecundity model. Therefore, fecundity data was pooled across cohorts and generations to calculate mean fecundity at each temperature. Fecundity increased with increase in

temperature from 13 °C to 30 °C and decreased at 33 and 36 °C (Table 3-3). Mean fecundity ranged from 29.2 eggs (13 °C) to 165.3 eggs (30 °C).

Life Table Parameters

Temperature had a significant effect on l_x and m_x values. Generations and the modeled interactions did not provide significant sources of variation in the models for l_x and m_x (Table 3-4). Therefore, data were pooled across generations to calculate means for these periods. Both l_x and m_x increased with increase in temperature from 13 °C to 30 °C and decreased at 33 and 36 °C (figs. 3-1a to 3-1i).

Temperature had a significant effect on the life table parameters r , R_0 , λ , T , and DT (Table 3-4). Generations and the modeled interactions were not significant sources of variation in the models for these parameters. Therefore, data were pooled across generations to calculate means for these periods. The values for r , R_0 , λ , T , and DT calculated at tested temperatures are presented in Table 3-5. The value of r increased with increase in temperature from 13 °C (0.02) to 30 °C (0.14) and then decreased at 36 °C (0.07). Similarly, R_0 was greatest at 30 °C (65.2) and lowest at 13 °C (9.2). The value of T was greatest (130.5 d) at 13 °C and lowest (27.6 d) at 33 °C. The value of DT decreased with increase in temperature from 40.8 d at 13 °C to 5.1 d at 30 °C. The value of λ increased with increase in temperature from 1.02 at 13 °C to 1.14 at 30 °C and then decreased at 36 °C.

Model Evaluation

The fitted coefficients and the model evaluation parameters are presented in Table 6. The Briere-2 model was the best fit to the data with greatest r^2 (0.9833) and r^2_{adj} (0.9733), and lowest RSS (0.0003) and AIC (- 96.14) values. The Logan-6, Lactin,

Taylor, and polynomial (fourth order) models explained less variation than the Briere-1 and Briere-2 models. The fitted curve for the Briere-2 model representing the relationship between r and temperature for lesser cornstalk borer on sugarcane is presented in fig. 3-2.

Discussion

Reproduction

The values for the reproductive parameters on sugarcane fell mostly within the ranges of those determined for *E. lignosellus* on other crops. The mean (\pm SEM) pre-oviposition period found in this study (2.3 ± 0.1 d at 33 °C to 9.7 ± 0.1 d at 13 °C) is similar to the value of 2.8 d reported by Stone (1968) for *E. lignosellus* on an artificial diet. The mean oviposition period on sugarcane (1.2 ± 0.1 d at 13 °C to 4.6 ± 0.1 d at 27 °C) was shorter than those reported on an artificial diet (10.4 d, Luginbill and Ainslei 1917; 11.8 d, Stone 1968; and 6.4 d, Simmons and Lynch 1990). The results of our study on oviposition period fit within the range determined by Dupree (1965) on southern pea (Mean: 4.1 d, range 1 to 9 d). The 4.7 d post-oviposition period reported by Leuck (1966) on soybean is consistent with that found on sugarcane (2.5 ± 0.1 to 5.9 ± 0.1 d).

Lesser cornstalk borer mean fecundity (number of eggs/female) reported in earlier studies was 192 on cowpeas (Luginbill and Ainslei 1917), ranged from 124 to 129 on soybean (King et al. 1961, Dupree 1965, and Leuck 1966), and ranged from 67 (Calvo 1966) to 419.5 on artificial diet (Stone 1968). Mean fecundity in all of these reports except Stone (1968) fell in the range reported in present study (29 to 165 eggs). The results of our study are similar to those of Mack and Backman (1984) who reported an increase in fecundity with an increase in temperature from 17 to 27.5 °C, peaks at 27.5

and 30.5 °C, and large decreases at 17 and 35 °C. On sugarcane, fecundity increased with an increase in temperature from 13 °C (29 ± 1 eggs / female) to 30 °C (165 ± 6 eggs / female), and then decreased at 33 °C and 36 °C.

Life Table Parameters

Life table parameters reported for other pyralid pests and lesser cornstalk borer are presented in Table 7 for comparison purposes. Life table parameters of sugarcane borer, *Diatraea lineolata* (F.) on corn and artificial diet were not significantly different when compared at 25 °C (Rodríguez Del Bosque et al. 1989), but r and λ were lower than for lesser cornstalk borer on sugarcane. At 30 °C on artificial diet, sugarcane borer and Mexican rice borer, *Eoreuma loftini* (Dyar) (Sètamou et al. 2002), recorded lower r and λ , and higher T and DT parameters than those reported in our study. Mexican rice borer had a greater R_0 than lesser cornstalk borer indicating its high reproductive potential, but the intrinsic rate of increase for Mexican rice borer was lower on an artificial diet than for lesser cornstalk borer on sugarcane. The life table parameters for *E. lignoselus* on sugarcane are comparable to those of *Ephestia kuehniella* Zeller (Amir-Maafi and Chi 2006) on artificial diet at 28 °C. The life table parameters for *Cactoblastis cactorum* (Berg) (Legaspi and Legaspi 2007) on artificial diet at 30 °C show its low reproductive potential compared to lesser cornstalk borer on sugarcane. The high reproductive potential of lesser cornstalk borer compared to other sugarcane pyralid pests, especially at 27 and 30 °C, indicates the importance of its early detection or prediction in the field.

Model Evaluation

The same mathematical models used in the present study were also used to determine the relationship between temperature and r for *Sitotroga cerealella* (Olivier)

(Lepidoptera: Gelechiidae) on corn, *Zea mays* L. (Hansen et al. 2004), and for *Halyomorpha halys* (Stal) (Hemiptera: Pentatomidae) (Nielsen et al. 2008) on green beans, *Vigna radiata* (L.) Wilczek. The Briere-1 model was reported as the best fit for both of these insects compared to the Briere-2 model for lesser cornstalk borer on sugarcane based on the evaluation parameters (r^2 , r^2_{adj} , RSS, and AIC values). The Briere-2 model was the best model for describing the positively curvilinear response of lesser cornstalk borer to temperature up to the optimal temperature and sharp decline immediately following the optimum of any of the tested models. Differences in model performance reported in the literature were possibly caused by differences in thermal adaptation of the insect species or by differences in the host crops and diets.

Model Application

Population predictions for lesser cornstalk borer can begin to be made based on the results of this study to improve their management in sugarcane. The equation of the best fitted model (Briere-2 model) can be used to calculate r at any given temperature (T). Based on the initial population (N_0) and value of r , the Malthusian equation $N_t = N_0e^{rt}$ (where N_t is the population at time t , N_0 is initial population, r is intrinsic rate of increase, and t is time period) can be used for population predictions (Stimac 1982). Using air temperature data from two weather stations (Belle Glade and Clewiston), FL within the predominant sugarcane cultivation area of southern Florida (University of Florida IFAS extension 2009), lesser cornstalk borer populations were predicted to increase by <2 to >8 times (Fig 3-3) per month during different months of the year.

Commercial sugarcane is reproduced vegetatively and new fields are normally planted September through December in Florida. As a result, late planted fields are particularly susceptible to lesser cornstalk borer attack. The most vulnerable shoots

emerge January through May as the lesser cornstalk borer population growth potential increases from 2x to 8x and can reduce stand establishment. This is also the dry season for southern Florida and dry soil surfaces are ideal for lesser cornstalk borer oviposition and immature survival. Sugarcane is harvested annually and ratooned two to more times in southern Florida. Shoots produced in early harvested fields (mid-October through November) are under less lesser cornstalk borer population pressure following the wet summer months as lesser cornstalk borer population growth potential is declining and at a low during the winter months. Shoots emerging in fields harvested mid-December through April face the same elevated lesser cornstalk borer damage potential as plant cane fields. However, because stools in ratooned sugarcane are already established, early, strong shoot establishment is more of a concern for yield reduction than stand establishment.

Conclusion

Life table analysis shows that the lesser cornstalk borer has high potential to increase its population level in sugarcane quickly. Temperatures of 27 and 30 °C were most favorable for reproduction and survival. The results of this temperature-dependent study on reproduction (pre-oviposition, oviposition, post-oviposition periods, and fecundity) and estimation of life table parameters provide important information for predicting outbreaks of lesser cornstalk borer which can improve its management in sugarcane. Additional factors remain to be estimated and the models require field testing before they can reach their full potential. For example, elevated soil moisture at the soil surface plays an important role in reduced oviposition and larval survival under field condition (Smith and Ota 2002). Larval parasitoids and predators may also play an

important role in regulating *E. lignosellus* population growth in sugarcane (Falloon 1974).

Table 3-1. Mathematical equations of development models tested to describe the relationship between temperature and intrinsic rate of natural increase (r) of *E. lignosellus* on sugarcane

Model	Equation	References
Linear	$K / (T - T_0)$	Roy et al. 2002
Briere-1	$aT(T - T_0) \times (\text{sqrt}(T_m - T))$	Briere et al. 1999
Briere-2	$aT(T - T_0) \times ((T_m - T)^{(1/d)})$	Briere et al. 1999
Logan-6	$mx(\exp(\rho T) - \exp(\rho T_m - (T_m - T)/\Delta))$	Logan et al. 1976
Lactin	$\exp(\rho T) - \exp(\rho T_m - ((T_m - T)/\Delta)) + \lambda$	Lactin et al. 1995
Taylor	$R_m \times \exp(-.5((T - T_{opt})/T_0)^2)$	Taylor 1981
Polynomial (4th order)	$a(T)^4 + b(T)^3 + c(T)^2 + d(T) + e$	Lamb et al. 1984

K, thermal constant or degree days; T , rearing temperature; T_0 , lower temperature threshold; T_m , upper temperature threshold; T_{opt} , optimum temperature; a, b, c, d, e, empirical constant; mx, growth rate at given base temperature; ρ , developmental rate at optimal temperature; Δ , number of degrees over the base temperature over which thermal inhibition becomes predominant; λ , empirical constant which forces the curve to intercept the y-axis at a value below zero; R_m , is the maximum developmental rate.

Table 3- 2. Analysis of variance for effects of temperature, cohort and generation on reproductive parameters of *E. lignosellus* on sugarcane

Source	Pre-oviposition			Oviposition			Post-oviposition			Fecundity		
	df	F	P	df	F	P	df	F	P	df	F	P
Model	80	236.70	< 0.0001	80	58.30	< 0.0001	80	40.00	< 0.0001	80	523.10	< 0.0001
Error	570			570			570			570		
Temp.	8	236.10	< 0.0001	8	579.60	< 0.0001	8	395.10	< 0.0001	8	457.80	< 0.0001
Cohort	8	1.05	0.3511	8	0.19	0.8291	8	0.77	0.4640	8	2.15	0.2420
Generation	2	0.78	0.5881	2	0.18	0.9820	2	0.84	0.5380	2	3.04	0.1941
T x C	64	0.69	0.9670	64	0.41	1.0000	64	0.51	0.9990	64	1.54	0.6412
T x G	16	0.74	0.6421	16	0.69	0.5240	16	0.76	0.6120	16	2.15	0.3540
C x G	16	1.02	0.3950	16	1.11	0.4520	16	1.25	0.4550	16	1.89	0.5411
T x C x G	128	0.89	0.5490	128	0.86	0.5131	128	0.78	0.6290	128	0.97	0.6242

F, df, and P values represent ANOVA of temperature, cohort and generation treatments within a reproductive stage (PROC MIXED, SAS Institute 2008)

Table 3-3. Mean (\pm SEM) pre-oviposition, oviposition, post-oviposition periods and fecundity of *E. lignosellus* on sugarcane under laboratory conditions

Temp (°C)	Pre-oviposition (d)	Oviposition (d)	Post-oviposition (d)	Fecundity (eggs / female)
13	9.7 \pm 0.1a	2.2 \pm 0.1f	5.9 \pm 0.1a	29.2 \pm 3.1f
15	7.2 \pm 0.1b	2.8 \pm 0.1e	5.3 \pm 0.1b	42.3 \pm 4.2e
18	5.8 \pm 0.1c	4.5 \pm 0.1c	4.2 \pm 0.1c	51.1 \pm 4.7d
21	3.5 \pm 0.1d	4.5 \pm 0.1c	4.0 \pm 0.1d	56.3 \pm 4.9d
24	2.9 \pm 0.1e	4.8 \pm 0.1b	3.8 \pm 0.1e	97.5 \pm 5.3c
27	2.7 \pm 0.1f	5.6 \pm 0.1a	3.2 \pm 0.1fg	158.4 \pm 6.1a
30	2.5 \pm 0.1g	4.5 \pm 0.1c	3.3 \pm 0.1f	165.3 \pm 6.5a
33	2.3 \pm 0.1h	3.2 \pm 0.1d	3.1 \pm 0.1g	110.2 \pm 5.1b
36	4.4 \pm 0.1d	2.8 \pm 0.1e	2.5 \pm 0.1h	62.3 \pm 4.2d
<i>F</i>	249.20	593.49	439.28	523.10
df	8, 570	8, 570	8, 570	8, 570
<i>P</i>	< 0.0001	< 0.0001	< 0.0001	< 0.0001

F, df, and *P* values represent ANOVA of temperature, cohort and generation treatments within a reproductive stage (PROC MIXED, SAS Institute 2008). Means within a column followed by the same letters are not significantly different (Tukey's test, $\alpha = 0.05$).

Table 3- 4. Analysis of variance for effects of temperature, cohort and generation on life table parameters for *E. lignosellus* on sugarcane

Source	df	F	P	df	F	P	df	F	P	df	F	P	
		l_x			m_x			r			R		
Model	26	15.94	< 0.0001	26	5.11	< 0.0001	26	812.67	< 0.0001	26	218.39	< 0.0001	
Error	333			333			54			54			
Temp.	8	50.19	< 0.0001	8	16.05	< 0.0001	8	263.09	< 0.0001	8	709.79	< 0.0001	
Generation	2	0.52	0.5972	2	0.13	0.8805	2	1.04	0.3608	2	0.50	0.6071	
T x G	16	0.75	0.7384	16	0.26	0.9984	16	0.91	0.5605	16	1.07	0.4079	
		λ			T			DT					
Model	26	250.20	< 0.0001	26	382.04	< 0.0001	26	255.10	< 0.0001				
Error	54			54			54						
Temp.	8	461.50	< 0.0001	8	124.16	< 0.0001	8	829.30	< 0.0001				
Generation	2	0.61	0.5942	2	0.20	0.8198	2	0.12	0.8906				
T x G	16	0.72	0.4891	16	0.57	0.8929	16	0.08	1.0006				

r , intrinsic rate of natural increase (female/female/day); R_0 , net reproductive rate (female/female/generation); T , generation time (d); DT , population doubling time (d); λ , finite rate of increase (female/female/day).

F , df , and P values represent ANOVA of temperature, cohort and generation treatments within a life table parameter (PROC MIXED, SAS Institute 2008).

Table 3-5. Life table parameters of *E. lignosellus* on sugarcane at nine constant temperatures

Temp.	r	R ₀	T	DT	λ
13	0.02 ± 0.005f	6.5 ± 0.9i	130.5 ± 2.9a	40.8 ± 1.1a	1.02 ± 0.05g
15	0.03 ± 0.006 f	13.8 ± 1.1h	102.6 ± 2.4b	26.7 ± 1.0b	1.03 ± 0.04f
18	0.04 ± 0.004e	16.4 ± 1.2g	77.9 ± 1.8c	18.2 ± 0.9c	1.04 ± 0.05e
21	0.05 ± 0.005d	19.3 ± 1.5f	55.3 ± 1.7d	12.8 ± 0.7d	1.06 ± 0.05d
24	0.08 ± 0.006c	37.9 ± 0.7d	45.7 ± 1.3e	8.7 ± 0.5f	1.08 ± 0.06c
27	0.12 ± 0.007b	63.2 ± 1.4b	30.1 ± 0.8g	5.9 ± 0.3g	1.12 ± 0.07b
30	0.14 ± 0.006a	65.2 ± 1.3a	30.9 ± 0.9g	5.1 ± 0.3h	1.14 ± 0.09a
33	0.13 ± 0.006a	39.4 ± 0.6c	27.6 ± 0.7h	5.2 ± 0.2h	1.14 ± 0.09a
36	0.07 ± 0.005c	21.1 ± 0.5e	42.1 ± 1.2f	9.5 ± 0.8e	1.08 ± 0.07c
<i>F</i>	263.9	709.8	124.2	82.9	46.2
<i>df</i>	8, 80	8, 80	8, 80	8, 80	8, 80
<i>P</i>	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

r, intrinsic rate of natural increase (female/female/day); R₀, net reproductive rate (female/female/generation); T, generation time (d); DT, population doubling time (d); λ, finite rate of increase (female/female/day).

F, *df*, and *P* values represent ANOVA for temperature treatments within a life table parameter (PROC MIXED, SAS Institute 2008).

Means within a column followed by the same letters are not significantly different (Tukey's test, α = 0.05).

Table 3-6. Fitted coefficients and evaluation indices for six non-linear models tested to describe the relationship between intrinsic rate of natural increase (r) of *E. lignosellus* and temperature

Parameters	Non-linear models					
	Briere-1	Briere-2	Logan-6	Lactin	Taylor	Polynomial (4 th order)
a ($\times 10^{-5}$)	9.00	10.00	--	--	--	-0.112
b ($\times 10^{-3}$)	--	--	--	--	--	7.000
c	--	--	--	--	--	-0.003
d	2.00	4.10	--	--	--	0.037
e	--	--	--	--	--	-0.213
mx	--	--	0.01	--	--	--
ρ	--	--	0.09	0.01	--	--
Δ	--	--	--	0.19	--	--
R_m	--	--	--	--	0.04	--
T_0	12.09	9.89	--	--	9.39	--
T_m	36.98	36.09	36.23	36.45	--	--
$T_{opt.}$	33.12	32.57	33.44	32.68	31.02	--
r^2	0.9563	0.9833	0.6101	0.5614	0.6525	0.6213
r^2_{adj}	0.9417	0.9733	0.4210	0.4021	0.5142	0.4563
RSS	0.0007	0.0003	0.0047	0.0059	0.0079	0.0062
AIC	-89.67	-96.14	-68.63	-39.81	-42.65	-43.13

a, b, c, d, e, empirical constants; mx, growth rate at given base temperature; ρ , developmental rate at optimal temperature; Δ , number of degrees over the base temperature over which thermal inhibition becomes predominant; λ , empirical constant which forces the curve to intercept the y-axis at a value below zero; R_m , is the maximum developmental rate; T_0 , lower temperature threshold; T_m , upper temperature threshold; $T_{opt.}$, optimum temperature; --, absence of coefficient in the model.

Table 3-7. Life table parameters for Pyralidae (Lepidoptera) pests on artificial diet and lesser cornstalk borer on sugarcane in this study

Pest	Temp. (°C)	Host	Life-table parameters					Source
			r	R ₀	T	DT	λ	
<i>D. lineolata</i>	25	Corn	0.053	15.6	51.5	--	1.06	Rodríguez Del Bosque et al. 1989
<i>D. lineolata</i>	25	Artificial diet	0.054	19.92	55.37	--	1.06	Rodríguez Del Bosque et al. 1989
<i>D. saccharalis</i>	30	Artificial diet	0.066	15.5	41.6	10.5	1.06	Sètamou et al. 2002
<i>E. loftini</i>	30	Artificial diet	0.096	122.0	50.2	7.2	1.10	Setamou et al. 2002
<i>E. kuehniella</i>	28	Artificial diet	0.137	11.9	18.2	--	1.14	Amir-Maafi and Chi 2006
<i>C. cactorum</i>	30	Artificial diet	0.056	43.7	67.1	12.3	1.05	Legaspi and Legaspi 2007
<i>E. lignosellus</i>	30	Sugarcane	0.14	65.2	30.9	5.1	1.14	Present study

r, intrinsic rate of natural increase; R₀, net reproductive rate; T, generation time; DT, population doubling time; λ, finite rate of increase.

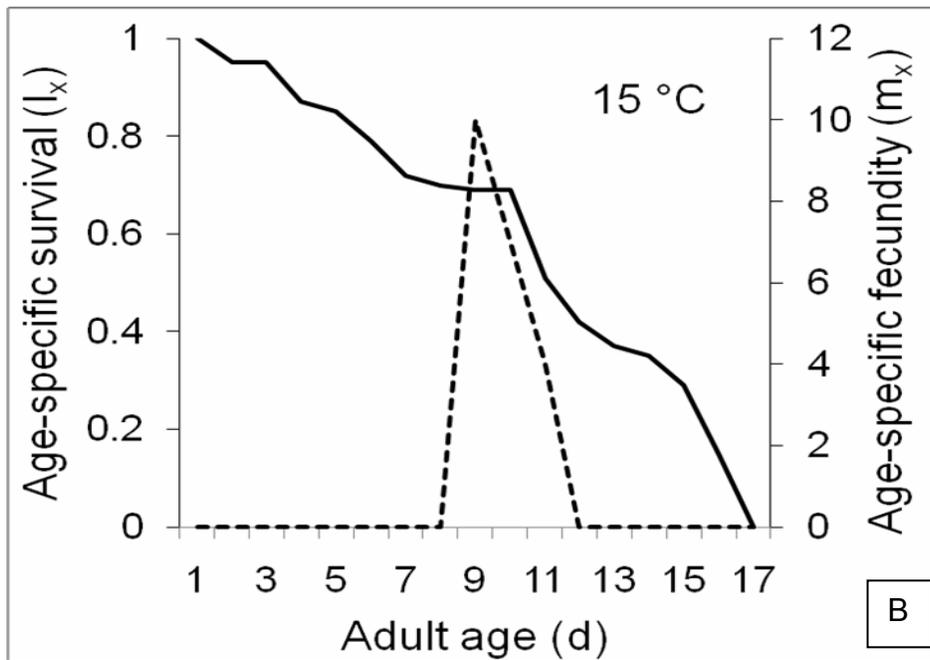
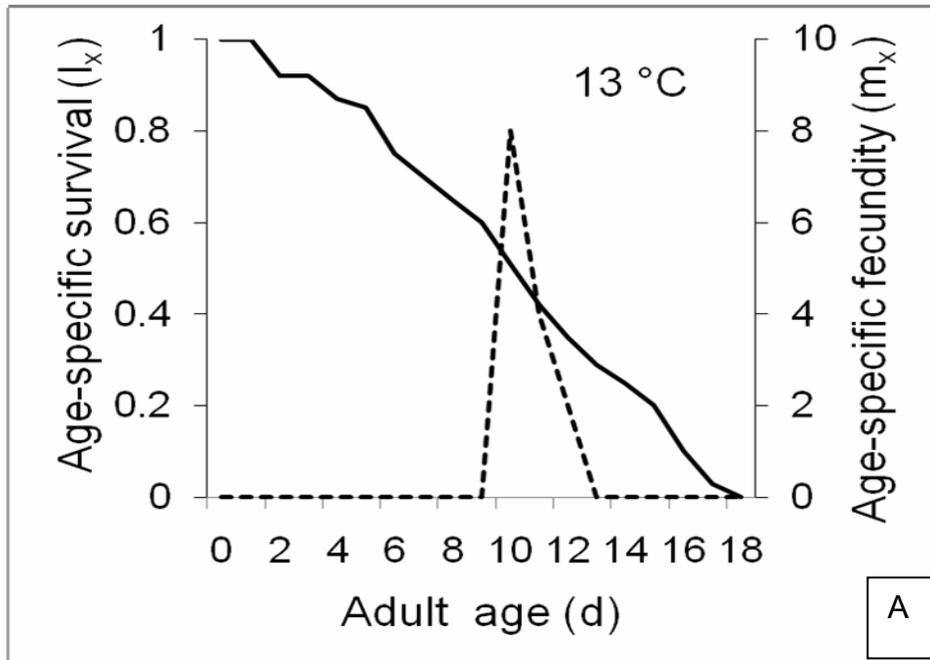


Figure 3-1. Relationship between the temperature (°C) and age-specific survival, l_x (solid line), and age specific daily fecundity, m_x (dashed line), for *E. lignosellus* at the tested temperatures. A) 13 °C, B) 15 °C, C) 18 °C, D) 21 °C, E) 24 °C, F) 27 °C, G) 30 °C, H) 33 °C, I) 36 °C.

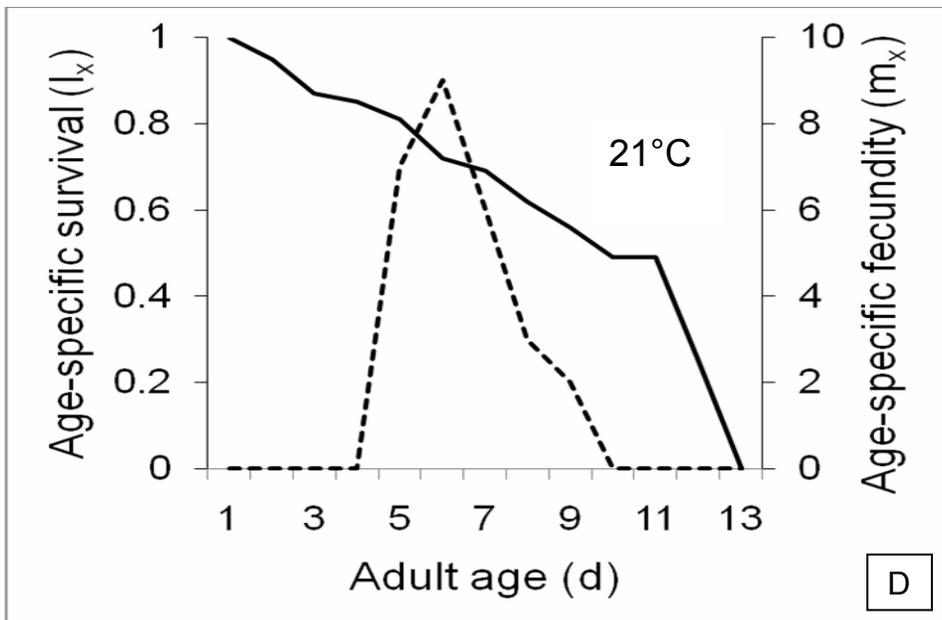
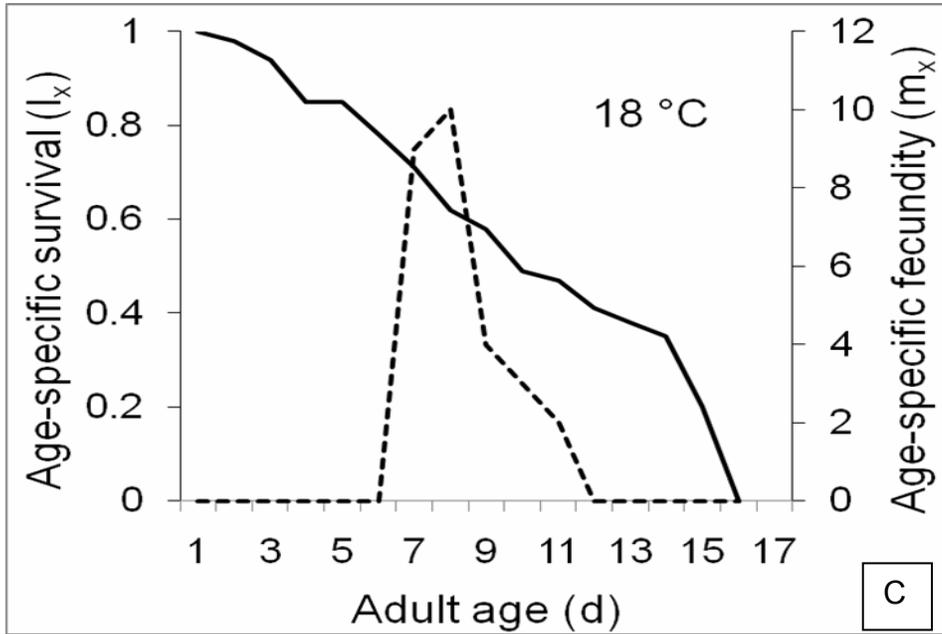


Figure 3-1 continued.

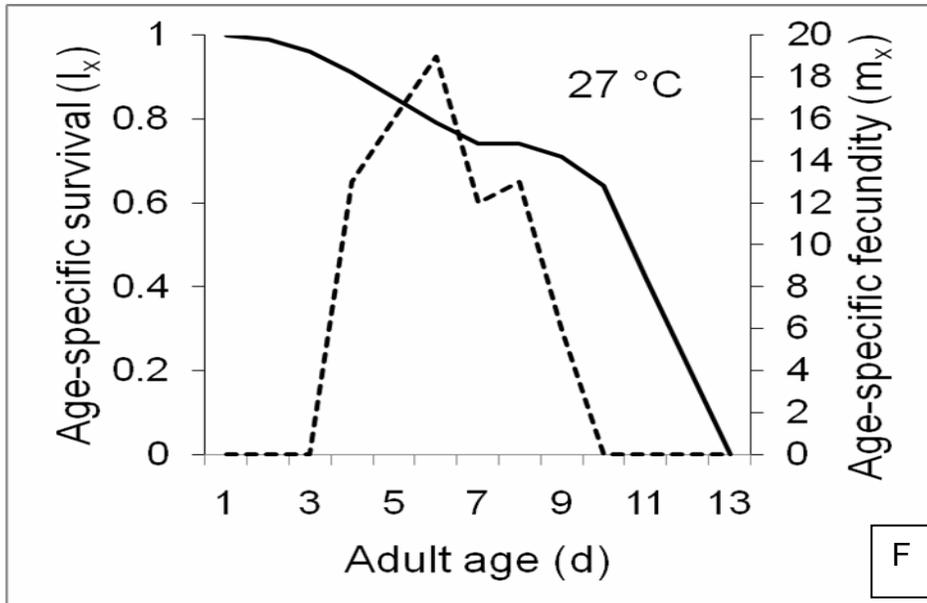
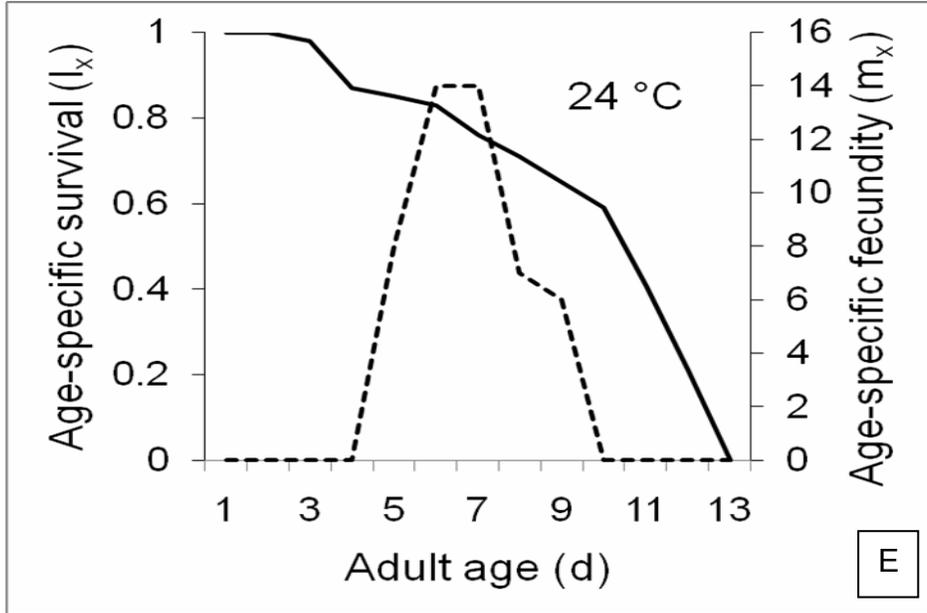


Figure 3-1 continued.

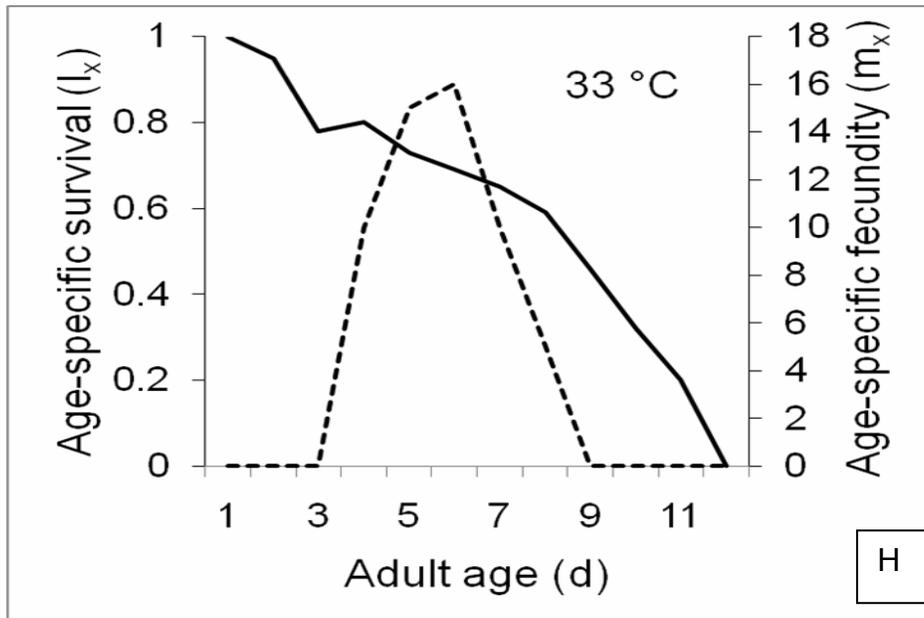
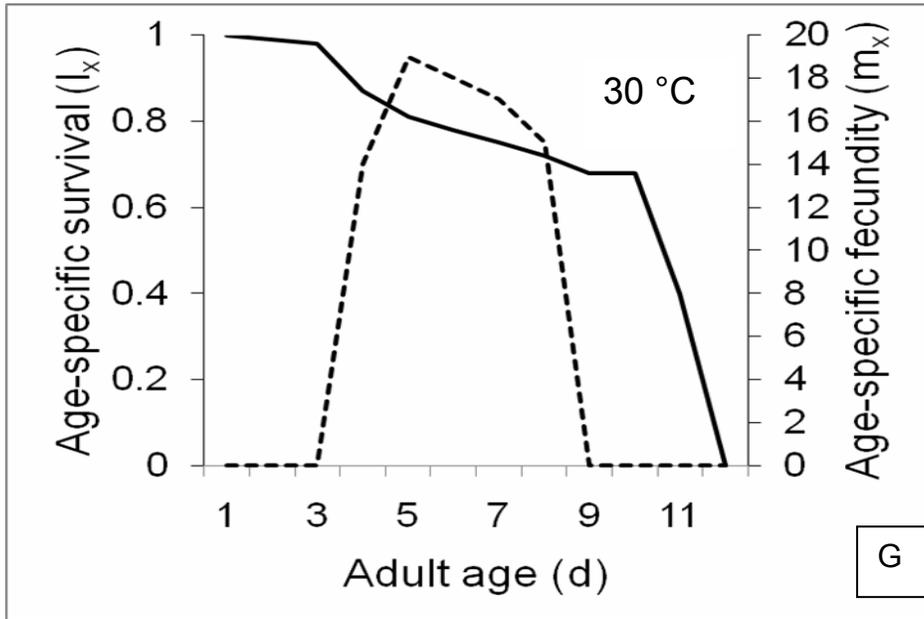


Figure 3-1 continued.

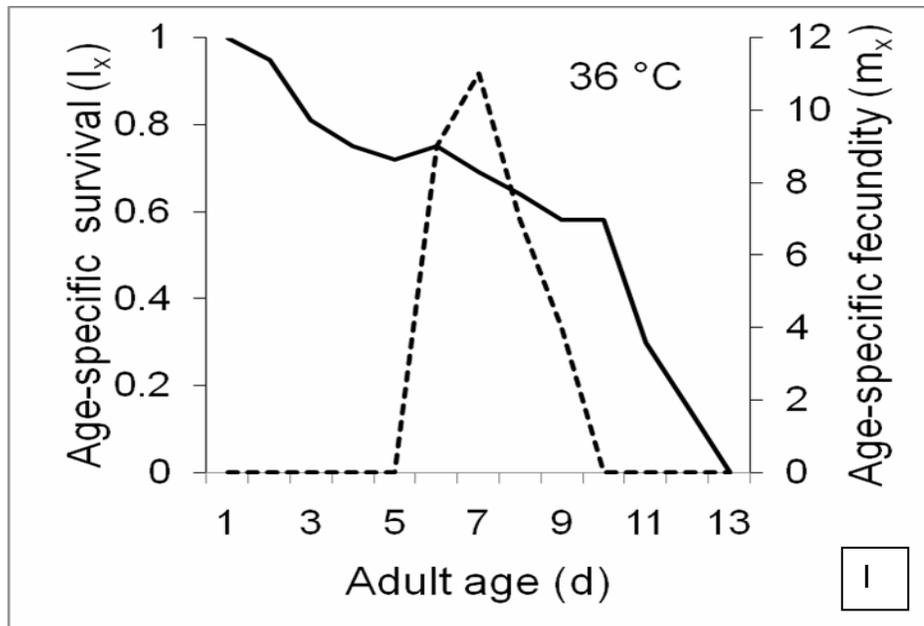


Figure 3-1 continued.

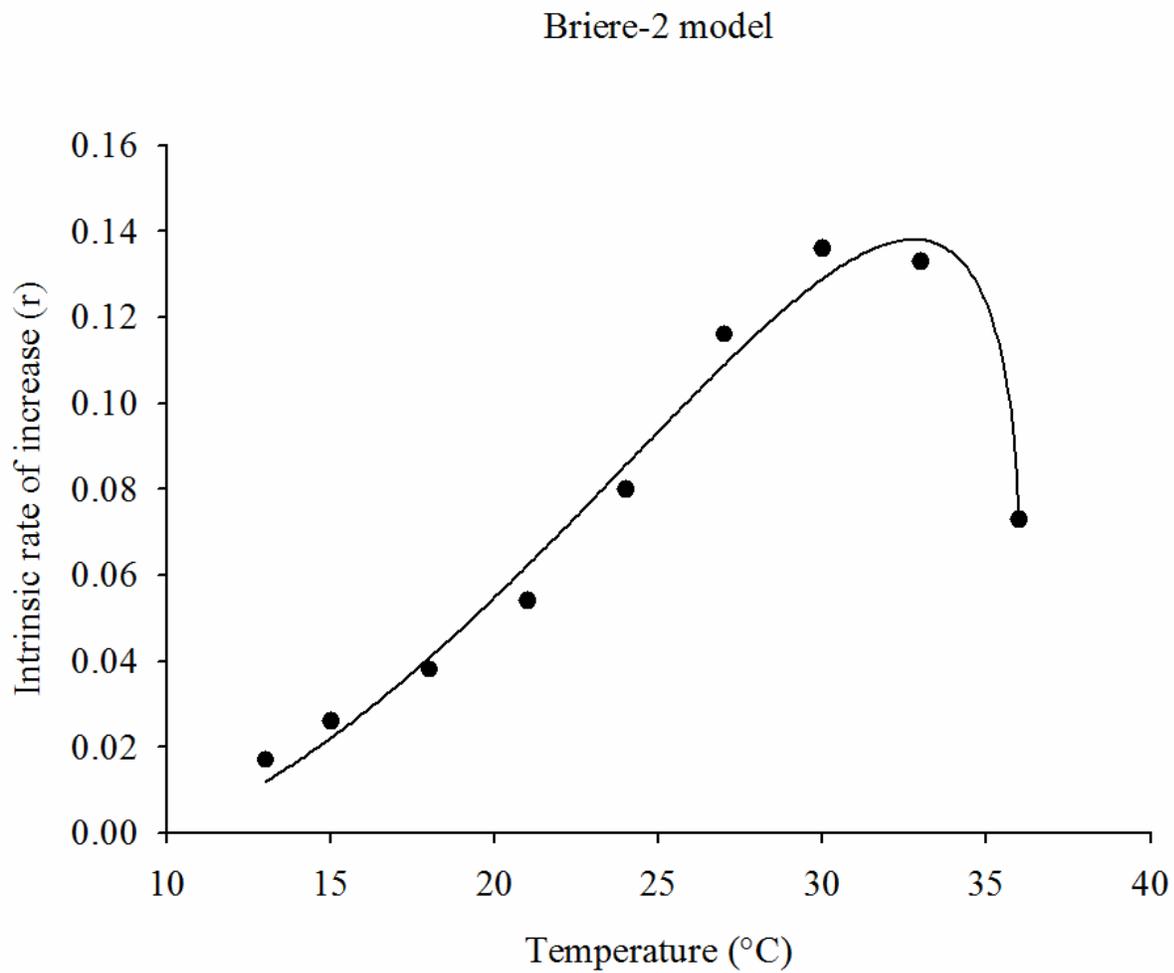


Figure 3-2. Relationship between temperature (°C) and intrinsic rate of natural increase (r) for *E. lignosellus* with mean (\pm SEM) lower (T_0) and upper (T_m) developmental thresholds estimated by Briere-2 model $aT(T - T_0) \times ((T_m - T)^{1/d})$ for *E. lignosellus* on sugarcane.

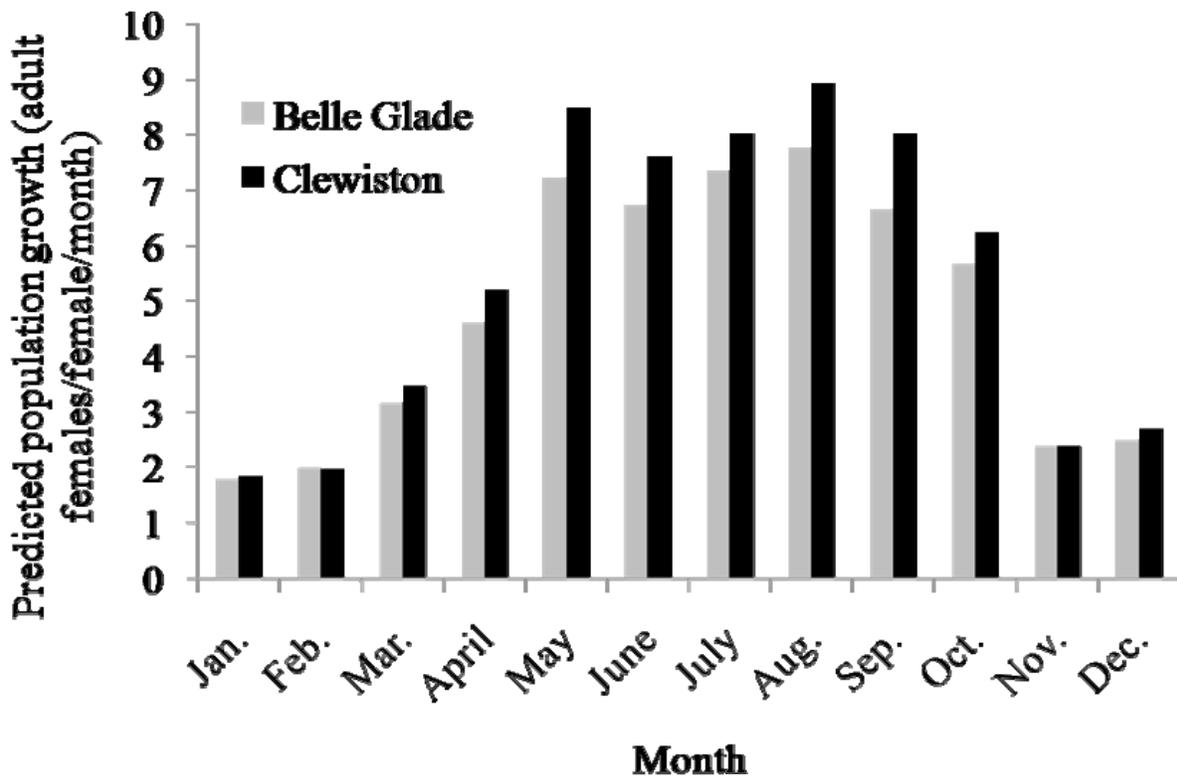


Figure 3-3. Predicted population growth of *E. lignosellus* on sugarcane based on the Briere-2 model and average monthly temperatures at two locations in southern Florida.

CHAPTER 4
COMPENSATORY RESPONSE OF SUGARCANE TO *ELASMOPALPUS*
LIGNOSELLUS DAMAGE

Introduction

'Compensation' is the process by which plants respond positively to an insect injury (Bardener and Fletcher 1974) and decrease the negative effect on yield (Pedigo 1991). Compensatory growth can result from the suppression of growth regulating substances (Dillewijn 1952), or reallocation of resources within individual plants following herbivory, depending on source-sink relationships (Larson and Whitham 1997, Stowe et al. 2000). The growing point suppresses bud development through growth regulating substances, and removal of the primary shoot can alter the effect of these substances allowing more tillers to develop. In source-sink relationships, sources are photosynthetic organs or storage tissues (e.g., leaves) for net carbon gain, while sinks are the organs used for growth and reproduction (i.e., apical meristems, flowers and fruits) (Whitham et al. 1991). The source-sink relationship can be modified by removing either the source or sink through herbivory. Honkanen et al. (1994) reported that the damage to apical bud in Scots pine (*Pinus sylvestris*) resulted in significant increase in mass and length of needles in lateral shoots.

Compensatory plant growth in response to insect damage caused at early growth stages has been reported in many field crops. For example, rice compensates for injury at the vegetative stage by the stem borer *Scirpophaga incertulas* (Walker) (Lepidoptera: Pyralidae) (Rubia et al. 1990) by producing new vegetative (Soejitno 1979, Tian 1981, Akinsola 1984, Viajante and Heinrichs 1987) and reproductive tillers (Luo 1987). Studies have also shown that low insect infestation levels at early growth stages may

increase plant yield in field beans (Banks and Macaulay 1967), wheat (Gouch 1947, Bardener 1968), potato (Skuhravy 1968), and cotton (Kincade et al. 1970).

Florida is the leading sugarcane producing state in the U.S. with 401,000 acres of sugarcane valued at \$398.9 million dollars in 2008 (USDA 2008). The majority of the sugarcane acreage is grown in Palm Beach, Martin, Hendry, and Lee counties in southern Florida. Sugarcane is vegetatively propagated by planting mature stalks. Buds start developing shoots soon after planting. These shoots are called mother shoots or primary shoots. Primary shoots have many small internodes each carrying a lateral bud. These lateral buds develop into secondary shoots that in turn may produce tertiary shoots (Dillewijn 1952). Sugarcane has a great capacity to compensate for damage to young shoots. Compensation ability depends on the plant variety and age of the plant at which damage occurred, with the greatest compensation in young sugarcane and diminishing with plant age. Demandt (1929) reported 50% compensatory growth of sugarcane in response to mechanically damaged shoots. He showed that this compensation was partly due to the production of new tillers, and partly due to survival of the stalks which otherwise would have died due to lack of nutrients in the presence of the primary shoot. Wen and Shee (1948) later showed that mechanical removal (topping) of the primary shoots increased the number of millable stalks by 11.3% and sugarcane yield by 25.9%.

Lesser cornstalk borer, *Elasmopalpus lignosellus* (Zeller) (Lepidoptera: Pyralidae), is a serious pest of sugarcane in southern Florida, particularly on silica soils. There are multiple varieties of sugarcane grown in this area (Rice et al. 2009) that are attacked by lesser cornstalk borer at different growth stages. Larvae enter the young shoot of

sugarcane causing two types of damage (Fig. 4-1). Larvae that reach the center of the shoot and damage or sever the youngest leaves produce dead heart symptoms. Non-lethal damage is caused when larvae only chew a few millimeters into the shoot and becomes evident when the leaves push out to reveal one to several symmetrical rows of holes (Schaaf 1974, Carbonell 1978). We observed a third type of damage in which shoots died in response to larval *E. lignosellus* feeding and did not produce tillers. However, initial feeding damage does not always result in stand or yield loss. Carbonell (1978) reported 27.8% recovery in plant canes and 48.1% recovery in stubble canes in response to *E. lignosellus* damage. Information on variety specific sugarcane recovery to *E. lignosellus* damage would be useful for the industry in their variety selection program. This information is also important for developing damage thresholds for use in integrated management of this pest in the numerous susceptible grass and vegetable crops grown throughout the southeastern United States. The objective of this study was to document variety and age specific feeding damage in sugarcane by lesser cornstalk borer larvae and the potential for damaged plants to compensate for early season damage.

Materials and Methods

Effects of damage caused by lesser cornstalk borer on sugarcane growth and yield were evaluated in two, 11-mo. greenhouse studies during 2008 (January to November) and 2009 (November 2008 to September 2009) conducted at the Everglades Research and Education Center (EREC), Belle Glade, Florida. The sugarcane varieties CP78-1628, CP89-2143 and CP88-1762 were selected for this study. These varieties occupy the greatest acreage grown on Immokalee fine sand (sandy soil) where lesser cornstalk borer is considered to be a major perennial problem

(Rice et al. 2009). CP89-2143 and CP88-1762 were also ranked as first and second in total Florida sugarcane acreage. Three early growth stages (3-, 5-, and 7-leaf stage) were selected for infestation with lesser cornstalk borer larvae based on damage reports during the first 2-3 months of sugarcane growth (Carbonell 1978). These three selected growth stages were present approximately 3, 5, and 8 wk after primary shoot emergence.

Production of Sugarcane Plants

Mature stalks of each variety were harvested from fields at the EREC to obtain viable buds for planting. Stalks were cut into 10 cm-long seed pieces each with one bud (i.e., single eye sets) and planted in plastic trays (50 × 36 × 9.5 cm) filled with Immokalee fine sand to germinate the buds and produce shoots. Immokalee fine sand was used as a medium for plant growth throughout the experiment, because lesser cornstalk borer causes more damage in sandy soil than muck soil, and Immokalee fine sand is one of the major sandy soils in the sugarcane growing area around Lake Okeechobee in south central Florida. Two days after emergence, uniform sized seedlings were selected and transplanted to 19.0 liter (5 gal) buckets (two seedlings per bucket) filled with Immokalee fine sand. Plants were fertilized by adding 50 g of ammonium sulfate and 20 g of a balanced granular fertilizer (14-14-14) to the soil of each bucket at planting time and again every 3 mo. until harvest. Irrigation was applied every 2 d.

Insect Rearing

Insects used in this study were obtained from a laboratory colony of lesser cornstalk borer maintained at EREC. The colony was started 4 mo. before the start of the experiment, by using larvae and adults of *E. lignosellus* collected from sugarcane

fields at Belle Glade and Moore Haven, Florida. The colony was maintained on a wheat germ and soy flour based artificial diet as described in Sandhu et al. (2010a). Third instar larvae were used to infest sugarcane plants. To produce larvae for the trial, first and second instar larvae were removed from artificial diet and reared on 3-4 leaf stage shoots of respective sugarcane varieties to avoid the effect of host change on larval feeding. The choice to use third instar for infestation was based on preliminary trials on green house plants, where it was observed that first and second instars had high mortality and their feeding on leaves did not cause major damage. Third instar larvae move from leaves to the soil to feed on shoots and tillers.

Experiment Design

A randomized complete block design with a 3 × 4 factorial arrangement was used during both experiment years to evaluate sugarcane response to *E. lignosellus* feeding damage. The factors were three sugarcane varieties (CP78-1628, CP88-1762, and CP89-2143) and three leaf stages infested plus one control (i.e., no infestation and infestation at 3-, 5-, and 7-leaf stages). The combinations of these factors (3 × 4) were applied randomly to the 12 buckets in each block. The buckets in each block were arranged in 2 rows of 6 buckets each. Each block was replicated 12x in 2008 and 15x in 2009. Four, third instar (6-7 d old) larvae conditioned on sugarcane as above were released near the base of plants in each bucket with the aid of a camel hair brush at the respective leaf stages. The number of larvae per bucket was selected based on preliminary trials on greenhouse plants. Sugarcane in the buckets was exposed to a single generation of lesser cornstalk borer. After completion of the larval stage, pupae were collected and returned to the colony by removing and straining the top 6 cm of soil. Timing for the completion of the larval stage was estimated based on the results of

temperature-dependent developmental studies on sugarcane seedlings in the laboratory (Sandhu et al. 2010a).

Damage Assessment

Feeding damage was recorded for primary shoots and tillers in each bucket. Secondary and tertiary shoots will be referred to as tillers in this report. The number of dead hearts, number of shoots with symmetrical rows of holes in leaves, and number of dead plants per bucket were recorded weekly starting one week after infestation at each leaf stage. Plants were counted as dead heart if feeding lead to chlorosis and necrosis of only the primary shoot. A plant with damage that led to necrosis of both primary shoot and tillers and the cessation of tiller production was counted as a dead plant. Buckets were first observed for dead plants, then dead hearts and then holes in the leaves. Plants counted as dead could not be counted as dead hearts, and plants with dead hearts could not also be counted as plant with holes in leaves. Mean percentage of plants with dead hearts, holes in the leaves, and dead plants were calculated using the final observation (4 wk after infestation) on all damaged and undamaged shoots and tillers per bucket. Total damage by lesser cornstalk borer was calculated as the summation of dead hearts, holes in the leaves and dead plants per bucket. The number of tillers per bucket was counted 4 mo. after emergence to account for varietal and leaf stage differences in tiller production.

Sugarcane Yield Assessment

Sugarcane yield was determined using the number and weight of millable stalks, and the sucrose concentration of juice squeezed from those stalks. Millable stalks are primary shoots and tillers > 1.5 m in height and are traditionally counted 8 mo. after the first emergence of sugarcane shoots. Millable stalks are counted 3 mo. before

harvesting, because lodging in sugarcane at harvest time interferes with determining the height and exact number of millable stalks. Millable stalks from each bucket were harvested 11 mo. after sugarcane emergence. Individual stalks were weighed separately, and sugarcane yield (Kg per bucket) was calculated as the product of the number of millable stalks and the mean stalk weight in each bucket. To determine sucrose concentration, two randomly selected millable stalks per bucket from each block were milled and crusher juice-analyzed for brix and pol values as described by Gilbert et al. (2008). Sucrose (Kg per bucket) was calculated according to the theoretical recoverable sugar method (Glaz et al. 2002).

Data Analysis

The data were analyzed using analyses of variance (ANOVA) (SAS Institute 2008). The data on response variables (dead hearts, holes in the leaves, dead plants, number of tillers, stalk count, cane yield and sugar yield) were recorded for each bucket and analyzed for the effect of year, varieties, infested leaf stages and their interactions. Proportionate data were arcsine transformed before analysis and retransformed for presentation purposes. Orthogonal contrasts were used to test for significant differences between specific factors (SAS Institute 2008) due to the incomplete factorial experimental design and for better comparisons between the untreated control and treatments.

Results

Damage

The experiment year ($df = 1, 300$) was not a significant source of variation in the model for dead hearts ($F = 1.64, P = 0.2272$), holes in the leaves ($F = 0.03, P = 0.8588$), dead plants ($F = 0.01, P = 0.9880$) or total damage ($F = 0.10, P = 0.7546$). The data on

damage types were pooled over the two years and analyzed together by using year as a random effect with blocks nested within year (Table 4-1). The data were also pooled for two years to calculate the means for all damage types. No feeding damage was observed in the untreated controls and resulted in significantly higher percentages for all damage types for all variables than the untreated control.

Dead hearts were the most commonly observed result of *E. lignosellus* feeding damage to sugarcane. Variety was a significant source of variation in the model for dead hearts (Table 4-1) with CP89-2143 (55.7 ± 2.5) having a significantly greater percentage of plants with dead hearts than CP78-1628 (48.3 ± 2.1) (Table 4-2). Leaf stage was a significant source of variation in the model (Table 4-1); the earlier the plants were infested, the greater the resulting dead heart symptoms were produced. Percentage of plants with dead hearts was greater in the sequence 3- > 5- > 7-leaf stage (Table 4-2). In all three varieties, plants infested at the 3-leaf stage had a greater percentage of plants with dead hearts than those infested at the 7-leaf stage.

Symmetrical rows of holes in the leaves were the second most commonly observed damage by *E. lignosellus* feeding on sugarcane. Variety, leaf stage, and their interaction were significant sources of variation in the model for holes in the leaves (Table 4-1). CP78-1628 (34.3 ± 3.1) had a significantly greater percentage of plants with holes in the leaves than CP89-2143 (23.0 ± 2.9) (Table 4-2). In contrast to dead hearts, mean percentage of plants with holes in leaves was greater in late-infested (7-leaf stage) than early-infested (3-leaf stage) plants. The mean percentage of plants with holes in the leaves at the 7-leaf stage was significantly greater than at the 5-leaf stage, and more were found on plants infested at the 5-leaf stage than at the 3-leaf

stage. In all three varieties, plants infested at the 7-leaf stage had a greater percentage of plants with rows of holes than those infested at the 3-leaf stage.

Dead plants were the third type of observed damage caused by *E. lignosellus* feeding on sugarcane, especially in variety CP89-2143. Variety, leaf stage, and their interaction were significant sources of variation in the model for dead plants (Table 4-1). The mean percentage of dead plants in CP89-2143 (16.0 ± 3.4) was significantly greater than CP88-1762 (5.8 ± 2.1) and CP78-1628 (3.2 ± 1.2) (Table 4-2). The mean percentage of plants that died when infested at the 3- (11.3 ± 2.2) and 5-leaf (9.7 ± 1.9) stages were significantly greater than at the 7-leaf (3.9 ± 0.6) stage. Infestation at the 3- and 5-leaf stages in CP78-1628 and CP88-1762, and 3-leaf stage in CP89-2143 produced greater percentages of dead plants than infestation at the 7-leaf stage in respective varieties. In CP78-1628, no plant died in late infested plants; however, early infestation in CP89-2143 caused the greatest percentage (19.5 ± 5.8) of plant deaths.

The sum of plant feeding damage caused by *E. lignosellus* (dead hearts, holes in leaves and dead plants) was analyzed as the total damage. Variety had a significant effect on total damage percentage (Table 4-1) with CP89-2143 (94.7 ± 3.1) having a greater percentage total damage than CP78-1628 (85.8 ± 2.4) and CP88-1762 (86.0 ± 2.7) (Table 4-2). Leaf stage was also a significant source of variation in the model with greater total damage at the 3- (90.1 ± 2.0) and 5- (90.8 ± 2.1) leaf stages than at the 7- (85.5 ± 1.7) leaf stage. Total damage in CP88-1762 and CP89-2143 did not vary significantly with infestation stage, but CP78-1628 had greater damage at the 3- than at the 7-leaf stage.

Tiller Production

Experiment year significantly affected tiller production ($df = 1, 300, F = 137.41, P < 0.0001$) with approximately one additional tiller produced per bucket in 2009 than in 2008. Due to the significant year effect, the data were analyzed separately for 2008 and 2009 (Table 4-3). Variety, leaf stage and variety \times leaf stage were all significant sources of variation in the model for number of tillers per bucket in both years. CP78-1628 and CP88-1762 produced significantly greater number of tillers than CP89-2143 in both years (Tables 4-4, 4-5). Buckets infested at 3-leaf stage produced significantly more tillers than those infested at 7-leaf stage in both years. In the variety \times leaf stage interaction, *E. lignosellus* damage at the 3-leaf stage to CP78-1628 and CP88-1762 resulted in increased tiller production over the untreated controls in both years. However, CP89-2143 plants infested at all three leaf stages produced significantly fewer tillers than the untreated control plants. In late infested plants, CP78-1628 produced more tillers than the other two varieties in 2008, but in 2009 both CP78-1628 and CP88-1762 produced more tillers than CP89-2143.

Sugarcane Yield Traits

Yield traits refer to the number of millable stalks, sugarcane yield and sucrose yield. The experiment year ($df = 1, 300$) was again a significant source of variation in the models for numbers of millable stalks ($F = 120.98, P < 0.0001$), sugarcane yield ($F = 88.27, P < 0.0001$), and sucrose yield ($F = 17.21, P < 0.0001$). Therefore, the data were analyzed separately for 2008 and 2009 (Table 4-3). The significant year effect resulted from greater yield traits in 2009 than in 2008, but the relative patterns for these traits among varieties, leaf stages and their interaction were the same in both years. Overall there was approximately one extra stalk per bucket in 2009 than in 2008, which lead to

0.75 kg increase in sugarcane yield and 0.05 kg increase in sucrose yield per bucket in 2009 than in 2008. Mean (\pm SEM) values of yield traits for 2008 and 2009 are presented in Table 4-4 and Table 4-5, respectively.

Variations among varieties and leaf stages for millable stalk production were similar to tiller production, except that infestation at the 5-leaf stage of CP78-1628 resulted in production of significantly more millable stalks than the control. Variety, leaf stage and variety \times leaf stage were significant sources of variation in the model for the mean number of millable stalks per bucket during both years (Table 4-3). Production of millable stalks in CP78-1628 and CP88-1762 was significantly greater than CP89-2143 in both years (Tables 4-4, 4-5). Similar to tiller production, early infestation produced a greater number of millable stalks than late infestation in both years. In the variety \times leaf stage interaction, *E. lignosellus* damage at the 3- and 5-leaf stages in CP78-1628 resulted in increased millable stalk production over the untreated controls and those damaged at the 7-leaf stage in both years. In CP88-1762, plants infested at the 3-leaf stage produced more millable stalks than untreated controls and plants infested at the 5- and 7-leaf stages. Untreated controls in CP89-2143 produced more millable stalks than plants infested at all three leaf stages.

Variety, leaf stage and variety \times leaf stage were significant in 2008, but variety \times leaf stage was not a significant source of variation in the model in 2009 for sugarcane yield (Table 4-3). Sugarcane yield in CP78-1628 was significantly greater than in CP88-1762 and CP89-2143 in 2008 (Table 4-4), but in 2009 both CP78-1628 and CP88-1762 produced greater sugarcane yield than CP89-2143 (Table 4-5). Untreated control plants produced greater sugarcane yield than plants infested at all three leaf stages in

both years. Plants infested at the 3- and 5-leaf stages produced greater sugarcane yield than those infested at the 7-leaf stage. In variety × leaf stage interactions, infestation at the 3- and 5-leaf stages of CP78-1628 did not affect sugarcane yield compared to control, but infestation at the 7-leaf resulted in significantly reduced yield. Although infestation at the 3-leaf stage in CP88-1762 resulted in more millable stalks produced than in the untreated control, the sugarcane yield was greater in the untreated control than in all the infested stages. In CP89-2143, plants in the untreated control produced greater sugarcane yield than those infested at all the leaf stages.

Variety, leaf stage and variety × leaf stage were significant sources of variation in 2008, but variety × leaf stage was not significant in the 2009 model for sucrose yield (Table 4-3). Although the sugarcane yield of CP88-1762 was lower than CP78-1628 in 2008, sucrose yields for the two varieties were the same. Sucrose yield in CP78-1628 was significantly greater than CP89-2143 in 2008 (Table 4-4), but in 2009 both CP78-1628 and CP88-1762 produced greater sugarcane yield than CP89-2143 (Table 4-5). Plants in the untreated control produced more sucrose than at all the infested stages. Infestation at the 3- and 5-leaf stages resulted in greater sucrose production than late infestation in both years. In the variety × leaf stage interactions, CP78-1628 had reduced sucrose yield only when infested at the 7-leaf stage. *Elasmopalpus lignosellus* damage to CP88-1762 and CP89-2143 caused significant sucrose yield losses at all the infested leaf stages compared to untreated controls.

Percent reduction in sugarcane and sucrose yield in infested plants compared to untreated control plants in 2008 and 2009 are presented in Tables 4-5 and 4-6, respectively. Compared with untreated controls, CP78-1628 had the least reduction in

sugarcane (14% in 2008 and 19% in 2009) and sucrose yields (18% in 2008 and 19% in 2009), while CP89-2143 had the greatest reduction in sugarcane (34% in 2008 and 42% in 2009) and sucrose (30% in 2008 and 38% in 2009) yields. However, yield reduction does not provide details about plant compensation for early season lesser cornstalk borer damage. Percentage compensation to initial damage was calculated by deducting percentage reduction in yield from damage percentage. The resulting compensation values were then compared among varieties infested at different leaf stages.

Variety ($df = 2, 99, F = 1.81, P = 0.1686$) was not significant, but infested leaf stage ($df = 3, 99, F = 33.18, P < 0.0001$) and variety \times leaf stage ($df = 6, 99, F = 3.89, P < 0.0001$) were significant sources of variation in the model for percentage compensation in sugarcane yield in 2008. Similarly in 2009, variety ($df = 2, 126, F = 1.95, P = 0.1469$) was not significant, but leaf stage ($df = 3, 126, F = 177.95, P < 0.0001$) and variety \times leaf stage ($df = 6, 126, F = 7.35, P < 0.0001$) were significant sources of variation in the model for percentage compensation in sugarcane yield. Overall, no significant difference was detected among the tested varieties for compensation for lesser cornstalk borer damage, but compensation was greater when infested at 3- followed by 5- and 7-leaf stages in both years (Tables 4-6, 4-7). In variety \times leaf stage interaction, CP78-1628 and CP88-1762 compensated better than CP89-2143 for sugarcane yield at 3-leaf stage infestation in 2009. However, sugarcane yield compensation following infestation at the 7-leaf stage was greater in CP89-2143 than in CP78-1628. For sucrose yield compensation following infestation at the 7-leaf stage, CP89-2143 compensated better than CP78-1628 and CP88-1762 during both years. In

CP78-1628 and CP88-1762, percentage compensation was significant in the sequence of 3- > 5- > 7- leaf stage. In CP89-2143, percentage compensation in the plants infested at the 3- and the 5-leaf stage was same and it was greater than the plants infested at the 7-leaf stage.

Compensation in sucrose yield was similar to sugarcane yield compensation. Again variety (df = 2, 99, $F = 1.92$, $P = 0.1394$) was not significant, but infested leaf stage (df = 3, 99, $F = 39.25$, $P < 0.0001$) and variety \times leaf stage (df = 6, 99, $F = 4.16$, $P < 0.0001$) were significant sources of variation in the model for sucrose yield compensation in 2008. Similarly in 2009, variety (df = 2, 126, $F = 0.84$, $P = 0.4251$) was not significant, but leaf stage (df = 3, 126, $F = 192.14$, $P < 0.0001$) and variety \times leaf stage (df = 6, 126, $F = 6.12$, $P < 0.0001$) were again significant sources of variation for sucrose yield compensation. Compensation in sucrose yield varied similarly among varieties and the infested leaf stages as compensation in sugarcane yield.

Discussion

Damage

Results of this study showed that lethal damage (dead hearts or dead plants) and non-lethal damage (holes in leaves) by lesser cornstalk borer feeding varied with variety and time of infestation. Equal numbers of lesser cornstalk borer larvae produced the greatest lethal damage in CP89-2143 and non-lethal damage in CP78-1628. CP89-2143 displayed greater susceptibility to lesser cornstalk borer damage than the other two varieties. Damage differences among varieties may be due to morphological, physiological or biochemical resistance in plants. Agarwal (1969) reported that the physical and chemical make-up of sugarcane plants greatly influences their protection from insect damage. He reported that cell wall lignification and the number of

sclerenchymatous cell layers play an important role in imparting resistance against stem borers. Varietal differences in percentage lesser cornstalk borer damage were also reported by Chang and Ota (1989) with < 5% dead hearts in sugarcane varieties H83-6818 and H83-7498 compared to 23% dead hearts in H77-6359. Similar varietal differences were also reported for damage caused by other Pyralidae stem borers. Bessin et al. (1990) reported seasonal differences in injury by sugarcane borer, *Diatraea saccharalis* (F.) (Lepidoptera: Pyralidae) among tested sugarcane clones that may have been due to resistance to stalk entry or antibiosis (larval survival). In another study, Pfannenstiel and Meagher (1991) reported significant differences among sugarcane varieties to injury by the Mexican rice borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Pyralidae).

Infestation at the 3- and 5-leaf stages resulted in greater percentages of dead hearts and dead plants than when infested at the 7-leaf stage. Infestation at the 7-leaf stage resulted in a greater percentage of plants with symmetrical rows of holes in the leaves. This may be due to increasing stem thickness with plant age that allowed fewer larvae to enter the stem to cause dead hearts. This statement is supported by Rojanaridpiched et al. (1984) who found that silica and lignin contents of some maize varieties increases with age and are major factors of resistance to stem borers at later plant development stages.

Tiller Production

Increased tiller production in plants infested at the 3-leaf stage in CP78-1628 and CP88-1762 may be the result of changes in growth regulating substances in damaged primary shoots (Dillewijn 1952). Changes in source-sink relationship due to damaged primary shoot may also be responsible for increased tiller production (Honkanen et al.

1994). They reported that the damage to apical bud in *P. sylvestris* resulted in significant increase in mass and length of needles in lateral shoots. Lower tiller production in plants infested late rather than early may be due to lesser cornstalk borer larval damage to both tillers and primary shoots of the 7-leaf stage plants. In early-infested plants, only primary shoots were damaged because tillers had not yet developed. Larvae completed their development by the time of tiller emergence in early-infested leaf stages and tillers escaped from the damage. Tillers had already emerged by the time of the 7-leaf stage infestation and both primary shoots and tillers were available for borer damage. The lower tiller production in CP89-2143 than other two varieties was likely due to the greater percentage of dead plants that could not produce any tillers after damage.

Compensation through increased tiller production in response to damage was also observed by Carbonell (1978), who reported the recovery of lesser cornstalk borer damaged sugarcane plants through production of additional tillers. Similarly, Hall (1990) and Cherry and Stansly (2009) reported that early stand loss due to wireworm damage was compensated by increased tiller production during the sugarcane growing season. In rice, Rubia et al. (1996) reported that main stem injury due to *Scirpophaga incertulas* (Walker) (Lepidoptera: Pyralidae) resulted in translocation of assimilates from the main stem to primary tillers, which might help in compensation for loss of the primary shoot. They also indicated that 33% dead hearts in 30 d old plants did not have a significant effect on productive tillers or grain yield. Jiang and Cheng (2003) reported that rice plants infested with striped stem borer, *Chilo suppressalis* (Walker)

(Lepidoptera: Pyralidae) produced approximately one more tiller than untreated control plants 2 wk after infestation.

Sugarcane Yield Traits

Although the mean number of millable stalks produced in the untreated controls was less than in the plants infested at the 3- and 5-leaf stages in CP78-1628, sugarcane and sucrose yield in the untreated controls were the same as in the infested plants. Similarly, the number of millable stalks in plants infested at the 3-leaf stage in CP88-1762 was greater than or equivalent to plants in the untreated control, but sugarcane and sucrose yield were greater in the untreated controls than in all the infested leaf stages. The greater sugarcane yield in the untreated controls than in the infested leaf stages was due to greater millable stalk weight in the untreated controls, because sugarcane yield was a product of the number of millable stalks and stalk weight in each bucket. This disparity in millable stalk weight among treatments was likely due to proportionately fewer primary shoots remaining and more tillers produced in early-infested than in untreated control plants at harvest. Early research by Stubbs (1900) and by Rodrigues (1928) determined a gradient in stalk weight and sugar content among shoots with primary shoots having the greatest weight and “richest juice” (i.e., greater brix values) followed by secondary and then tertiary tillers.

Compensatory response in sugarcane and sucrose yield in response to lesser cornstalk borer damage was dependent on infested leaf stage and variety × leaf stage interaction. The greater compensation in early damaged plants than late damaged plants may be due to more time available for early infested plants than late infested plants to compensate for the damage. Variations in sugarcane yield compensatory response with time of infestation were also reported by White and Richard (1985). They

manually removed 25, 50 and 75% randomly selected sugarcane shoots (at 2-5 cm below soil level) in mid-March, mid-April, and mid-May to determine the effect of this shoot removal on sugarcane yield. They reported that the reductions in sugar yields tended to increase with the delay of shoot removal date during the crop season.

Conclusions

Lesser cornstalk borer's ability to cause damage to sugarcane was dependent on variety and time of infestation. Equal numbers of lesser cornstalk borer larvae produced greater damage in CP89-2143 than in CP78-1628 and CP88-1762. Infestation of plants at the 3- and 5-leaf stages produced more lethal damage (dead hearts + dead plants) than infestation at the 7-leaf stage. Tiller production among varieties was dependent upon the level of damage: as damage increased, tillers production decreased. Tiller counts were greater in early damaged plants than late damaged plants, because *E. lignosellus* larvae damaged tillers in late-infested plants that were not present in early-infested plants. Millable stalk production was similar to tiller production. Sugarcane and sucrose yield among varieties also varied according to the damage; more damage in CP89-2143 resulted in lower yield than the other two varieties. Early infestation resulted in more yield than late infestation in all the varieties. The compensation for damage was dependent on time of infestation and variety \times time of infestation. Comparison of sugarcane and sucrose yield reduction with lethal damage shows that the varieties had equal ability to compensate for lesser cornstalk borer damage. Compensation varied with the time of infestation with greater compensation in early-infested than late-infested sugarcane.

Future Directions

The above conclusions were made based on the experiments conducted in the green house. In field conditions, many climatic factors (sunlight, temperature, moisture) and biological factors (insect population, other pests, natural enemies) can affect the results. This experiment could be conducted in the field to determine how season-long exposure to lesser cornstalk borers and population limiting factors (e.g., soil moisture and high summer soil surface temperatures) may affect damage throughout the season and resulting yields.

Table 4-1. Analysis of variance of year, variety, leaf stage and their interactions on percentage *E. lignosellus* damage to sugarcane in 2008 and 2009

Source of variance	df	Dead hearts ¹		Holes in leaves ²		Dead plants ³		Total damage ⁴	
		F	P	F	P	F	P	F	P
Block (B)	14	0.80	0.6494	0.62	0.8037	0.91	0.5465	0.45	0.9560
Variety (V)	2	3.52	0.0417	3.51	0.0328	4.25	0.0189	3.93	0.0149
Leaf Stage (LS)	3	60.98	<0.0001	31.33	<0.0001	10.68	<0.0001	112.24	<0.0001
B × V	28	0.61	0.9389	1.06	0.5483	0.38	0.9428	1.52	0.0542
B × LS	42	3.15	<0.0001	1.92	0.2795	0.81	0.6864	1.09	0.3772
V × LS	6	4.74	0.0161	2.39	0.0312	2.44	0.0280	3.56	<0.0026
B × V × LS	84	0.92	0.6635	1.00	0.4924	0.94	0.6136	0.92	0.6541
Error	300								

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Necrosis of primary shoot and tillers and the cessation of further tiller production

⁴Summation of dead hearts, holes in leaves, and dead plants per bucket

Table 4-2. Mean (\pm SEM) percentage *E. lignosellus* damage to sugarcane pooled across 2008 and 2009

Treatment variables		Dead hearts ¹	Holes in leaves ²	Dead plants ³	Total damage ⁴
Main effects					
Variety	CP78-1628	48.3 \pm 2.1B	34.3 \pm 3.1A	3.2 \pm 1.2B	85.8 \pm 2.4B
	CP88-1762	51.0 \pm 2.3AB	29.2 \pm 3.3AB	5.8 \pm 2.1B	86.0 \pm 2.7B
	CP89-2143	55.7 \pm 2.5A	23.0 \pm 2.9B	16.0 \pm 3.4A	94.7 \pm 3.1A
Leaf stage	untreated	0d	0d	0c	0c
	3-leaf	64.6 \pm 4.4a	14.2 \pm 2.0c	11.3 \pm 2.2a	90.1 \pm 2.0a
	5-leaf	54.9 \pm 3.1b	26.2 \pm 2.3b	9.7 \pm 1.9a	90.8 \pm 2.1a
	7-leaf	35.5 \pm 2.2c	46.1 \pm 2.5a	3.9 \pm 0.6b	85.5 \pm 1.7b
Interaction effects					
Variety	Leaf stage	Dead hearts	Holes in leaves	Dead plants	Total damage
CP78-1628	untreated	0Ac	0Ac	0Ab	0Ac
	3-leaf	63.1 \pm 8.9Aa	19.3 \pm 3.5Ab	6.4 \pm 3.3Ba	88.8 \pm 4.0Aa
	5-leaf	50.8 \pm 7.0Aa	33.8 \pm 4.5Aab	3.2 \pm 2.0Ba	87.8 \pm 5.1Aab
	7-leaf	31.1 \pm 5.3Ab	49.8 \pm 5.9Aa	0Cb	80.9 \pm 3.2Ab
CP88-1762	untreated	0Ac	0Ad	0Ac	0Ab
	3-leaf	67.8 \pm 7.7Aa	11.3 \pm 2.5Bbc	8.0 \pm 3.2Ba	87.1 \pm 3.1Aa
	5-leaf	51.3 \pm 7.1Aab	28.2 \pm 4.6Ab	7.9 \pm 3.6Ba	87.4 \pm 2.6Aa
	7-leaf	33.9 \pm 4.0Ab	48.1 \pm 6.2Aa	1.4 \pm 0.3Bb	83.4 \pm 2.4Aa
CP89-2143	untreated	0Ac	0Ad	0Ac	0Ac
	3-leaf	62.9 \pm 7.9Aa	12.0 \pm 1.3Ac	19.5 \pm 5.8Aa	94.4 \pm 4.5Aa
	5-leaf	62.8 \pm 9.4Aa	16.5 \pm 6.0Bb	18.0 \pm 5.9Aab	97.3 \pm 5.7Aa
	7-leaf	41.4 \pm 6.9 Ab	40.5 \pm 7.4 Aa	10.4 \pm 3.9 Ab	92.3 \pm 5.9Aa

Means followed by different letters are significantly different (orthogonal contrasts, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate contrasts among varieties (main effects) and among varieties at the same leaf stage (interaction effects). Small letters indicate contrasts among leaf stages (main effects) and among leaf stages in the same variety (interaction effects).

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Necrosis of both primary shoot and tillers and the cessation of further tiller production

⁴Summation of dead hearts, holes in leaves, and dead plants per bucket

Table 4-3. Analysis of variance effects on tillers, millable stalks, sugarcane yield, and sucrose yield per bucket during 2008 and 2009

Source of variance	2008								
	Tillers ¹			Millable stalks ²		Sugarcane yield ³		Sucrose ⁴	
	df	F	P	F	P	F	P	F	P
Block (B)	11	3.80	<0.0001	1.35	0.2169	2.05	0.0352	2.13	0.0296
Variety (V)	2	19.90	<0.0001	8.29	0.0006	25.98	<0.0001	27.86	<0.0001
Leaf Stage (LS)	3	4.69	0.0032	4.78	0.0029	8.02	<0.0001	10.91	<0.0001
B × V	22	6.58	<0.0001	1.70	0.0504	1.27	0.2135	1.34	0.1824
B × LS	33	2.03	0.0011	1.87	0.1669	1.12	0.489	0.92	0.5928
V × LS	6	6.00	<0.0001	3.77	0.0017	2.15	0.0684	1.95	0.0849
B × V × LS	66	4.13	<0.0001	1.15	0.4216	1.18	0.3145	1.23	0.2325
Error	143								
Source of variance	2009								
	Tillers			Millable stalks		Sugarcane yield		Sucrose	
	df	F	P	F	P	F	P	F	P
Block (B)	14	5.24	<0.0001	1.90	0.0376	5.29	<0.0001	6.15	<0.0001
Variety (V)	2	75.47	<0.0001	7.47	0.0010	83.08	<0.0001	95.90	<0.0001
Leaf Stage (LS)	3	28.41	<0.0001	15.36	<0.0001	123.66	<0.0001	122.26	<0.0001
B × V	28	8.02	<0.0001	1.79	0.0219	5.93	<0.0001	6.23	<0.0001
B × LS	42	0.68	0.9372	1.13	0.3180	1.02	0.4571	0.81	0.7658
V × LS	6	10.77	<0.0001	3.22	0.0068	9.14	0.0004	13.69	<0.0001
B × V × LS	84	2.05	0.5245	1.69	0.1564	1.29	0.3416	2.45	0.2516
Error	179								

¹No. secondary and tertiary shoots

²No. stalks ≥ 1.5 m in height

³Total weight (Kg) of millable stalks in each bucket

⁴Raw sugar weight (Kg per bucket) calculated from brix and pol values

Table 4-4. Mean (\pm SEM) tiller production and yield traits per bucket in 2008

Treatment variables					
Main effects		Tillers ¹	Millable stalks ²	Sugarcane yield ³	Sucrose yield ⁴
Variety	CP78-1628	4.3 \pm 0.3A	3.6 \pm 0.2A	2.6 \pm 0.2A	0.26 \pm 0.02A
	CP88-1762	3.9 \pm 0.2A	3.2 \pm 0.2A	2.1 \pm 0.2B	0.23 \pm 0.02AB
	CP89-2143	3.1 \pm 0.2B	2.2 \pm 0.1B	1.9 \pm 0.1B	0.21 \pm 0.02B
Leaf stage	untreated	3.8 \pm 0.2ab	3.0 \pm 0.2ab	2.7 \pm 0.2a	0.28 \pm 0.02a
	3-leaf	4.1 \pm 0.2a	3.2 \pm 0.2a	2.3 \pm 0.1b	0.24 \pm 0.02b
	5-leaf	3.8 \pm 0.2ab	3.0 \pm 0.2ab	2.1 \pm 0.1b	0.23 \pm 0.02b
	7-leaf	3.4 \pm 0.2b	2.8 \pm 0.2b	1.7 \pm 0.1c	0.18 \pm 0.01c
Interaction					
Variety	Leaf stage	Tillers	Millable stalks	Sugarcane yield	Sucrose yield
CP78-1628	untreated	4.0 \pm 0.2Ab	3.3 \pm 0.2Ab	2.9 \pm 0.2Aa	0.3 \pm 0.02Aa
	3-leaf	4.9 \pm 0.3Aa	3.9 \pm 0.2Aa	2.8 \pm 0.1Aa	0.28 \pm 0.02Aa
	5-leaf	4.5 \pm 0.3Aab	3.8 \pm 0.3Aa	2.6 \pm 0.1Aa	0.27 \pm 0.02Aa
	7-leaf	4.0 \pm 0.2Ab	3.3 \pm 0.2Ab	2.1 \pm 0.2Ab	0.19 \pm 0.01Ab
CP88-1762	untreated	3.7 \pm 0.2Abc	3.1 \pm 0.1Ab	2.7 \pm 0.1Aa	0.28 \pm 0.03Aa
	3-leaf	4.5 \pm 0.3Aa	3.6 \pm 0.2Aa	2.2 \pm 0.2Bb	0.24 \pm 0.02Bb
	5-leaf	4.0 \pm 0.2Ab	3.2 \pm 0.2Ab	2.1 \pm 0.1Bb	0.23 \pm 0.02Bb
	7-leaf	3.2 \pm 0.2Bc	3.0 \pm 0.1Ab	1.7 \pm 0.2Ac	0.17 \pm 0.01Ac
CP89-2143	untreated	3.7 \pm 0.3Aa	2.8 \pm 0.2Aa	2.6 \pm 0.2Aa	0.27 \pm 0.03Aa
	3-leaf	3.0 \pm 0.3Bb	2.0 \pm 0.2Bb	1.8 \pm 0.1Cb	0.20 \pm 0.02Cb
	5-leaf	3.0 \pm 0.2Bb	2.1 \pm 0.1Bb	1.7 \pm 0.1Cb	0.19 \pm 0.02Cb
	7-leaf	2.9 \pm 0.2Bb	2.1 \pm 0.1Bb	1.5 \pm 0.1Ab	0.17 \pm 0.01Ab

Means followed by different letters are significantly different (orthogonal contrasts, $\alpha = 0.05$) (SAS Institute). Capital letters indicate contrasts among varieties (main effects) and among varieties at the same leaf stage (interaction effects). Small letters indicate contrasts among leaf stages (main effects) and among leaf stages in the same variety (interaction effects).

¹No. secondary and tertiary shoots

²No. stalks ≥ 1.5 m in height

³Total weight (Kg) of millable stalks in each bucket

⁴Raw sugar weight (Kg per bucket) calculated from brix and pol values

Table 4-5. Mean (\pm SEM) tiller production and yield traits per bucket in 2009

Treatment variables				Sugarcane yield ³	Sucrose yield ⁴
Main effects		Tillers ¹	Millable stalks ²		
Variety	CP78-1628	5.4 \pm 0.3A	4.7 \pm 0.3A	3.1 \pm 0.2A	0.30 \pm 0.02A
	CP88-1762	5.2 \pm 0.3A	4.4 \pm 0.2A	3.0 \pm 0.2A	0.28 \pm 0.02A
	CP89-2143	3.5 \pm 0.2B	3.2 \pm 0.2B	2.5 \pm 0.1B	0.22 \pm 0.02B
Leaf stage	untreated	4.6 \pm 0.2ab	4.3 \pm 0.3ab	3.6 \pm 0.2a	0.33 \pm 0.02a
	3-leaf	4.9 \pm 0.2a	4.4 \pm 0.2a	2.9 \pm 0.1b	0.28 \pm 0.02b
	5-leaf	4.7 \pm 0.2ab	4.2 \pm 0.2ab	2.8 \pm 0.1b	0.26 \pm 0.02b
	7-leaf	4.5 \pm 0.1b	3.8 \pm 0.2b	2.0 \pm 0.1c	0.19 \pm 0.01c
Interaction effects					
Variety	Leaf stage	Tillers	Millable stalks	Sugarcane yield	Sucrose yield
CP78-1628	untreated	5.0 \pm 0.4Ab	4.4 \pm 0.4Ab	3.7 \pm 0.3Aa	0.35 \pm 0.03Aa
	3-leaf	6.0 \pm 0.4Aa	5.3 \pm 0.4Aa	3.6 \pm 0.2Aa	0.33 \pm 0.02Aa
	5-leaf	5.5 \pm 0.3Aab	5.1 \pm 0.4Aa	3.3 \pm 0.2Aa	0.31 \pm 0.02Aa
	7-leaf	5.1 \pm 0.3Ab	4.0 \pm 0.3Ab	2.0 \pm 0.1Ab	0.21 \pm 0.01Ab
CP88-1762	untreated	5.0 \pm 0.2Ab	4.3 \pm 0.3Ab	3.6 \pm 0.3Aa	0.34 \pm 0.02Aa
	3-leaf	5.6 \pm 0.3Aa	4.9 \pm 0.3Aa	3.1 \pm 0.2Bb	0.30 \pm 0.02Bb
	5-leaf	5.1 \pm 0.2Aab	4.3 \pm 0.3Ab	2.9 \pm 0.1Bb	0.28 \pm 0.02Bb
	7-leaf	4.9 \pm 0.2Ab	3.9 \pm 0.2Ab	2.1 \pm 0.1Ac	0.19 \pm 0.01Ac
CP89-2143	untreated	4.4 \pm 0.3Aa	4.0 \pm 0.3Aa	3.6 \pm 0.3Aa	0.31 \pm 0.03Aa
	3-leaf	3.2 \pm 0.2Bb	2.8 \pm 0.2Bb	2.2 \pm 0.2Cb	0.21 \pm 0.02Cb
	5-leaf	3.4 \pm 0.2Bb	3.0 \pm 0.3Bb	2.1 \pm 0.1Cb	0.19 \pm 0.01Cb
	7-leaf	3.4 \pm 0.1Bb	3.0 \pm 0.2Bb	2.0 \pm 0.1Ab	0.18 \pm 0.01Ab

Means followed by different letters are significantly different (orthogonal contrasts, $\alpha = 0.05$) (SAS Institute). Capital letters indicate contrasts among varieties (main effects) and among varieties at the same leaf stage (interaction effects). Small letters indicate contrasts among leaf stages (main effects) and among leaf stages in the same variety (interaction effects).

¹No. secondary and tertiary shoots

²No. stalks \geq 1.5 m in height

³Total weight (Kg) of millable stalks in each bucket

⁴Raw sugar weight (Kg per bucket) calculated from brix and pol values

Table 4-6. Change in tiller production and yield traits in response to lethal damage (dead hearts + dead plants) caused by *E. lignosellus* in 2008.

Main effects		Damage ¹ (%)	Percent change compared to control			
			Tillers ²	Stalks ³	Sugarcane yield ⁴	Sucrose yield ⁵
Variety	CP78-1628	51.5	+ 10	+ 11	- 14 (37.5A)	- 18 (33.5A)
	CP88-1762	56.8	+ 05	+ 05	- 28 (28.8A)	- 24 (32.8A)
	CP89-2143	71.7	- 20	- 18	- 34 (37.7A)	- 30 (41.7A)
Leaf stage	3-leaf	75.9	+ 08	+ 07	- 17 (58.9a)	- 14 (61.9a)
	5-leaf	64.6	00	+ 01	- 23 (41.6b)	- 18 (46.6b)
	7-leaf	39.4	- 11	- 06	- 35 (04.4c)	- 36 (03.4c)
Interaction effects		Damage (%)	Percent change compared to control			
Variety	Leaf stage		Tillers	Stalks	Sugarcane yield	Sucrose yield
CP78-1628	3-leaf	69.5	+ 20	+ 18	- 04 (65.5Aa)	- 07 (62.5Aa)
	5-leaf	54.0	+ 11	+ 15	- 11 (43.0Ab)	- 10 (44.0Ab)
	7-leaf	31.1	- 01	+ 00	- 29 (02.1Ac)	- 37 (-6.1Bc)
CP88-1762	3-leaf	75.8	+ 22	+ 17	- 19 (56.8Aa)	- 14 (61.8Aa)
	5-leaf	59.2	+ 07	+ 02	- 27 (32.2Ab)	- 18 (41.2Ab)
	7-leaf	35.3	- 14	- 03	- 37 (-1.7Ac)	- 39 (-4.3Bc)
CP89-2143	3-leaf	82.4	- 20	- 21	- 28 (54.4Aa)	- 26 (56.4Aa)
	5-leaf	80.8	- 19	- 17	- 34 (46.8Aa)	- 30 (50.8Aa)
	7-leaf	51.8	- 22	- 17	- 41 (10.8Ab)	- 37 (14.8Ab)

Values in parenthesis refer to compensation percentage

Means followed by different letters are significantly different (Tukey's, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate contrasts among varieties (main effects) and among varieties at the same leaf stage (interaction effects). Small letters indicate contrasts among leaf stages (main effects) and among leaf stages in the same variety (interaction effects).

¹Summation of percentage of plants with dead hearts and dead plants

²No. secondary and tertiary shoots

³No. stalks ≥ 1.5 m in height

⁴Total weight (Kg) of millable stalks in each bucket

⁵Raw sugar weight (Kg per bucket) calculated from brix and pol values

Table 4-7. Change in tiller production and yield traits in response to lethal damage (dead hearts + dead plants) caused by *E. lignosellus* in 2009.

Main effects		Damage ¹ (%)	Percent change compared to control			
			Tillers ²	Stalks ³	Sugarcane yield ⁴	Sucrose yield ⁵
Variety	CP78-1628	51.5	+ 12	+ 10	- 19 (32.5A)	- 19 (32.5A)
	CP88-1762	56.8	+ 03	+ 02	- 23 (33.8A)	- 26 (30.8A)
	CP89-2143	71.7	- 22	- 27	- 42 (29.7A)	- 38 (33.7A)
Leaf stages	3-leaf	75.9	+ 07	+ 02	- 19 (56.9a)	- 15 (60.9a)
	5-leaf	64.6	+ 02	- 02	- 22 (42.6b)	- 21 (43.6b)
	7-leaf	39.4	- 12	- 14	- 45 (-6.4c)	- 42 (-2.6c)
Interaction effects		Damage (%)	Percent change compared to control			
Variety	Leaf stage		Tillers	Stalks	Sugarcane yield	Sucrose yield
CP78-1628	3-leaf	69.5	+ 21	+ 21	- 03 (66.5Aa)	- 06 (63.5Aa)
	5-leaf	54.0	+ 11	+ 17	- 09 (45.0Ab)	- 11 (43.0Ab)
	7-leaf	31.1	+ 03	- 09	- 44 (-12.9Bc)	- 40 (-8.9Bc)
CP88-1762	3-leaf	75.8	+ 11	+ 14	- 14 (61.8Aa)	- 12 (63.8Aa)
	5-leaf	59.2	+ 01	+ 00	- 16 (43.2Ab)	- 18 (41.2Ab)
	7-leaf	35.3	- 02	- 09	- 40 (-4.7ABc)	- 44 (-8.7Bc)
CP89-2143	3-leaf	82.4	- 17	- 31	- 39 (43.4Ba)	- 32 (50.4Aa)
	5-leaf	80.8	- 12	- 26	- 42 (38.8Aa)	- 39 (41.8Aa)
	7-leaf	51.8	- 13	- 26	- 46 (05.8Ab)	- 42 (09.8Ab)

Values in parenthesis refer to compensation percentage

Means followed by different letters are significantly different (Tukey's, $\alpha = 0.05$) (SAS Institute). Capital letters indicate contrasts among varieties (main effects) and among varieties at the same leaf stage (interaction effects). Small letters indicate contrasts among leaf stages (main effects) and among leaf stages in the same variety (interaction effects).

¹Summation of percentage of plants with dead hearts and dead plants

²No. secondary and tertiary shoots

³No. stalks ≥ 1.5 m in height

⁴Total weight (Kg) of millable stalks in each bucket

⁵Raw sugar weight (Kg per bucket) calculated from brix and pol values

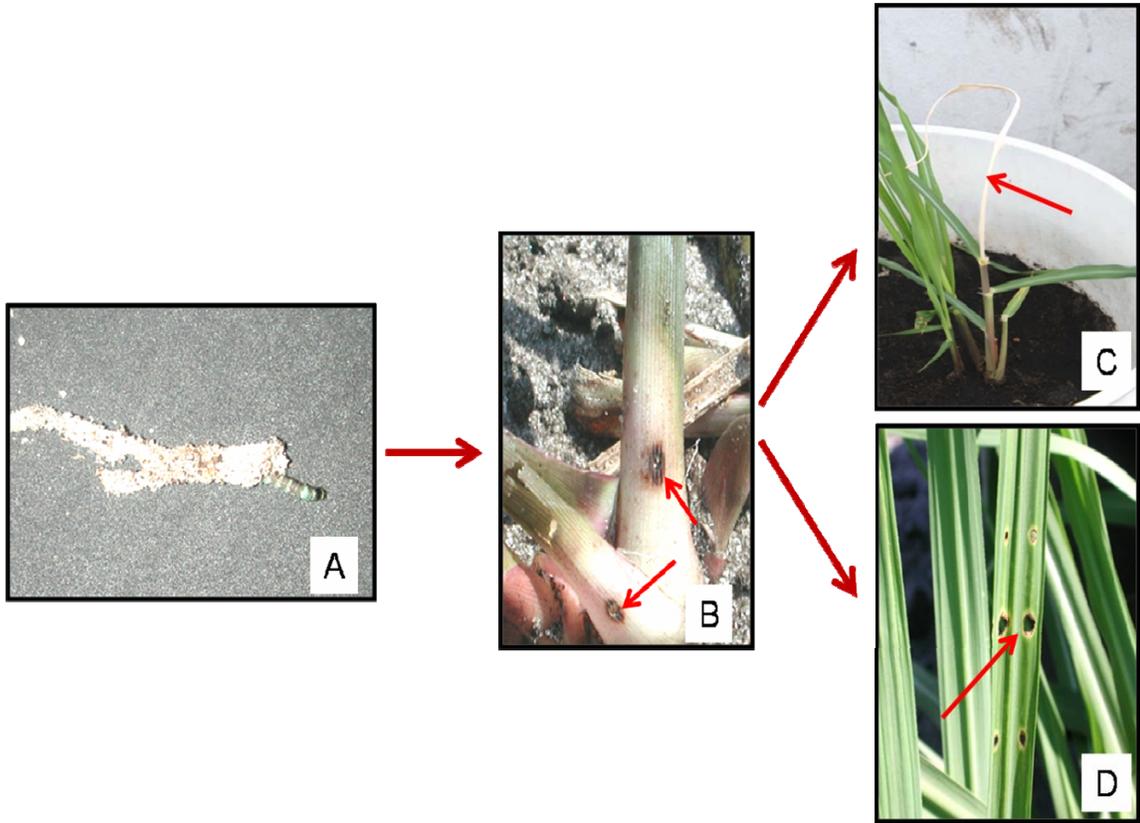


Figure 4-1. Lesser cornstalk borer damage in sugarcane: A) Larva coming out of silken tunnel, B) Larval entry site in the plant, C) Dead heart, D) Holes in the leaves.

CHAPTER 5
EFFECTS OF HARVEST RESIDUE AND TILLAGE LEVEL ON *ELASMOPALPUS*
LIGNOSELLUS DAMAGE TO SUGARCANE

Introduction

Lesser cornstalk borer, *Elasmopalpus lignosellus* (Zeller) (Lepidoptera: Pyralidae) is a pest of many crops, including sugarcane (Falloon 1974). Sugarcane is produced vegetatively from mature stalks with new plants formed from shoots emerging from growth points above each node (Dillewijn 1952). Larval feeding on sugarcane primary, secondary and tertiary shoots results in dead heart symptoms and dead plants that can translate into reduced sugarcane and sugar yield at harvest (Sandhu et al. 2010b). Sugarcane is harvested annually in southern Florida, with ratoon crops usually produced for several years following the first harvest (Baucum and Rice 2009). This habitat provides a year-round food source and reservoir for lesser cornstalk borer from which to renew its attack on the sensitive crop following each harvest and to move out to surrounding crop hosts, such as corn and peanuts.

Chemical insecticides have been tested for many years to control lesser cornstalk borer with varying success (Arthur and Arant 1956, Reynold et al. 1959, Harding 1960, Chalfant 1975, Hyche et al. 1984, Mack et al. 1989, Mack et al. 1991, Chapin and Thomas 1998). Many of the successful materials are no longer labeled for use on these or any other crops. Most recently, the United States Environmental Protection Agency revoked tolerances for carbofuran which was labeled for multiple insect control in sugarcane, effectively removing the last of the effective products for controlling lesser cornstalk borer larvae protected within plants (EPA 2009). Many authors have come to the conclusion that the lesser cornstalk borer is difficult to control with insecticides (Arthur and Arant 1956, Reynold et al. 1959, Harding 1960, and Chalfant 1975), but

chemical insecticides remain important for its control in some crops, such as peanuts (Chapin and Thomas 1998). Natural control of *E. lignosellus* is poorly understood in southern Florida. Falloon (1974) claimed that low levels of predation and parasitism in sugarcane in Jamaica were a result of larvae protected in the soil by the silken tunnels, and due to destruction of the natural enemy complex by pre-harvest burning.

Cultural practices were reported to be efficient in lesser cornstalk borer in different crops. For fall beans, Isley and Miner (1944) recommended inspecting crop residues before planting to determine whether a thorough soil preparation was necessary to kill half-grown larvae. They believed that larvae from eggs deposited after planting would not have enough time to develop to destructive size before the plants passed the most susceptible stage of growth. Cowan and Dempsey (1949) observed a reduction in lesser cornstalk borer damage to pimiento plants in thoroughly cultivated land compared to conservation tillage before planting. Dupree (1964) reported that land kept fallow for 8-10 wk before planting resulted in a significant reduction of borer damage to peanuts and soybean. In Hawaii, Smith and Ota (2002) reported that prompt irrigation application at the appearance of adults in the field was the most efficient practice to control lesser cornstalk borer in sugarcane.

Sugarcane can be harvested following a pre-harvest burn or harvested green without burning (i.e., green harvesting). Green harvesting leaves a blanket of leaf and stalk residues (i.e., trash blanket) on the soil surface after harvesting while pre-harvest burning results in the soil being mostly exposed following harvest. Lesser cornstalk borer outbreaks in sugarcane are frequently associated with either the pre-harvest burning of sugarcane to remove leaf material from the harvest stream, or with post-

harvest burning of the trash left on the soil surface to improve fertilizer penetration and water percolation into the soil (Plank 1928, Wolcott 1948, Bennett 1962, Metcalfe 1966). Release of smoke during sugarcane burning was reported to attract lesser cornstalk borer adults towards the burning field (Bennett 1962). Leuck (1966) observed that female *E. lignosellus* prefer to deposit eggs in the soil. High soil moisture has previously been associated with high larval mortality (Knutson 1976) and low egg deposition (Mack and Backman 1984). Therefore, oviposition and larval survival may be hindered by a trash blanket covering the soil surface. However, production of a trash blanket may result in other agronomic problems for sugarcane.

Retention of sugarcane trash interferes with fertilizer and herbicide applications, water percolation, and can immobilize N and P (Ng Kee Kwong et al. 1987). Soil incorporation of sugarcane trash has been found to increase decomposition rates and increase yield (Kennedy and Arceneaux 2006). Tillage with discs (disking) can be used to incorporate sugarcane trash into the soil, but this can result in re-exposure of the soil surface, thereby increasing the favorability for lesser cornstalk borer egg deposition. In sugarcane, lesser cornstalk borer preferably deposits eggs near the plant base (Smith and Ota 2002); therefore, it is possible that egg deposition may be reduced by retaining a trash blanket around the plant bases. The remaining trash could be disked into the soil potentially eliminating grower concerns for fertilizer application and water percolation problems associated with trash blankets.

Due to growing worldwide interest in reducing environmental pollution, the practice of pre-harvest burning of sugarcane has become either illegal or highly regulated. Additionally, with few insecticides currently available for controlling *E. lignosellus* in

sugarcane, alternative strategies are needed to control this insect. Therefore, trash blankets could play an important future role in the interaction of lesser cornstalk borer and sugarcane. The first objective of this study was to compare the effects of trash blankets on lesser cornstalk borer damage and yield in plant cane versus ratoon sugarcane fields. The second objective was designed to address grower concerns of reduced water percolation and fertilization penetration associated with trash blankets by comparing the combined effects of harvest method (green cane and burnt cane harvesting) and tillage levels (no-tillage, intermediate, and conventional tillage) on lesser cornstalk borer damage and yield.

Materials and Methods

Experimental Design

The first study was conducted at Graham Dairy farm, Moore Haven, Florida, to evaluate the effect of harvest residue (trash or no-trash) on lesser cornstalk borer damage and sugarcane yield in plant cane and ratoon fields. The farm location was selected based on grower complaints of annual excessive sugarcane stand loss to lesser cornstalk borer. Plant cane and ratoon fields of sugarcane variety CP89-2143, widely grown on sandy soil (Rice et al. 2009), were selected for the trial. The farm was located in northeastern Hendry County, Florida comprised of mostly Immokalee fine sand soil. A first ratoon crop was green harvested in April 2006, leaving a 15-20 cm deep trash blanket on the soil surface. Approximately one week earlier in a neighboring field, CP89-2143 stalks harvested from within the same farm were planted to produce the plant cane field. An experiment was designed with a split plot design with plant and ratoon sugarcane fields as the main plots and plots with and without trash blankets as the subplots. Main plots 21.5 m long and 4 rows (6 m) wide were marked off within

each field at least 25 m from field edges and separated from other main plots by > 33 m. Two subplots 10 m long by 4 rows wide (6 m) were established within each main plot separated by 1.5 m along the row axes. The trash blanket was manually removed from one of the subplots in each main plot to produce trash and no-trash subplots in the ratoon sugarcane field. The harvest trash removed from the ratoon sugarcane field was collected in trucks and distributed onto the trash subplots in the plant sugarcane field. Trash removed from one subplot in the ratoon sugarcane field was used to cover one subplot in the plant sugarcane field. Paired subplots were replicated six times in the ratoon and plant sugarcane fields. Weed control and fertilization were applied as needed to local standards. No insecticides or fungicides were applied to either plant or ratoon sugarcane field.

The effects of harvesting method (green harvest versus pre-harvest burning) combined with tillage level on damage caused by lesser cornstalk borer and sugarcane yield were evaluated in two separate field studies during 2008 (March to November) and 2009 (March 2009 to January 2010). Studies were conducted at different field locations of the same sugarcane farm located near Clewiston, Florida. Fields planted to variety CP78-1628, also widely grown on sandy soils (Rice et al. 2009), were selected in both years. The sugarcane fields were in their second ratoon in 2008 and first ratoon in 2009. The experimental design was again a split plot design with harvesting method as the main plots and tillage level as subplots. Main plots were established in neighboring fields by applying pre-harvest burning to one field and harvesting the adjacent field green. Green cane harvesting left a 10-15 cm deep trash blanket on the soil surface during both years. There was minimal plant residue following harvest in the fields with

pre-harvest burning in both years. Three tillage levels were applied randomly in vertical strips (8 rows wide each) adjacent to each other along the entire field in each main plot. Out of eight rows with each tillage treatment, sample subplots 10 m long were selected from only the central four rows (6 m wide) with the two remaining rows on either side used as buffers. Therefore, main plots with harvesting method were 10 m long and 24 rows (36 m) wide, and subplots with each tillage level were 10 m long and 4 rows (6 m) wide with 4 rows separation between subplots within the same main plot. Main plots were separated from each other by 45 m. Main plots were replicated 6x in 2008 and 12x in 2009 in each harvesting method field. Trials were begun in March 2008 and March 2009.

To establish no-tillage subplots, soil was left undisturbed or uncultivated following harvest in both green cane and burnt cane harvested plots. To establish conventional tillage plots, a single disking was performed 2 wk after harvest of the previous season's crop. A 5-m wide commercial disc cultivator was used to cultivate soil after harvesting. Discs were arranged on 2 tool bars (front and rear rows) and were used to cultivate 4 rows on each pass through the field. In the conventional tillage treatment, the combined front and rear rows of discs resulted in cultivated lines evenly distributed between planted rows with a minimum of 6-8 cm distance from the planted row centers. To establish plots with intermediate tillage, discs were manually adjusted towards the row middles to increase the distance from the planted row centers to ≥ 15 cm. No insecticide or fungicide was applied to plant or ratoon cane fields in 2008 or 2009. Weed control and fertilization were applied as needed to local standards.

Damage Assessment

In all these experiments, feeding damage was recorded for primary shoots and tillers (secondary or tertiary shoots) in randomly selected 3-m sections of row in each of the 4 rows of each subplot. The number of dead hearts, number of plants with symmetrical rows of holes in leaves, and number of plants damaged by other foliar feeders (e.g. grasshopper, armyworms) were recorded biweekly beginning 3 wk after plant emergence in each treatment. Damage was recorded for the first 3 mo of growth period, which was reported to be the critical exposure period for lesser cornstalk borer damage to sugarcane (Carbonell 1978). Plants were counted as dead hearts if lesser cornstalk borer feeding lead to chlorosis and necrosis of only the primary shoot. Plants were also counted that displayed symmetrical rows of holes in leaves following non-lethal feeding by lesser cornstalk borer to a few superficial layers of sugarcane shoot. Plants with leaves notched by foliage feeder pests (e.g., grasshoppers and armyworms) were counted as damage by other pests. Plants were first observed for dead hearts, then holes in the leaves, and then damage by other pests. Plants counted as dead hearts could not be counted as holes in leaves, and plants with holes in leaves could not be counted for damage by other pests. Lesser cornstalk borer damage was confirmed by observing randomly selected damaged plants for the presence of subsoil surface silken tunnels attached to the point of larval entry to the plant. The mean percentage of plants with dead hearts, holes in the leaves, and damaged by other pests were calculated using the observations on all damaged and undamaged plants per 3 m row section at the time of maximum damage. Total damage by lesser cornstalk borer was calculated as the summation of dead hearts and plants with holes in the leaves per 3 m row section.

Sugarcane Yield Assessment

Millable stalks (primary shoots and tillers > 1.5 m height) from all the rows in each plot were counted 8 mo. after the first emergence of sugarcane shoots in all the trials. Millable stalks were counted in the 8 mo. old crop, because lodging in sugarcane at harvest time interferes with determining the height and exact number of millable stalks. Randomly selected stalks greater than 1.5 m in height were cut for yield determination by hand using cane knives at < 20 cm above the soil surface and then weighed using a truck-mounted sling scale. Ten stalks from each of the 4 rows of each subplot (total 40 stalks) were harvested in 2006 and 2008. Ten stalks from the middle two rows (total 20 stalks) were harvested in 2009. Plant fresh weights were used to determine individual stalk weight (Kg per stalk), and biomass yield as tons of cane per acre (TCA) was calculated as the product of stalk number and stalk weight. To determine sucrose concentration, 10 stalks (randomly selected from harvested stalks of each plot) were milled and the crusher juice analyzed for brix and pol as described by Gilbert et al. (2008). Sugar yield as tons of sugar per acre (TSA) was calculated according to the theoretical recoverable sugar method (Glaz et al. 2002).

Data Analysis

PROC MIXED (SAS Institute 2008) with the repeated measures statement was used to analyze the damage data due to potential covariance structure associated with repeated damage assessments over time in the same locations. Dates were used as the repeated variable in the repeated measures statement. Several covariance structures were fitted to the data. The unstructured covariance type fit well and was used for the analysis (Littell et al. 1998). Percentage data were arcsin transformed before analysis and retransformed for presentation purposes. Data on yield traits were

analyzed using PROC GLM procedure for a split plot design (SAS Institute 2008). The Tukey's HSD test (SAS Institute 2008) was used for means separation with $\alpha = 0.05$.

Results

Results of the 2006 study on the effects of crop age and trash blankets (Tables 5-1 to 5-3) are presented separately from the 2008 and 2009 studies on the effects of harvesting method and tillage (Tables 5-4 to 5-9). Dead hearts were the most commonly observed result of *E. lignosellus* feeding damage to sugarcane in both studies. Symmetrical rows of holes in leaves were the second (after dead hearts) most commonly observed damage in both studies. The sum of plant feeding damage caused by *E. lignosellus* (dead hearts, holes in leaves) was analyzed as total damage in both studies.

Effects of Crop Age and Trash Blanket

Crop age significantly affected lesser cornstalk borer damaged plants with holes in leaves and total damage (Table 5-1). Harvest residue and harvest residue \times crop age were significant sources of variation in the model for dead hearts and total damage. Plant cane had significantly greater percentage of plants with dead hearts, holes in leaves and total damage than ratoon cane (Table 5-2). Overall, plots with trash blankets had significantly reduced mean percentage of plants with dead hearts, holes in leaves and total damage. However, separation of the means by interaction with the crop age determined that the presence of a trash blanket significantly affected lesser corn stalk borer damage only in the plant cane field. There were significantly greater percentages of plants with dead hearts, rows of holes in leaves, and total damage in plant cane plots without trash than in the ratoon field plots without trash. There was a significantly greater percentage of plants with rows of holes in the plant cane plots with

trash than the ratoon cane field with trash. Total damage was > 3x greater in the plant cane field plots without a trash blanket compared to plots with a trash blanket.

Damage by other foliar feeders was < 3% in both plant and ratoon cane fields. Crop age was significant, but harvest residue and their interaction were not significant sources of interaction in the model for damage by other pests (Table 5-1). Plant cane had significantly greater percentage of shoots damaged by other pests than ratoon cane (Table 5-2). Trash blanket did not have a significant effect on damage by other pests either in plant cane or in ratoon cane. There was significantly greater percentage of plants damaged by other pests in plant cane with trash than ratoon cane with trash.

Crop age was a significant source of variation in the model for millable stalks per row and mean stalk weight (Table 5-1). Neither the harvest residue nor the interaction of crop age with harvest residue had significant effects on these two yield parameters. The mean number of millable stalks was greater in ratoon cane than plant cane, but mean stalk weight was greater in plant cane than ratoon cane (Table 5-3). The trash blanket did not have a significant effect on the mean number of millable stalks per row or stalk weight. Ratoon cane with trash produced greater number of millable stalks than plant cane with trash, and ratoon cane without trash produced greater number of millable stalks than plant cane without trash. However, the reverse was true for stalk weight with plant cane plots with and without trash having greater stalk weight than ratoon cane plots with and without trash, respectively.

Neither TCA nor TSA were affected by crop age, harvest residue or their interaction (Table 5-1). The mean TCA and TSA were equivalent in plant and ratoon cane, and with trash or without trash blankets.

Effects of Harvesting Method and Tillage

In this second study, the experiment year ($df = 1, 431$) was a significant source of variation in the model for dead hearts ($F = 123.54, P < 0.0001$), holes in leaves ($F = 253.96, P < 0.0001$), total damage ($F = 16.97, P < 0.0001$) and damage by other pests ($F = 551.33, P < 0.0001$). Therefore, the data were analyzed and presented separately for 2008 and 2009 (Table 5-4).

Harvesting method, tillage level, and their interaction were significant sources of variation in the model for dead hearts, holes in leaves and total damage caused by lesser cornstalk borer in sugarcane during both years (Table 5-4). Plots in the field with pre-harvest burning had significantly greater percentages of plants with dead hearts, plants with holes in leaves, and total damage than in plots in the green harvested field in both years (Tables 5-5 and 5-6). Percentage of plants with dead hearts and the total percentage of damaged plants were $> 3x$ greater in the field burned prior to harvest than in the green harvested field in both years. Subplots with conventional tillage had significantly greater percentage of plants with dead hearts, holes in the leaves and total damage than the subplots with no-tillage or intermediate tillage. Lesser cornstalk borer caused approximately $1.5x$ greater damage in subplots with conventional tillage than subplots with no-tillage and intermediate tillage. However, tillage levels significantly affected lesser cornstalk borer damage in green cane harvested plots only, where again subplots with conventional tillage had greater percentages of plants with dead hearts, holes in leaves, and total damage than the subplots with no-tillage and intermediate tillage. Percentage of plants with dead hearts in subplots with conventional tillage ($20.4 \pm 0.9\%$) was $> 21x$ greater than in subplots with no-tillage ($0.93 \pm 0.2\%$), and $> 13x$ greater than subplots with intermediate tillage ($1.5 \pm 0.3\%$). Similarly, percentage of

total damage in conventional tillage subplots was >13x greater than in no-tillage and intermediate tillage subplots.

Neither main effects nor their interaction were significant sources of variation in the model for damage by other pests in 2008, but harvesting method was significant in 2009 (Table 5-4). Plots in the green harvested field had a greater percentage of plants damaged by other pests than burnt cane harvesting in 2009 (Table 5-6). Tillage level did not produce any significant effect on damage by other pests in main effects or in interaction with harvesting method during both years (Tables 5-5 and 5-6).

Experiment year ($df = 1, 287$) was also a significant source of variation in the models for mean number of millable stalks ($F = 104.84, P < 0.0001$), mean stalk weight ($F = 46.11, P < 0.0001$), mean TCA ($F = 142.61, P < 0.0001$), and mean TSA ($F = 90.34, P < 0.0001$); therefore, the data were analyzed separately for 2008 and 2009 (Table 5-7). The significant year effect resulted from greater yield traits in 2009 than in 2008 (Tables 5-8 and 5-9).

Neither main effects nor their interaction were significant sources of variation in the model for millable stalks in 2008, but harvesting method was significant in 2009 (Table 5-7). In 2009, the mean number of millable stalks in burnt cane harvested plots (173.8 ± 3.4) was significantly greater than in green cane harvested plots (163.1 ± 3.3) (Table 5-9). In harvesting method \times tillage level interaction, subplots with no-tillage in green cane harvested plots had significantly greater number of millable stalks than same tillage level in burnt cane harvested plots in 2008 (Table 5-8). Similarly, the subplots with intermediate tillage in green cane harvested plots produced more number of millable stalks than same tillage level in burnt cane harvested plots in 2008. In green

cane harvested plots, the subplots with intermediate tillage produced greater number of millable stalks than subplots with conventional tillage. In 2009, subplots with no-tillage, conventional and intermediate tillage levels in burnt cane harvested plots produced greater number of millable stalks than the subplots with respective tillage levels in green cane harvested plots (Table 5-9).

Harvesting method and harvest method × tillage level were significant sources of variation in the model for stalk weight in 2008, and harvesting method and tillage level were significant in 2009 (Table 5-7). Green cane harvested plots had greater stalk weight than burnt cane harvested plots during both years (Table 5-8 and 5-9). Tillage levels did not affect stalk weight in 2008, but the subplots with intermediate tillage (0.72 ± 0.03) and conventional tillage (0.70 ± 0.02) had greater stalk weight than subplots with no-tillage (0.65 ± 0.02) in 2009 (Table 5-9). In harvesting method × tillage level, subplots with no-tillage in green cane harvested plots had greater stalk weight than subplots with same tillage in burnt cane harvested plots during both years. Similarly, intermediate tillage subplots in green cane harvested plots produced heavier stalks than the same tillage level subplots in burnt cane harvested plots during both years. In green cane harvested plots, the stalk weight was greater in subplots with intermediate tillage than subplots with no-tillage and conventional tillage during both years. However in burnt cane harvested plots, conventional tillage subplots produced heavier stalks than no-tillage subplots during both years.

Harvesting method and harvesting method × tillage level were significant sources of variation in the model for TCA in 2008 (Table 5-7). In 2009, harvesting method was not significant source of variation in the model, but tillage level and harvesting method ×

tillage level were significant for TCA. Green cane harvested plots (33.2 ± 0.6) produced greater TCA than burnt cane harvested plots (30.2 ± 0.5) in 2008, but there was no difference in 2009 (Table 5-8 and 5-9). TCA was not affected by tillage levels in 2008, but the subplots with conventional tillage (37.8 ± 1.3) and intermediate tillage (38.2 ± 1.3) had greater TCA than subplots with no-tillage (34.9 ± 1.2) in 2009 (Table 9). In harvesting method \times tillage level, subplots with intermediate tillage (35.1 ± 0.6) had greater TCA than subplots with conventional tillage (31.3 ± 0.7) in green cane harvested plots in 2008. In 2009, subplots with intermediate tillage (40.1 ± 1.4) had greater TCA than subplots with no-tillage (36.1 ± 1.3) in green cane harvested plots. In burnt cane harvested plots, subplots with conventional tillage (32.0 ± 0.7) had greater TCA than subplots with no-tillage (28.7 ± 0.6) and intermediate tillage (29.8 ± 0.6) in 2008, but the difference between conventional tillage and intermediate tillage was not significant in 2009.

Only the interaction of harvesting method \times tillage level had a significant effect on the model for TSA during both years (Table 5-7). In harvesting method \times tillage level, subplots with intermediate tillage (5.50 ± 0.19) had greater TSA than subplots with no-tillage (5.10 ± 0.18) in 2009 only (Table 5-9). In burnt cane harvested plots, subplots with conventional tillage produced more TSA than subplots with no-tillage during both years. The subplots with intermediate tillage in green cane harvested plots had greater TSA than subplots with intermediate tillage in burnt cane harvested plots in 2009.

Discussion

Effects of Crop Age and Trash Blanket

This study shows that trash blanket significantly reduced the lesser cornstalk borer damage to sugarcane plants. The presence of a trash blanket resulted in a reduction in

percentage of plants with dead hearts by approximately 11x in plant cane and 2x in ratoon cane plots. Hall (1999) also reported that only 0.5% shoots were killed by lesser cornstalk borer in the field with trash blanket compared to 7.0% shoots killed in fields without trash blankets. This reduction in lesser cornstalk borer damage might be due to inhibition of egg deposition by the trash blanket (Leuck 1966). The other probable reason for less damage in plots with trash was that trash blankets maintained higher moisture levels than exposed soil, which either inhibited egg deposition or increased larval mortality. Leuck (1966) reported inhibition of egg deposition by soil moisture. Knutson (1976) reported greater larval mortality when reared in soil with 100% water holding capacity than in dry soil. The damage by other foliage feeder pests remained low in all the plots and was not affected by the presence of a trash blanket.

Although the mean damage percentage was significantly greater in plots with trash than plots without trash, the effects of a trash blanket on millable stalks, stalk weight, TCA, and TSA were not significant. This lack of significant difference between the main treatments may be due to recovery of some damaged plants to normal growth or compensation of early season lesser cornstalk borer damage by production of additional tillers in the damaged plants. Carbonell (1978) reported 27.8% recovery in plant canes and 48.1% recovery in ratoon canes in response to lesser cornstalk borer damage. The compensatory response of CP89-2143 was also reported by Sandhu et al. (2010b). They reported that this variety can compensate for up to 37.7% of dead hearts and dead plants caused by lesser cornstalk borer without significant reduction in sugarcane yield.

Effects of Harvesting Method and Tillage

This study shows that the effect of tillage level on lesser cornstalk borer damage was dependent on harvesting method. Tillage level provided significant effects in green cane harvested plots only, in which subplots with conventional tillage had 13-21x greater percentage of plants with dead hearts than subplots with no-tillage and intermediate tillage. In conventional tillage subplots, the soil was cultivated very close (6-8 cm from row center) to the plant base thereby exposing the soil surface near the plant base while incorporating the trash into the soil. Lesser cornstalk borer deposits most of the eggs on soil surface near the plant base (Smith and Ota 2002), which was exposed in conventional tillage and covered with trash in no-tillage and intermediate tillage. In intermediate tillage, only the inter-row space was cultivated leaving the trash adjacent to the plant bases undisturbed, which may have inhibited lesser cornstalk borer egg deposition. The harvest residue trash blanket near the plant base also may provide a food source for lesser cornstalk borer larvae in no-tillage and intermediate tillage subplots thereby reducing the overall damage to sugarcane plants. This idea is supported by Cheshire and All (1979) who conducted greenhouse simulations of a corn cropping system using mulched no-tillage, mulched conventional tillage, and conventional tillage. They reported different lesser cornstalk borer larvae behavior on corn in no-tillage than in conventional tillage cultural practices. In 20 replicates of 2 corn plants per replicate, the number of attacked plants was only 4 in no-tillage with wheat and rye residues mulch compared to 22 in conventional tillage. They concluded that mulched residues in the no-tillage treatment provided an alternate food source resulting in reduced damage to the corn.

Yield differences between treatment years are probably attributable to a longer crop cycle in 2009 (10 mo) than 2008 (8 mo). In 2008, greater lesser cornstalk borer damage to sugarcane resulted in fewer millable stalks and lower TCA in conventional than intermediate tillage in the green harvested field. Feeding damage was not fully compensated for during the sugarcane growth cycle and resulted in yield loss. However, the same pattern of greater damage to plants in conventional than intermediate tillage plots in 2009 did not result in fewer millable stalks and lower TCA in conventional than intermediate tillage. These results suggest that the sugarcane plants had enough time to fully compensated for the damage in 2009 compared to 2008. Dillewijn (1952) also reported that plant compensation capability increased with longer sugarcane growth seasons.

Differences in TCA and TSA between seasons and tillage levels may be the result of differences in compensation time and mechanical damage to sugarcane stools. The reduction in TCA and TSA in the no-tillage compared to other tillage subplots in the green harvested field in 2009 may have been due to excessive soil moisture or lower soil temperature under the trash blanket. Excessive soil wetness and lower soil temperature in green harvested fields were reported to reduce sugarcane biomass and sugar yields compared to pre-harvest burned fields (Oliviera et al. 2001). In the pre-harvest burned field, lesser cornstalk borer damage was the same for all tillage levels, but TCA and TSA were greatest in the conventional tillage subplots. The conventional tillage treatment likely caused more damage to the first shoots growing from the stools following harvest than in the intermediate and no-tillage subplots. Mechanical damage to these first shoots may have resulted in greater numbers of millable stalks and

elevated yields compared to other tillage levels. It is a common grower practice in southern Florida sugarcane to cultivate close to planted rows or to use tines to scratch over planted rows with the idea that this increases tillering and yield.

Conclusion

Overall, we can conclude that lesser cornstalk borer damage can be reduced by harvesting the sugarcane green or through application of harvest residue to cover the soil surface around sugarcane plants. Intermediate tillage allowed for greater rain percolation and fertilizer penetration while maintaining low levels of lesser cornstalk borer damage. In burnt cane harvested plots, all tillage levels had equal lesser cornstalk borer damage, but conventional tillage resulted in increased TCA and TSA. Although the sugarcane plants compensated for lesser cornstalk borer damage in our 2006 and 2009 studies, severe outbreaks of this pest can result in significant yield reduction.

Table 5-1. Analysis of variance of crop age, harvest residue and their interaction on *E. lignosellus* and other pests' damage to sugarcane, and sugarcane yield traits in 2006

Source of variation	Dead hearts ¹		Holes in leaves ²		Total damage ³		Other pests ⁴		
	df	F	P	F	P	F	P	F	P
Crop age (CS)	1	0.81	0.4096	36.17	0.0018	21.89	0.0054	9.90	0.0255
Harvest residue (HR)	1	45.14	0.0011	5.79	0.0611	16.71	0.0095	0.29	0.6150
HR × SC	1	18.33	0.0079	3.14	0.1367	7.52	0.0407	0.27	0.6244
Error	95								

Source of variation	Millable stalks ⁵		Stalk weight ⁶		TCA ⁷		TSA ⁸		
	df	F	P	F	P	F	P	F	P
Crop age (CS)	1	14.29	0.0129	22.33	0.0052	0.60	0.4719	1.31	0.3040
Harvest residue (HR)	1	1.73	0.2449	0.26	0.6292	0.00	0.9973	0.00	0.9605
CS × HR	1	4.77	0.0806	0.99	0.3655	0.01	0.9287	0.03	0.8706
Error	95								

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Summation of dead hearts and holes in leaves

⁴Primary shoots and tillers with leaves damaged by other foliage feeders (e.g. grasshoppers, armyworms)

⁵No. stalks ≥ 1.5 m in height

⁶Weight (Kg) of individual millable stalk

⁷Sugarcane biomass yield in metric tons of cane per acre (TCA)

⁸Raw sugar weight in metric tons of sugar per acre (TSA), calculated from brix and pol values

Table 5-2. Mean (\pm SEM) percentage of *E. lignosellus* and other pest's damage to sugarcane in 2006

Treatment variables			Holes in	Total	Other
Main effects		Dead hearts ¹	leaves ²	damage ³	pests ⁴
Crop age	Plant cane	4.3 \pm 0.7A	6.2 \pm 0.4A	10.4 \pm 0.9A	2.4 \pm 0.6A
	Ratoon cane	2.4 \pm 0.4B	0.6 \pm 0.2B	02.9 \pm 0.3B	0.3 \pm 0.1B
Harvest residue	Trash	1.2 \pm 0.2b	2.1 \pm 0.4b	03.2 \pm 0.3b	1.6 \pm 0.4a
	No-trash	5.5 \pm 0.8a	4.6 \pm 0.7a	10.1 \pm 1.1a	1.1 \pm 0.3a
Interaction effects			Holes in	Total	Other
Crop age	Harvest residue	Dead hearts	leaves	damage	pests
Plant cane	Trash	0.7 \pm 0.3Ab	3.7 \pm 0.8Ab	04.4 \pm 0.8Ab	2.9 \pm 0.8Aa
	No-trash	7.8 \pm 1.6Aa	8.6 \pm 1.4Aa	16.4 \pm 2.3Aa	1.9 \pm 0.7Aa
Ratoon cane	Trash	1.6 \pm 0.4Aa	0.5 \pm 0.3Ba	02.0 \pm 0.4Aa	0.3 \pm 0.1Ba
	No-trash	3.1 \pm 0.7Ba	0.6 \pm 0.2Ba	03.7 \pm 0.7Ba	0.3 \pm 0.2Aa

Means followed by different letters are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between crop ages (main effects) and between crop ages at the same harvest residue (interaction effects). Small letters indicate differences between harvest residues (main effects) and between harvest residues at the same crop age (interaction effects).

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Summation of dead hearts and holes in leaves

⁴Primary shoots and tillers with leaves damaged by other foliage feeders (e.g. grasshoppers, armyworms)

Table 5-3. Mean (\pm SEM) yield traits in crop age, harvest residue, and their interactions in 2006

Treatment variables		Millable stalks ¹	Stalk weight ²	TCA ³	TSA ⁴
Main effects					
Crop age	Plant cane	155.2 \pm 2.3B	1.36 \pm 0.04A	67.8 \pm 1.9A	10.0 \pm 0.4A
	Ratoon cane	176.1 \pm 2.4A	1.15 \pm 0.03B	64.4 \pm 1.8A	09.3 \pm 0.3A
Harvest residue	Trash	167.7 \pm 2.6a	1.24 \pm 0.03a	66.1 \pm 2.1a	09.6 \pm 0.4a
	No-trash	163.5 \pm 2.7a	1.27 \pm 0.04a	66.1 \pm 1.9a	09.7 \pm 0.3a
Interaction effects					
Crop age	Harvest residue	Millable stalks	Stalk weight	TCA	TSA
Plant cane	Trash	154.4 \pm 4.1Ba	1.37 \pm 0.05Aa	67.9 \pm 3.7Aa	09.9 \pm 0.6Aa
	No-trash	155.9 \pm 4.2Ba	1.35 \pm 0.05Aa	67.6 \pm 3.6Aa	10.1 \pm 0.6Aa
Ratoon cane	Trash	181.0 \pm 4.6Aa	1.11 \pm 0.04Ba	64.2 \pm 3.5Aa	09.3 \pm 0.6Aa
	No-trash	171.1 \pm 4.4Aa	1.18 \pm 0.04Ba	64.5 \pm 3.5Aa	09.2 \pm 0.6Aa

Means followed by different letters are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between crop ages (main effects) and between crop ages at the same harvest residue (interaction effects). Small letters indicate differences between harvest residue (main effects) and between harvest residues at the same crop age (interaction effects).

¹No. stalks \geq 1.5 m in height

²Weight (Kg) of individual millable stalk

³Sugarcane biomass yield in metric tons of cane per acre (TCA)

⁴Raw sugar weight in metric tons of sugar per acre (TSA), calculated from brix and pol values

Table 5-4. Analysis of variance of harvesting method, tillage level and their interaction on *E. lignosellus* and other pests' damage to sugarcane in 2008 and 2009

2008									
Source of variance	df	Dead hearts ¹		Holes in leaves ²		Total damage ³		Other pests ⁴	
		F	P	F	P	F	P	F	P
Harvesting method (HM)	1	769.78	<0.0001	366.52	<0.0001	833.14	<0.0001	0.10	0.7699
Tillage level (TL)	2	85.31	<0.0001	89.99	<0.0001	88.95	<0.0001	0.29	0.7551
HM × TL	2	157.81	<0.0001	34.22	<0.0001	125.23	<0.0001	1.33	0.3066
Error	143								
2009									
Source of variance	df	Dead hearts		Holes in leaves		Total damage		Other pests	
		F	P	F	P	F	P	F	P
Harvesting method (HM)	1	940.37	<0.0001	867.16	<0.0001	1255.48	<0.0001	44.57	<0.0001
Tillage level (TL)	2	74.54	<0.0001	210.62	<0.0001	142.38	<0.0001	0.33	0.7228
HM × TL	2	228.77	<0.0001	287.14	<0.0001	333.53	<0.0001	0.54	0.5908
Error	287								

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Summation of dead hearts and holes in leaves

⁴Primary shoots and tillers with leaves damaged by other foliage feeders (e.g. grasshoppers, armyworms)

Table 5-5. Mean (\pm SEM) percentage damage by *E. lignosellus* and other pests to sugarcane in 2008

Treatment variables			Holes in	Total	Other
Main effects		Dead hearts ¹	leaves ²	damage ³	pests ⁴
Harvesting method	Green cane	07.6 \pm 0.4B	1.5 \pm 0.1B	09.2 \pm 0.4B	0.4 \pm 0.1A
	Burnt cane	26.4 \pm 0.6A	7.0 \pm 0.1A	33.4 \pm 0.7A	0.3 \pm 0.1A
Tillage level	No-tillage	15.1 \pm 0.5b	3.9 \pm 0.3b	18.9 \pm 0.7b	0.4 \pm 0.1a
	Conventional	21.8 \pm 0.6a	5.9 \pm 0.5a	27.6 \pm 0.9a	0.4 \pm 0.1a
	Intermediate	14.2 \pm 0.5b	3.2 \pm 0.3b	17.4 \pm 0.6b	0.3 \pm 0.1a
Interaction effects					
Harvesting method	Tillage level	Dead hearts	Holes in leaves	Total damage	Other pests
Green cane	No-tillage	0.93 \pm 0.2Bb	0.9 \pm 0.2Bb	01.8 \pm 0.3Bb	0.5 \pm 0.2Aa
	Conventional	20.4 \pm 0.9Aa	3.5 \pm 0.2Ba	23.9 \pm 1.0Aa	0.4 \pm 0.1Aa
	Intermediate	01.5 \pm 0.3Bb	0.2 \pm 0.1Bb	01.8 \pm 0.2Bb	0.4 \pm 0.2Aa
Burnt cane	No-tillage	29.2 \pm 0.8Aa	6.8 \pm 0.2Aa	36.0 \pm 0.9Aa	0.2 \pm 0.1Aa
	Conventional	23.1 \pm 0.9Aa	8.2 \pm 0.2Aa	31.3 \pm 0.8Aa	0.4 \pm 0.1Aa
	Intermediate	26.9 \pm 0.8Aa	6.1 \pm 0.2Aa	33.0 \pm 0.9Aa	0.2 \pm 0.1Aa

Means followed by different letters in the columns are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between harvesting methods (main effects) and between harvesting methods at the same tillage level (interaction effects). Small letters indicate differences among tillage levels (main effects) and among tillage levels in the same harvesting method (interaction effects).

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Summation of dead hearts and holes in leaves

⁴Primary shoots and tillers with leaves damaged by other foliage feeders (e.g. grasshoppers, armyworms)

Table 5-6. Mean (\pm SEM) percentage damage of *E. lignosellus* and other pests to sugarcane in 2009

Treatment variables		Dead hearts ¹	Holes in leaves ²	Total damage ³	Other pests ⁴
Main effects					
Harvesting method	Green cane	05.1 \pm 0.2B	02.6 \pm 0.1B	07.7 \pm 0.3B	4.9 \pm 0.7A
	Burnt cane	20.3 \pm 0.4A	10.8 \pm 0.2A	31.1 \pm 0.5A	2.6 \pm 0.3B
Tillage level	No-tillage	12.8 \pm 0.5b	06.8 \pm 0.2b	19.6 \pm 0.6b	3.7 \pm 0.4a
	Conventional	14.5 \pm 0.5a	08.1 \pm 0.3a	22.6 \pm 0.7a	4.0 \pm 0.4a
	Intermediate	11.0 \pm 0.4c	05.2 \pm 0.2c	16.1 \pm 0.5c	3.6 \pm 0.3a
Interaction effects					
Harvesting method	Tillage level	Dead hearts	Holes in leaves	Total damage	Other pests
Green cane	No-tillage	01.9 \pm 0.1Bb	01.1 \pm 0.1Bb	03.0 \pm 0.2Bb	4.9 \pm 0.5Aa
	Conventional	11.9 \pm 0.5Ba	06.7 \pm 0.2Ba	18.6 \pm 0.7Ba	5.0 \pm 0.7Aa
	Intermediate	01.5 \pm 0.2Bb	00.0 \pm 0.0Bb	01.5 \pm 0.2Bb	4.7 \pm 0.5Aa
Burnt cane	No-tillage	23.6 \pm 0.7Aa	12.5 \pm 0.4Aa	36.1 \pm 0.8Aa	2.4 \pm 0.5Aa
	Conventional	17.0 \pm 0.4Aa	09.5 \pm 0.3Aa	26.5 \pm 0.3Aa	2.9 \pm 0.7Aa
	Intermediate	20.4 \pm 0.5Aa	10.3 \pm 0.2Aa	30.6 \pm 0.7Aa	2.4 \pm 0.5Aa

Means followed by different letters in the columns are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between harvesting methods (main effects) and between harvesting methods at the same tillage level (interaction effects). Small letters indicate differences among tillage levels (main effects) and among tillage levels in the same harvesting method (interaction effects).

¹Chlorosis and necrosis of only the primary shoot

²Primary shoots and tillers with symmetrical rows of holes in the leaves

³Summation of dead hearts and holes in leaves

⁴Primary shoots and tillers with leaves damaged by other foliage feeders (e.g. grasshoppers, armyworms)

Table 5-7. Analysis of variance of harvesting method, tillage level, and their interaction on sugarcane yield traits in 2008 and 2009

2008									
Source of variance	df	Millable stalks ¹		Stalk weight ²		TCA ³		TSA ⁴	
		F	P	F	P	F	P	F	P
Harvesting method (HM)	1	4.63	0.0840	12.08	0.0177	17.91	0.0082	1.16	0.3313
Tillage level (TL)	2	0.90	0.4366	0.86	0.4514	2.62	0.1217	1.75	0.2223
HM × TL	2	2.94	0.0988	5.92	0.0201	11.14	0.0029	9.26	0.0053
Error	143								
2009									
Source of variance	df	Millable stalks		Stalk weight		TCA		TSA	
		F	P	F	P	F	P	F	P
Harvesting method (HM)	1	47.66	<0.0001	29.29	0.0002	3.22	0.1003	2.10	0.3120
Tillage level (TL)	2	0.63	0.5398	11.07	0.0005	9.40	0.0011	3.31	0.0681
HM × TL	2	1.36	0.2764	2.11	0.1451	3.44	0.0501	7.10	0.0220
Error	287								

¹No. stalks ≥ 1.5 m in height

²Weight (Kg) of individual millable stalk

³Sugarcane biomass yield in metric tons of cane per acre (TCA)

⁴Raw sugar weight in metric tons of sugar per acre (TSA), calculated from brix and pol values

Table 5-8. Mean (\pm SEM) sugarcane yield traits by harvesting method, tillage level and their interaction in *E. lignosellus*-infested fields during 2008

Treatment variables					
Main effects		Millable stalks ¹	Stalk weight ²	TCA ³	TSA ⁴
Harvesting method	Green cane	160.1 \pm 3.3A	0.65 \pm 0.01A	33.2 \pm 0.6A	4.25 \pm 0.19A
	Burnt cane	153.6 \pm 3.2A	0.62 \pm 0.01B	30.2 \pm 0.5B	4.05 \pm 0.18A
Tillage level	No-tillage	155.1 \pm 2.7a	0.62 \pm 0.01a	30.9 \pm 0.6a	4.04 \pm 0.18a
	Conventional	155.9 \pm 2.3a	0.64 \pm 0.01a	31.7 \pm 0.7a	4.21 \pm 0.19a
	Intermediate	159.6 \pm 2.8a	0.64 \pm 0.01a	32.5 \pm 0.7a	4.22 \pm 0.18a
Interaction effects					
Harvesting method	Tillage level	Millable stalks	Stalk weight	TCA	TSA
Green cane	No-tillage	160.9 \pm 3.6Aab	0.64 \pm 0.01Ab	33.1 \pm 0.8Aab	4.30 \pm 0.21Aa
	Conventional	154.2 \pm 3.5Ab	0.64 \pm 0.01Ab	31.3 \pm 0.7Ab	4.04 \pm 0.20Aa
	Intermediate	165.2 \pm 3.7Aa	0.67 \pm 0.01Aa	35.1 \pm 0.6Aa	4.42 \pm 0.23Aa
Burnt cane	No-tillage	149.3 \pm 3.8Ba	0.60 \pm 0.01Bb	28.7 \pm 0.6Bb	3.78 \pm 0.20Ab
	Conventional	157.6 \pm 3.9Aa	0.64 \pm 0.01Aa	32.0 \pm 0.7Aa	4.37 \pm 0.20Aa
	Intermediate	154.0 \pm 3.5Ba	0.61 \pm 0.01Bab	29.8 \pm 0.6Bb	4.01 \pm 0.22Aab

Means followed by different letters in the columns are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between harvesting methods (main effects) and between harvesting methods at the same tillage level (interaction effects). Small letters indicate differences among tillage levels (main effects) and among tillage levels in the same harvesting method (interaction effects).

¹No. stalks \geq 1.5 m in height

²Weight (Kg) of individual millable stalk

³Sugarcane biomass yield in metric tons of cane per acre (TCA)

⁴Raw sugar weight in metric tons of sugar per acre (TSA), calculated from brix and pol values

Table 5-9. Mean (\pm SEM) sugarcane yield traits by harvesting method, tillage level and their interaction in *E. lignosellus*-infested fields during 2009

Treatment variables					
Main effects		Millable stalks ¹	Stalk weight ²	TCA ³	TSA ⁴
Harvesting method	Green cane	163.1 \pm 3.3B	0.73 \pm 0.02A	37.9 \pm 1.2A	5.21 \pm 0.17A
	Burnt cane	173.8 \pm 3.4A	0.65 \pm 0.01B	36.1 \pm 1.2A	5.03 \pm 0.15A
Tillage level	No-tillage	167.5 \pm 3.3a	0.65 \pm 0.02b	34.9 \pm 1.2b	4.98 \pm 0.16a
	Conventional	170.0 \pm 3.4a	0.70 \pm 0.02a	37.8 \pm 1.3a	5.23 \pm 0.17a
	Intermediate	167.8 \pm 3.3a	0.72 \pm 0.03a	38.2 \pm 1.3a	5.23 \pm 0.16a
Interaction effects					
Harvesting method	Tillage level	Millable stalks	Stalk weight	TCA	TSA
Green cane	No-tillage	162.4 \pm 3.8Ba	0.70 \pm 0.02Ab	36.1 \pm 1.3Ab	5.10 \pm 0.18Ab
	Conventional	163.0 \pm 3.8Ba	0.72 \pm 0.03Ab	37.5 \pm 1.4Aab	5.20 \pm 0.19Aab
	Intermediate	163.8 \pm 3.9Ba	0.77 \pm 0.03Aa	40.1 \pm 1.4Aa	5.50 \pm 0.19Aa
Burnt cane	No-tillage	172.6 \pm 3.9Aa	0.61 \pm 0.02Bb	33.7 \pm 1.3Ab	4.86 \pm 0.18Ab
	Conventional	177.1 \pm 3.8Aa	0.67 \pm 0.02Aa	38.1 \pm 1.4Aa	5.25 \pm 0.19Aa
	Intermediate	171.8 \pm 3.8Aa	0.66 \pm 0.02Bab	36.4 \pm 1.3Aab	4.98 \pm 0.18Bab

Means followed by different letters in the columns are significantly different (Tukey, $\alpha = 0.05$) (SAS Institute 2008). Capital letters indicate differences between harvesting methods (main effects) and between harvesting methods at the same tillage level (interaction effects). Small letters indicate differences among tillage levels (main effects) and among tillage levels in the same harvesting method (interaction effects).

¹No. stalks \geq 1.5 m in height

²Weight (Kg) of individual millable stalk

CHAPTER 6 SUMMARY

Sugarcane, *Saccharum officinarum* L. is an important crop grown in many southern temperate through tropical regions of the world. Florida, Louisiana, Texas and Hawaii are the main sugarcane producing states in the U.S. Florida is the leading sugarcane producing state in the U.S. with 401,000 acres of sugarcane valued at \$398.9 million dollars in 2008. There are several factors that can result in decreased sugarcane yield, including insect damage. Lesser cornstalk borer is an important pest of Florida sugarcane.

Biological parameters of the lesser cornstalk borer, *E. lignosellus* life cycle were studied on different crops like cowpea, peanut, southern pea, and soybean. Published studies on lesser cornstalk borer development on sugarcane were conducted under uncontrolled, natural climatic conditions. Therefore, it was not possible to determine the relationship between temperature and development rates of this pest on sugarcane. Also there was lack of knowledge regarding the effect of temperature on reproductive biology and life table parameters of lesser cornstalk borer reared on sugarcane. Understanding the physiological relationship between temperature, immature development and reproductive biology is important for the prediction of population outbreaks and timely management of pests.

The first objective of this study was to determine the relationships between temperature and development and survivorship of the immature stages of *E. lignosellus* on sugarcane under controlled temperature conditions. The second objective was to study the reproductive biology and life table parameters of this pest at constant temperatures.

To address the first objective, the development of immature stages (eggs, larvae, pre-pupae, and pupae) of lesser cornstalk borer were observed on sugarcane at constant temperatures (13, 15, 18, 21, 24, 27, 30, 33, and 36 °C), 65-70% relative humidity, and a photoperiod of 14:10 (L:D) h. All immature stages of lesser cornstalk borer completed their development at temperatures from 13 °C to 36 °C.

Developmental time decreased with increase in temperature from 13 to 33 °C and then increased markedly at 36 °C in all immature stages. Mean egg developmental time (\pm SEM) ranged from 1.8 ± 0.1 d at 33 °C to 17.5 ± 0.1 d at 13 °C. The mean developmental time for larvae ranged from 15.5 ± 0.1 d at 33 °C to 65.7 ± 0.4 d at 13 °C. Larvae completed six instars before pupating. Mean pre-pupal development ranged from 1.3 ± 0.1 d at 33 °C to 10.5 ± 0.1 d at 13 °C. Pupal development ranged from a mean of 5.9 ± 0.1 d at 33 °C to 29.5 ± 0.2 d at 13 °C. Mean total development ranged from 22.8 ± 0.3 d at 33 °C to 120.7 ± 2.8 d at 13 °C.

The mean survivorship rose with increasing temperature for all immature stages, peaking at 27 °C, and then decreasing with further increases in temperature. At extreme temperatures (13 °C and 36 °C), percentage survival was quite low with $\leq 50\%$ of eggs, larvae, pre-pupae and pupae surviving at 13 °C. Egg and larval survival dropped below 50% at 36 °C. Temperature had a significant effect on the survival of all immature stages of *E. lignosellus*.

One linear and six non-linear models were evaluated to describe the relationship between temperature and development of immature stages. The linear model (without the data from 36 °C) provided a good fit to the data in all immature stages with high r^2 (> 0.96) and low RSS (< 0.027) and AIC (< -60.56) values. The linear regression model

estimated that lesser cornstalk borer required 543.5 degree days (DD) to complete development from egg deposition to adult emergence on sugarcane with a lower developmental threshold of 9.5 °C. Among all non-linear models, the Briere-1 model provided the best fit to the data with high r^2 values, and low RSS and AIC values for each immature developmental stage. The estimated lower and upper development thresholds for total immature development were 9.35 ± 1.8 °C and 37.90 ± 0.7 °C, respectively.

To address the second objective, the reproductive, generation and population life table parameters of adult female lesser cornstalk borer were studied at constant temperatures (13, 15, 18, 21, 24, 27, 30, 33, and 36 °C), 65-70% relative humidity, and a photoperiod of 14:10 (L:D) h. Mean pre-oviposition period decreased with increase in temperature from 9.7 d at 13 °C to 2.3 d at 33 °C. Mean oviposition period was longest (4.6 d) at 27 °C and decreased with increase or decrease in temperature. However, the post-oviposition period was shortest at 27 °C (2.6 d) and increased with increase or decrease in temperature. Fecundity was also significantly affected by temperature and increased with increase in temperature from 13 °C to 30 °C and decreased at 33 and 36 °C.

Temperature had a significant effect on stage specific survival rate (l_x) and stage specific fecundity (m_x) values. Both l_x and m_x increased with increase in temperature from 13 °C to 30 °C and decreased at 33 and 36 °C. The temperatures of 27 °C and 30 °C were best for survival and fecundity of lesser cornstalk borer in sugarcane. The calculated life table parameters (r , R_0 , λ , T , and DT) were also significantly affected by temperature. The value of r increased with increase in temperature from 13 °C (0.02)

to 30 °C (0.14) and then decreased at 36 °C (0.07). Similarly, R_0 was greatest at 30 °C (65.2) and lowest at 13 °C (9.2). The value of T was greatest (130.5 d) at 13 °C and lowest (27.6 d) at 33 °C. The value of DT decreased with increase in temperature from 40.8 d at 13 °C to 5.1 d at 30 °C. The value of λ increased with increase in temperature from 1.02 at 13 °C to 1.14 at 30 °C and then decreased at 33 and 36 °C. Six non-linear models were evaluated to describe the relationship between r and temperature. The Briere-2 model was the best fit to the data with greatest r^2 (0.9833) and $r^2_{adj.}$ (0.9733), and lowest RSS (0.0003) and AIC (- 96.14) values.

Lesser cornstalk borer larvae enter the young shoot of sugarcane causing two types of damage. Larvae that reach the center of the shoot and damage or sever the youngest leaves produce dead heart symptoms. Non-lethal damage is caused when larvae only chew a few millimeters into the shoot and becomes evident when the leaves push out to reveal one to several symmetrical rows of holes. We observed a third type of damage in which shoots died in response to larval *E. lignosellus* feeding and did not produce tillers. Literature shows that initial feeding damage does not always result in stand or yield loss in different crops. Based on this, our third objective was to determine the effect of lesser cornstalk borer damage on growth and yield of sugarcane plants.

To address this objective, two, 11-mo. greenhouse studies during 2008 and 2009 conducted at the Everglades Research and Education Center (EREC), Belle Glade, Florida. The sugarcane varieties CP78-1628, CP89-2143 and CP88-1762 were selected for this study. Three early growth stages (3-, 5-, and 7-leaf stage) were selected for infestation with lesser cornstalk borer larvae based on damage reports during the first 2-3 months of sugarcane growth. A randomized complete block design

with a 3 × 4 factorial arrangement was used during both experiment years to evaluate sugarcane response to *E. lignosellus* feeding damage. The factors were three sugarcane varieties (CP78-1628, CP88-1762, and CP89-2143) and three leaf stages infested plus one control (i.e., no infestation and infestation at 3-, 5-, and 7-leaf stages). The number of dead hearts, number of shoots with symmetrical rows of holes in leaves, and number of dead plants per bucket were recorded weekly starting one week after infestation at each leaf stage. The plant response to the damage was recorded as tiller production and yield traits. Sugarcane yield was determined using the number and weight of millable stalks, and the sucrose concentration of juice squeezed from those stalks.

Results showed that CP89-2143 had significantly greater percentage of plants with dead hearts, dead plants and total damage than other two varieties. The percentage of holes in leaves was greater in CP78-1628 than other two varieties. Lethal damage as dead hearts and dead plants was greater in plants infested at 3-leaf stage and decreased with delay in infestation. Non-lethal damage as holes in the leaves was low at 3-leaf stage infestation and increased with delay in infestation. In response to lesser cornstalk borer damage, CP78-1628 and CP88-1762 produced significantly greater number of tillers than CP89-2143 in both years. Buckets infested at 3-leaf stage produced significantly more tillers than those infested at 7-leaf stage in both years. In the variety × leaf stage interaction, *E. lignosellus* damage at the 3-leaf stage to CP78-1628 and CP88-1762 resulted in increased tiller production over the untreated controls in both years. However, CP89-2143 plants infested at all three leaf stages produced significantly fewer tillers than the untreated control plants. In late infested plants, CP78-

1628 produced more tillers than the other two varieties in 2008, but in 2009 both CP78-1628 and CP88-1762 produced more tillers than CP89-2143. Variations among varieties and leaf stages for millable stalk production were similar to tiller production.

Sugarcane yield in CP78-1628 was significantly greater than in CP88-1762 and CP89-2143 in 2008, but in 2009 both CP78-1628 and CP88-1762 produced greater sugarcane yield than CP89-2143. Untreated control plants produced greater sugarcane yield than plants infested at all three leaf stages in both years. Plants infested at the 3- and 5-leaf stages produced greater sugarcane yield than those infested at the 7-leaf stage. In variety \times leaf stage interactions, infestation at the 3- and 5-leaf stages of CP78-1628 did not affect sugarcane yield compared to control, but infestation at the 7-leaf resulted in significantly reduced yield. Although infestation at the 3-leaf stage in CP88-1762 resulted in more millable stalks produced than in the untreated control, the sugarcane yield was greater in the untreated control than in all the infested stages. In CP89-2143, plants in the untreated control produced greater sugarcane yield than those infested at all the leaf stages. Variations among varieties and leaf stages for sucrose yield were similar to sugarcane yield.

Percentage compensation to initial damage was calculated by deducting percentage reduction in yield from damage percentage. Overall, no significant difference was detected among the tested varieties for compensation for lesser cornstalk borer damage, but compensation was greater when infested at 3- followed by 5- and 7-leaf stages in both years. In variety \times leaf stage interaction, CP78-1628 and CP88-1762 compensated better than CP89-2143 for sugarcane yield at 3-leaf stage infestation in 2009. However, sugarcane yield compensation following infestation at the

7-leaf stage was greater in CP89-2143 than in CP78-1628. For sucrose yield compensation following infestation at the 7-leaf stage, CP89-2143 compensated better than CP78-1628 and CP88-1762 during both years. In CP78-1628 and CP88-1762, percentage compensation was significant in the sequence of 3- > 5- > 7- leaf stage. In CP89-2143, percentage compensation in the plants infested at the 3- and the 5-leaf stage was same and it was greater than the plants infested at the 7-leaf stage. Compensation in sucrose yield was similar to sugarcane yield compensation.

Lesser cornstalk borer larvae are difficult to control with chemicals and biological control agents due to protection provided by silken tunnels. Many of the successful materials are no longer labeled for use on these or any other crops. Most recently, the United States Environmental Protection Agency revoked tolerances for carbofuran which was labeled for multiple insect controls in sugarcane, effectively removing the last of the effective products for controlling lesser cornstalk borer larvae protected within plants. Cultural practices were reported to be efficient in lesser cornstalk borer in different crops, and needed evaluation in sugarcane.

In fourth objective, two separate studies were conducted in commercial sugarcane fields. In first study, we compared the effects of trash blankets on lesser cornstalk borer damage and yield in plant cane versus ratoon sugarcane fields. The second study was designed to address grower concerns of reduced water percolation and fertilization penetration associated with trash blankets by comparing the combined effects of harvest method (green cane and burnt cane harvesting) and tillage levels (no-tillage, intermediate, and conventional tillage) on lesser cornstalk borer damage and yield.

In first study, an experiment was designed with a split plot design with plant and ratoon sugarcane fields as the main plots and plots with and without trash blankets as the sub plots. The data were recorded on feeding damage by lesser cornstalk borer as dead hearts, symmetrical rows of holes in leaves, and damage by other foliar feeders (e.g. grasshoppers, armyworms). The yield was estimated as sugarcane (TCA) and sucrose (TSA) yield. The results showed that the plots with trash blankets had significantly reduced mean percentage of plants with dead hearts, holes in leaves and total damage. However, separation of the means by interaction with the crop age determined that the presence of a trash blanket significantly affected lesser corn stalk borer damage only in the plant cane field. Damage by other foliar feeders was < 3% in both plant and ratoon cane fields. Plant cane had significantly greater percentage of shoots damaged by other pests than ratoon cane. Trash blanket did not have a significant effect on damage by other pests either in plant cane or in ratoon cane. Neither TCA nor TSA were affected by crop age, harvest residue or their interaction.

In second study, the effects of harvesting method (green harvest versus pre-harvest burning) combined with tillage level on damage caused by lesser cornstalk borer and sugarcane yield were evaluated during 2008 and 2009. The experimental design was again a split plot design with harvesting method (green cane versus burnt cane) as the main plots and tillage level (no-, conventional and intermediate tillage) as sub-plots. Damage and yield data was recorded in the same way as in the first study. Plots in the field with pre-harvest burning had significantly greater percentages of plants with dead hearts, plants with holes in leaves, and total damage than in plots in the green harvested field in both years. Tillage levels significantly affected lesser cornstalk

borer damage in green cane harvested plots only, where again sub-plots with conventional tillage had greater percentages of plants with dead hearts, holes in leaves, and total damage than the sub-plots with no-tillage and intermediate tillage. Plots in the green harvested field had a greater percentage of plants damaged by other pests than burnt cane harvesting in 2009. Tillage level did not produce any significant effect on damage by other pests in main effects or in interaction with harvesting method during both years. Green cane harvested plots produced greater TCA than burnt cane harvested plots in 2008, but there was no difference in 2009. In green cane harvested plots, sub-plots with intermediate tillage had greater TCA than sub-plots with conventional tillage in 2008. In 2009, sub-plots with intermediate tillage had greater TCA than sub-plots with no-tillage. In burnt cane harvested plots, sub-plots with conventional tillage had greater TCA than sub-plots with no-tillage and intermediate tillage in 2008, but the difference between conventional tillage and intermediate tillage was not significant in 2009.

Based on these studies, it can be concluded that the temperature range of 27 °C to 30 °C are critical for population increase due to high development rate, fecundity, survival rate and intrinsic rate of increase. Green house studies showed that CP89-2143 is more susceptible to *E. lignosellus* damage than CP78-1628 and CP88-1762. Early infestation resulted in greater lethal damage than late infestation. Compensatory response to *E. lignisellus* damage was same among all the varieties, but it was greater in early infested plants and decreased with delay in infestation. Field studies showed the positive effects of green harvesting and intermediate tillage for reducing *E. lignosellus* damage and increasing sugarcane yield.

Further research is required to test the temperature-dependent development and population increase models in the field before they can reach their full potential. Green house study could be conducted in the field to determine how season-long exposure to lesser cornstalk borers and population limiting factors (e.g., soil moisture and high summer soil surface temperatures) may affect damage throughout the season and resulting yields.

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BIOGRAPHICAL SKETCH

Hardev was born in 1980 in Ahli Kalan, Punjab, India. He received Bachelor of Science (hons.) in agriculture with major in plant protection from Punjab Agricultural University, Ludhiana, India in 2002. He started Master of Science degree in the Department of Entomology and Nematology under the supervision of Dr. Jaswant Singh in same institute. He was awarded with merit scholarship during bachelor's degree and fellowship from Monsanto during master's degree. Alongwith academics, he was a member of university team of folk dance (Bhangra), and won several state-level and national-level competitions. He was also awarded with university merit certificate both in academics and extracurricular activities. After finishing his master's degree, he joined India's topmost bank, State Bank of India as marketing and recovery officer in 2005. In spring 2006, he started Doctor of Philosophy degree in Entomology and Nematology Department of University of Florida under the supervision of Dr. Gregg S. Nuessly. He started his project on biology and control of lesser cornstalk borer on sugarcane. During most part of his research work, he lived at Everglades Research and Education Center, Belle Glade, FL to complete field and greenhouse experiments. During field research, he got a chance to interact with sugarcane growers of the area and United States Sugar Corporation and Florida Cystal personnels. He presented his research findings in several state and national level meetings. He also presented his research findings during extension meetings at the Everglades Research and Education Center and nearby research stations. He received several research and travel grants from the department, university and also from scientific societies like Florida Entomological Society. He also served as a team leader in University of Florida's student debate team

at 57th annual meeting of Entomological Society of America in Indianapolis. His future plans are to pursue his career in Integrated Pest Management.