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Integrated pest management of the banana weevil, *Cosmopolites sordidus* (Germar), in South Africa

by

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Integrated pest management of the banana weevil, *Cosmopolites sordidus* (Germar), in South Africa

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SUMMARY

The banana weevil, *Cosmopolites sordidus*, is an economical pest of *Musa*, distributed to most areas where the crop is grown. The beetle larvae produce feeding tunnels in the pseudostem and rhizome, reducing bunch weight and causing toppling or snapping of plants. In developing an integrated pest management system for South Africa, specific aims of the study were to quantify the genetic diversity of the species around the world, investigate the population dynamics of the insect, determine the potential of semiochemical mass trapping, elucidate the efficacy of cultural and chemical control methods and establish economic thresholds for the banana weevil on Cavendish bananas in South Africa.

Pest status of the insect is variable around the world, and may be influenced by genetically distinct populations of the weevil. Six populations from four countries were sampled: Australia, Costa Rica, South Africa (South Coast, North Coast and Tzaneen) and Uganda. DNA was isolated from 12 individuals per population and subjected to amplified fragment length polymorphism (AFLP) analysis. The AFLP analysis involved DNA restriction with *Eco*RI and *Pst*I enzymes, ligation of adapters, and a pre-selective and five selective PCR amplifications. Empirical analysis of the AFLP fingerprints showed that, within populations, genetic diversity varied from 16-53%, with the South Coast and Tzaneen/Australian populations the least and most variable, respectively. The coefficient of gene differentiation showed that the Tzaneen population were the most differentiated from the South Coast population, while the South and North Coast populations were the most similar. All the populations showed statistically distinct marker frequencies, except for the Costa Rican and South and North Coast populations, which were similar. Based on the simple mismatch coefficient, a neighbour-joining tree showed the Australian, Ugandan and South

African coastal populations produced monophyletic groups, while the South African Tzaneen population were removed from the other populations and presented an ancestral state.

The population dynamics of the insect was investigated over two seasons and at three locations in the South Coast of KwaZulu-Natal. Adult activity was monitored with semiochemical (Cosmolure®) baited pitfall traps. Traps were moved monthly to a random independent location, or left *in situ* for the duration of the experiment. The ontogeny was determined by dissecting felled plants and toppled plants (up to 2-week-old fresh residues), and harvested plants visually classified as an early and a late rotting stage (decayed residues). Replicated, randomised block designs were used in the experiments. The adult beetles were sexed and the percentage females with eggs and the number of eggs per female were recorded. Larval head capsule widths were measured with an electronic caliper. Ambient temperature and precipitation (rainfall + irrigation) were measured on site. Weevils were active throughout the year and mainly collected in stationary traps, with a collection peak in May and high numbers in early spring and late autumn/early winter. The activity was usually a negative and a positive function of ambient temperature and corrected rainfall, respectively. Eggs per female and percentage females with eggs were reduced during winter and a positive function of ambient temperature. The beetles sampled from plant material represented an equal sex ratio, while the pheromone traps collected a female biased sex ratio during spring and autumn/early winter. The beetle had overlapping generations with a peak of adults and larvae in autumn and late summer, respectively. Adults were mainly associated with decayed residues while larvae were mostly found in freshly toppled plants. Adults were the main over-wintering stage. The earliest larval instars were usually sampled during autumn. The data suggested that the beetle is multivoltine in the study areas and provided valuable information for the optimal management of the insect pest.

Semiochemical adult trapping methods were compared in field trials using a randomised block design. Pseudostem traps, pitfall traps containing a pheromone (either Cosmolure® (Pheromone A) or Cosmolure+® (Pheromone B)), and unbaited pitfall traps (control), were compared over 5 weeks during all seasons along the Southeast coast of South Africa. Pseudostem traps treated with an insecticide, and rhizome traps were included as additional treatments in autumn. In summer two treatments were also added: individual suspension of both pheromones above a pitfall

trap either in combination with or without a pseudostem trap. The adult beetles were sexed, and the number of internal eggs noted. Pheromone A proved to be the most effective of the different traps. Grouping of the pheromones resulted in a synergistic response, while combining the pseudostem did not enhance trap efficacy. The different plant material traps and the control were usually equally effective in catching weevils. Plant material traps caught greater numbers of fecund females, but pheromone traps captured a higher proportion of females. Treatment effects were much less pronounced in summer, and compared to a pseudostem trap, pitfall traps were the most efficacious during spring. Compared to conventional pseudostem trapping, Pheromone A pitfall traps should be optimally applied during spring in South Africa.

Cultural control methods were investigated over 2 years at an ongoing trial in the Southern KwaZulu Natal, South Africa. Harvesting at ground level and dissection of remnants, and covering of the mat with soil and moving debris to the inter-row, were compared to a positive control that involved treatment of plants with a registered pesticide, and a negative control that involved harvesting at approximately 150 cm with no soil or sanitation amendments. Yield, weevil damage and pseudostem girth of plants were measured from August to November annually, while adult beetle densities were assessed over 4 weeks in October/November and April. Nematode samples were analysed in October/November every year. Damage parameters included the Coefficient of Infestation, the Percentage Coefficient of Infestation (PCI) at two intervals, the summed PCI value, the percentage cross sectional damage of the central cylinder (XI) and cortex, and the mean cross sectional damage percentage (X mean). A replicated block design was used in the experiment. The parameters were similar before the onset of the trial. Fruit yield and plant girth, corrected by nematode densities, were not significantly different in any treatment, nor were the nematodes controlled. Soil cover and recession of remnants was the only effective treatment, significantly reducing the Coefficient of Infestation, but not the adult density or any other damage parameter. The former showed promise as a cultural control method because it only needs to be applied seasonally and reduced the XI, the damage parameter most closely related to yield, by 14.18%.

The weevil is difficult to control, and chemical control arguably provides the best opportunity to manage the pest. The efficacy of injecting bifenthrin, chlorpyrifos, fipronil, imidacloprid, oxamyl and water (control) into residual banana plants was

determined. The chemicals were administered every even numbered month over 2 years at two locations in Southern KwaZulu-Natal, South Africa. Yield, weevil damage and pseudostem girth of plants felled from August to October were measured, while adult beetle densities were assessed over 4 weeks in October and April. Nematode samples were analysed in October every year. Damage parameters included were similar to that of the cultural control trial. Replicated block designs were used in the experiments. The parameters were similar before the onset of the trial. Fruit yield and plant girth, corrected by nematode densities, were not significantly increased after chemical applications, nor were the nematodes controlled. Fipronil and imidacloprid were highly effective against *C. sordidus*, minimising damage to the periphery, cortex and central cylinder of the rhizome and significantly reduced adult density. Fipronil caused a 95% and imidacloprid a 100% reduction in the XI. Injection of fipronil and imidacloprid provides an optimal chemical strategy in an integrated pest management programme for the banana weevil.

Economic thresholds of the insect were investigated on bananas at four locations in the South Coast of KwaZulu-Natal. Yield (bunch weights) and larval damage to felled plants were measured from August to October in 2003, while adult densities were assessed over 4 weeks in October 2003. Nematode samples were collected and analysed in October 2003. Damage parameters included were similar to that of the cultural control trial. Replicated block designs were used in the experiments. The economic-injury level (EIL) for chemical and cultural control was calculated. Nematode densities did not influence the yield of plants. The XI was the best predictor of yield, but under certain conditions X mean was the most important. Chemical control showed the lowest EIL, with more than 1 and 7% damage to the central cylinder when applying fipronil and imidacloprid, respectively. The EIL for cultural control was more than 11% damage to the central cylinder. A recommendation algorithm, considering all the findings of the individual studies, is provided for IPM of the banana weevil in the South Africa. The potential use of microbial and invertebrate (especially parasitoids) biological control and semiochemical mass trapping of the weevil requires further research. Long-term research should focus on host resistance, and weevil damage to the central cylinder can serve as indicator of susceptibility of Cavendish bananas.

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Figure 6.1. The mean values of the Percentage Coefficient of Infestation (PCI) and Coefficient of Infestation (secondary axis) damage parameters of untreated (control) plants and plants treated bimonthly with four chemicals at Munster (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05) and upper case letters refer to the secondary axis. 20 = PCI from > 5 to 20 cm from the collar, To = Summed total PCI, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil and Oxa = Oxamyl.

Figure 6.2. The mean adult banana weevil density values of untreated (control) plots and plots treated bimonthly with four chemicals at Munster (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil and Oxa = Oxamyl.

Figure 6.3. The mean values of the Percentage Coefficient of Infestation (PCI) and Coefficient of Infestation (secondary axis) damage parameters of untreated (control) plants and plants treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05) and upper case letters refer to the secondary axis. 05 = PCI from 0 to 5 cm from the collar, 20 = PCI from > 5 to 20 cm from the collar, To = Summed total PCI, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 6.4. The mean values of the cross sectional damage parameters of untreated (control) plants and plants treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). XO = Cross section damage percentage of the cortex, XI = Cross section damage percentage of the central cylinder, X mean = Average cross sectional damage of the corm, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 6.5. The mean adult banana weevil density values of untreated (control) plots and plots treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 7.1. Recommendation algorithm for the integrated pest management of *Cosmopolites sordidus* in South Africa.

AIMS

The aims of the study were to:

1. Evaluate and review literature of *Musa* and *Cosmopolites sordidus* from a South African perspective.
2. Investigate the molecular phylogeny of *C. sordidus* from South Africa, Australia, Uganda and Costa Rica, using the amplified fragment length polymorphism technique.
3. Determine the population dynamics of *C. sordidus* under field conditions in South Africa.
4. Ascertain the relative efficacy of pheromone compared to conventional traps for *C. sordidus* during different seasons in South Africa.
5. Investigate the field efficacy of cultural control methods compared to registered chemicals in providing a curative control for *C. sordidus* in South Africa.
6. Quantify the field efficacy of chemical plant injections in providing a curative control for *C. sordidus* in South Africa.
7. Formulate an integrated pest management programme for *C. sordidus* in South Africa.

HYPOTHESIS

Null ($\mathbf{H_0}$) and alternative ($\mathbf{H_A}$) hypothesis included the following:

1. $\mathbf{H_0}$: There is no genetical disparity between *C. sordidus* from South Africa (Lowveld, North-east and Southeast Coast), Australia, Uganda and Costa Rica.

   $\mathbf{H_A}$: There is a genetical disparity between *C. sordidus* from South Africa (Lowveld, North-east and Southeast Coast), Australia, Uganda and Costa Rica.
2. $\mathbf{H_0}$: There is no significant difference in the density of *C. sordidus* larvae or adults in the field throughout the year.

   $\mathbf{H_A}$: There is a significant difference in the density of *C. sordidus* larvae or adults in the field throughout the year.
3. $\mathbf{H_0}$: No significant relationship exists between *C. sordidus* incidence (in plants and traps) and temperature and/or rainfall.

H_A: A significant relationship exists between *C. sordidus* incidence (in plants and traps) and temperature and/or rainfall.

4. **H_0**: There is no difference between pheromone and split-pseudostem-trap efficacy relative to season, adult, female and male catches, sex ratios, proportion of females with eggs and/or fecundity.

   H_A: There is a difference between pheromone and split-pseudostem-trap efficacy relative to season, adult, female and male catches, sex ratios, proportion of females with eggs and/or fecundity.

5. **H_0**: Cultural control over two years has no significant influence on adult densities, different plant damage assessments, plant girth and/or bunch weight.

   H_A: Cultural control over two years has a significant influence on adult densities, different plant damage assessments, plant girth and/or bunch weight.

6. **H_0**: Chemical injection of plants every second month over two years has no significant influence on adult densities, different plant damage assessments, plant girth and/or bunch weight.

   H_A: Chemical injection of plants every second month over two years has a significant influence on adult densities, different plant damage assessments, plant girth and/or bunch weight.

STATISTICAL ANALYSIS

The statistical analysis of all the data were conducted on the software program STATISTICA Version: 7 (Statsoft Inc. 2004). All data conformed to the assumptions of the specific statistic analysis applied (Sokal & Rohlf 1997). Where applicable, the specifics of the analysis are elaborated. Significance level was set at the biological standard 5% level.

Chapter 1

Biology, ecology and integrated pest management of the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), on *Musa* (Zingiberales: Musaceae): an evaluation of literature

1.1 Introduction

Historically, integrated pest management (IPM) was first promoted in the 1960s because of the failure of chemical insecticides, notably in cotton production (Gullan & Cranston 1994). An IPM philosophy acknowledges that total pest eradication is impractical and rather strives to manage the population below economic injury levels (Dent 1991). This is accomplished by combining all available control methods to increase cost-effectiveness and long-term reliability, whilst minimizing harmful side effects to non-target organisms, the environment and consumers of the produce (Anonymous 1973, Dent 1991; Gullan & Cranston 1994). To develop an IPM system, a thorough knowledge of the host plant and biology and ecology of a pest insect is required to allow the rational use of cultivation and control techniques under different circumstances. Successful IPM is based on an understanding of biotic and abiotic factors affecting the population processes of the pest (Gullan & Cranston 1994) and subsequent timely application of control measures.

Bananas, a major commodity in the world trade, are susceptible to a variety of serious and debilitating diseases and pests (Simmonds 1959, Royer *et al.* 1990, Gowen 1995, Robinson 1996; Viljoen & Robinson 2002). The most important insect pest, the banana weevil, *Cosmopolites sordidus* (Germar), is a significant production constraint and causes economic damage to the crop (Stover & Simmonds 1987, Gold *et al.* 1999c; Gold *et al.* 2003). The weevil is found almost everywhere in the tropics and subtropics where bananas are grown, including South Africa (Cuillé 1950). The weevil has periodically developed resistance to chemicals (Vilardebó 1967; Collins *et al.* 1991) and no single control method has shown universal long-term efficacy. The integration of control strategies is required to effectively manage the insect and reduce the use of hazardous pesticides. A comprehensive literature review has recently been published on the biology and IPM of the banana weevil (Gold *et al.* 2003). In this review, current knowledge on the classification, physiology and agronomy of the host plant, and literature concerning the classification, biology, ecology, sampling and management of *C. sordidus* is considered in order to develop an integrated pest management strategy for *C. sordidus* in South Africa.

1.2 *Musa*

1.2.1 Classification

Bananas belong to the order Zingiberales and the family Musaceae (Jones 2000). Family limits can be arbitrary, but according to Stover & Simmonds (1987) and Jones (2000), the Musaceae comprises the *Ensete* and *Musa* genera. The *Ensete* genus is composed of monocarpic herbs and does not produce edible fruits (Stover & Simmonds 1987). *Musa* originate from the Arabic word "Mouz" (Simmonds 1959). The word was probably derived from others, but the Arabs of the dark ages knew the plant and it entered the Koran as the "Tree of Paradise" (Simmonds 1959). According to Valmayor *et al*. (1991), the generic name *Musa* was selected to honour Antonius Musa, physician to the first emperor of Rome, Octavius Augustus.

The genus *Musa* contains five sections, with edible fruits only found in the Australimusa and Eumusa subdivisions (Stover & Simmonds 1987). The former is of minor importance in the Pacific, comprising Fe'i banana cultivars and *Musa textilis* Née (Abacá or Menila hemp) (Jones 2000). Eumusa is the biggest with wide distribution and has given rise to the majority of edible bananas (Stover & Simmonds 1987). Edibility first evolved in wild *M*. *acuminata* Colla with the primary centre of origin in Indochina and Southeast Asia (Simmonds 1962, Simmonds 1976; Valmayor *et al*. 1991). Edible bananas also originated from interspecific hybridization between the wild diploid species, *M*. *acuminata* (more important) and *M*. *balbisiana* Colla (from drier monsoon areas of India and the Philippines) (Simmonds 1976, Stover & Simmonds 1987; Robinson 1996). The latter species is considered more drought and disease resistant than the former and these qualities are usually evident in varieties with a *balbisiana* component in the genome (Price 1995b). *Musa balbisiana* genes also induce improved nutritional value, increased starchiness and provide hybrids that are suitable for cooking, in contrast to pure *M*. *acuminata* cultivars that are sweeter and more suited to dessert use (Robinson 1996).

The currently accepted classification is based on Simmonds & Shephard (1955), who scored the relative contribution of the wild species (A = *acuminata* genome; B = *balbisiana* genome) to the constitution of a given cultivar. Six genome groups are identified: AA, AAA, AAB, AB, ABB and ABBB (Simmonds & Shepherd 1955). In the Eumusa, cultivars are diploid, triploid (most numerous) or tetraploid, with the latter two more robust than diploids (Stover & Simmonds 1987). The main diversity centre of *Musa* is in Southeast Asia (Assam-Burma-Thailand-Indonesia-Papua-New-Guinea) (Simmonds 1966; Valmayor *et al*. 1991) with

secondary centres of diversity in East Africa (highland cooking bananas) and West Africa (plantains) (Stover & Simmonds 1987).

1.2.2 Morphology and growth

The banana plant is a monocotyledonous, herbaceous, evergreen perennial (Wardlaw 1961; Robinson 1996). The aerial parts and the root system arise from a sympodial rhizome (corm or bulb) (Simmonds 1959, Stover & Simmonds 1987; Price 1995a). Therefore a well developed banana or plantain consists of several meristems of different stages of development (Summerville 1939; Stover & Simmonds 1987), each producing both a stem and root system (Simmonds 1959). Bananas are, therefore, predominantly clumped in habit (referred to as a clump, stool or mat) (Simmonds 1959). In contrast, *Ensete* is monopodial (new meristems do not occur), reproduction is sexual and fertile seeds are produced (Price 1995a).

The corm is internally divided into two main regions, a central cylinder consisting of a starchy parenchyma and a whitish cortex (Simmonds 1966, Stover & Simmonds 1987; Price 1995a). Adventitious (main) roots arise from cambium-like meristematic tissue on the periphery of the central cylinder (Skutch 1932) and produce various laterals that produce root hairs (Simmonds 1959). Roots generally extend laterally up to 5 m from the plant, but are concentrated in a 60 cm radius of the pseudostem in the top 40 cm of the soil (Gousseland 1983, Price 1995a; Robinson 1996). The apical portion of the corm contains the meristematic tissues from which the vascular system, aerial parts, corm proper and central cylinder develop (Skutch 1932). The aerial part or pseudostem of the banana plant consists of compacted leaf sheaths (Simmonds 1966; Karamura & Karamura 1995). Free margins of the sheaths are forced apart by the growth of the new leaves enclosed within the pseudostem (Stover & Simmonds 1987). The lamina develops in the centre of the pseudostem as a rolled cylinder and while the leaf sheath elongates, the lamina is pushed clear of the leaf crown (Robinson 1996). After unfolding, the leaf (heart leaf) is more or less vertical, becoming horizontal and later droops as it ages (Karamura & Karamura 1995).

Floral initiation is characterised by the apical meristem at the base of the pseudostem ceasing to produce leaves and starting to develop a terminal inflorescence (Simmonds 1976; Robinson 1996). The internodes at the apex of the corm lengthen and change from a subterranean to an aerial true stem (Simmonds

1966). The aerial true stem (supported by the pseudostem) carries the inflorescence and bears the last leaves, important for bunch filling (Stover & Simmonds 1987). Elongation of the aerial stem forces the inflorescence through the centre of the pseudostem, until it is "shot" (Karamura & Karamura 1995). At emergence the inflorescence is initially erect but quickly points downwards due to its weight, the continued growth of the aerial stem and geotropic effects (Robinson 1996). Flowers are arranged in nodal clusters (in two rows on transverse cushions) and subtended by a protecting bract (Robinson 1996). The proximal nodes bear female flowers that develop into edible fruit and the distal nodes contain male flowers that remains tightly enclosed in bracts ("the bell") (Simmonds 1976; Robinson 1996). Nodes in between that of the male and female nodes contain hermaphrodite flowers (Robinson 1996).

1.2.3 Cultivation

1.2.3.1 Cultivation areas

Bananas were originally introduced from Southeast Asia to other areas and are currently grown in all tropical (North and South of 20° latitude) and subtropical regions (between 20 and 30° N and S latitude) of the world (Simmonds 1959, Wardlaw 1961, Stover & Simmonds 1987; Valmayor *et al.* 1991), including Asia, South and Central America, Oceana, Africa, Europe and Australia (Robinson 1996). In the tropics some clones are grown up to 2000 m above sea level (Central and East Africa), but mostly below 1500 m altitude (Stover & Simmonds 1987).

Banana cultivation in South Africa started in the 1920s in Natal (now KwaZulu-Natal) and in the 1930s in the former Transvaal (now Mpumalanga and Limpopo Provinces) (Anonymous 2005c). Current production is in these low elevation subtropical regions between 24° and 31° South (Willers *et al.* 2001), concentrated in the subtropical coastal (Southeast) and subtropical Lowveld (North-east) areas of the country. The local banana industry is well established, even though these areas may be considered suboptimal in terms of temperature variations, relatively low winter temperatures (± 11 °C) and low precipitation levels (± 1000 mm per year) (Robinson 1996).

1.2.3.2 Food production systems

Food production from *Musa* can generally be divided in two basic systems: AAA-type dessert varieties of Cavendish produced for sale from tropical and subtropical regions and all other dessert bananas, plantains and cooking bananas produced mainly for local consumption (Stover & Simmonds 1987; Price 1995b). The former is especially common in Latin America and Asia (although plantains are important in the local American and Caribbean market), while the latter system is usually found in Africa. (Seshu Reddy *et al*. 1999; Arias *et al*. 2003). Horticultural management varies drastically between the two systems. In commercial systems bananas are produced for the export or local market and management commonly include pesticides, tissue culture plants, fertilising, irrigation, weed control, sucker management and selection, mulching, leaf removal, windbreaks, greenhouse construction, bunch propping and bunch covering (Robinson 1996). In small scale subsistence systems, plants are propagated by suckers, soil is fertilised with household refuse and animal wastes, family or village labour are used and small areas are cultivated in backyards (Stover & Simmonds 1987; Robinson 1996). Plants are grown in clusters and management is usually limited to mulching, propping and harvesting (Robinson 1996), although weeding, desuckering and leaf removal may also be practised.

The commercial banana industry in South Africa is based on the production of the Cavendish subgroup of banana cultivars (AAA). Williams, Grand Nain, Chinese Cavendish and Dwarf Cavendish are the main cultivars grown (Wardlaw 1961; Willers *et al*. 2001). At planting, *in vitro* plantlets (tissue culture plants) are preferred to sucker and rhizome material. The planting density varies from 1666 to 2222 plants per hectare. Optimal timing of planting is governed by climatic conditions and harvests coinciding with high market prices (Robinson 1996). Hence, in the Lowveld area planting or replanting is usually done in autumn and summer and in the Southeast coastal areas during spring. Desuckering is used to maintain optimal plant density and manageability, and single followers (suckers) are usually selected between 5 and 10 months after planting, with direction of selection uniform to maintain spatial arrangement (Robinson 1996). In the South coast region of KwaZulu-Natal, sucker selections are usually made against slopes. Time from planting to harvest varies between 15-20 months and harvest-to-harvest from 11-13 months (Robinson 1996). As in other banana cropping systems, older ratoon stands are harvested throughout the year. The fruit is cut green and pseudostems felled at approximately 1 to 1.5 meter height and left *in situ*. Plantation care in commercial

operations usually includes irrigation, regular desuckering, weed control (herbicides) and leaf removal. Bunches are covered with perforated blue polyethylene bags and plants may be propped. Residual banana materials are mostly used as mulch, usually spread randomly within the plantation. Topography (sloping fields) is probably a contributing factor in relative sub optimal horticultural practises at the coastal KwaZulu-Natal areas.

1.2.4 Crop importance

The *Ensete* genus is of minor economic importance, with only *E. ventricosum* (Welw.) Cheesm. yielding a useful fibre, a starchy foodstuff and a boiled vegetable in East Africa (Stover & Simmonds 1987). Abacá produces cordage fibres and is used to make commercial cables and ropes (Jones 2000). It is mostly grown in the Philippines, where it is an important crop (Jones 2000). Bananas and plantains constitute the fourth most important crop of the developing world (Padmanaban *et al*. 2001), are a primary source of carbohydrates, vitamins and minerals for more than 400 million people (McNicol 1989) and is a widely consumed fruit in the world (Hallam 1995). In most developing countries, the majority of banana production is self-consumed or locally traded, thereby playing a crucial role in food security. *Musa* was cultivated on an area of approximately 9 million hectares in 2000; world production averaged 92 million tonnes per annum in 1998-2000 and was estimated at 99 million tonnes in 2001 (Arias *et al*. 2003). These figures only provide general indicators, because no statistics are available from relatively small plots and backyard gardens (Seshu Reddy *et al*. 1999; Arias *et al*. 2003). Cavendish is the major banana of the export trade (Price 1995b), but exports amount to less than 20% of world production (Hallam 1995, Robinson 1996; Jones 2000). By type, Cavendish bananas comprises 47% of production (Arias *et al*. 2003).

India is the main producer (about 16%) and Uganda the main consumer (>200 kg/ca/yr) of *Musa* in the world (Anonymous 2005f, g; Arias *et al*. 2003). The leading producer of Cavendish bananas in the world during 1998 to 2000 was India (19%), followed by Ecuador (12%), China (10%), Colombia (6%) and Costa Rica (5%) (Arias *et al*. 2003). Latin America contributes 80% of all exported bananas, with the leading countries being Ecuador, Costa Rica and Colombia (Arias *et al*. 2003). The value of the international banana trade ranges between US$ 4.5 and 5 billion per year (Arias *et al*. 2003).

The annual South African banana production in the mid-1960s averaged approximately 25 000 tonnes, which increased four fold in the mid to late 1970s (Annecke & Moran 1982; Anonymous 2005a). In 1992, 14 067 hectares of bananas, with a production of approximately 180 000-190 000 tonnes were reported (Robinson 1993, 1996). South Africa currently produces 260 000-280 000 tonnes (Anonymous 2005a; Anonymous 2005e) from 12 000-17 000 hectares (Govender & Viljoen 2002, Anonymous 2005d), exports 556 tonnes and consumes 5.6 kg/ca/yr of bananas (Anonymous 2005g). The industry is intensive, but relatively small, being limited by the demand of the local market.

1.3 *Cosmopolites sordidus*

1.3.1 Classification

The banana weevil is classified under the Coleoptera, the largest order of living organisms with an estimated 350 000 described species in approximately 23 000 genera (Zimmerman 1968b, c; Endrödy-Younga 1985); the superfamily Curculionoidea, regarded to represent the most highly evolved of all beetles and within the diverse Curculionidae (Zimmerman 1968b, c), the largest family of animals in the world with more than 45 000 described species (Oberprieler & Louw 1985; Picker *et al*. 2002). The family has a cosmopolitan distribution with members characterised by a globular head produced into a rostrum (Oberprieler & Louw 1985). The classification of Curculionidae into subfamilies and tribes is probably the largest outstanding problem in the higher classification of the Coleoptera (Oberprieler & Louw 1985). Traditionally curculionids are divided into the "short-nosed" Adelognatha and "long-nosed" Phanerognatha based on the ventral visibility of rostrums (Oberprieler & Louw 1985). The banana weevil is classified in the Phanerognatha, a tribe that represents the bulk of weevils arboreal in habits with larvae mainly developing in plant tissues (Oberprieler & Louw 1985). The banana weevil belongs to the Rhynchophorinae, an economically important subfamily in this group; some species are pests of stored grain and larvae of other members develop in and damage soft-trucked trees such as aloes, bananas, palms and sisal (Zimmerman 1968a; Oberprieler & Louw 1985). The subfamily has strong tropical links and in southern Africa, is restricted to the wetter eastern parts (Oberprieler & Louw 1985). The classification of the weevil extends into *Cosmopolites*, a genus comprising only

two species, the banana weevil, *C. sordidus* and *C. pruinosus* Heller (Zimmerman 1968a, b, c). *Cosmopolites pruinosus* was first described in 1934 and is morphologically very similar to *C. sordidus*, but differs externally in the nature of pruinosity on the dorsum and the character of the elytral striae (Zimmerman 1968a, c). The former is associated with bananas in Borneo, Philippines and the Caroline Islands (Zimmerman 1968a, b) and considered to be a secondary pest species (Masanza 2003). Zimmerman (1968c) provided taxonomic keys for the species.

The banana weevil was first described in 1824 as *Calandra sordida* Germar (Zimmerman 1968c). The name was changed to *C. sordidus* by Chevrolat in 1885 and is still recognized today (Zimmerman 1968c). *Sphenophorus striatus* Fahreus and *S. cribricollis* Walker are synonyms (Zimmerman 1968b, c). *Curculio mendicus* Olivier was reported as a synonym (Csiki 1936), but appeared to be in error (Zimmerman 1968b). Several common names including banana weevil, banana corm borer, banana beetle, banana root borer, rhizome weevil, black banana borer (Zimmerman 1968b, c; Masanza 2003), migratory borer (Smith 1995), plantain black weevil and many vernacular names have been assigned to *C. sordidus*. The common name “banana root borer” is especially misleading, because neither the larvae nor the adults feed on banana roots (Annecke & Moran 1982).

Further classification of the species may be necessary, because the limited mobility of banana weevils suggests isolated populations with limited gene flow and the evolution of biotypes (Gold *et al.* 2003). Biotypes have been defined as organisms that share a specified genotype or the genotype (or peculiarities) so shared (Anonymous 2005h) and as a population within an insect species that differs in their ability to utilise a crop plant (Gallun & Khush 1980). Maxwell & Jennings (1980) described a biotype as an individual or a population that is distinguished from the rest of its species by criteria other than morphology, e.g. a difference in parasitic ability. The latter definition should be applied with caution, as some homopteran biotypes are distinguishable by morphological differences (Starks & Burton 1972; Saxena & Rueda 1982). The occurrence of banana weevil biotypes was postulated after pathogenicity of a nematode strain varied between geographically different populations of *C. sordidus* (Parniski *et al.* 1990; Kermarrec *et al.* 1993). Traore *et al.* (1993) also suggested that weevil biotypes exist and studies on banana tolerance or resistance were cautioned to consider possible geographical differences between weevil populations (Fogain & Price 1994). Genetic research supported the existence

of weevil biotypes, but the results obtained were highly variable and relationships among populations remained largely unclear (Ochieng 2002; Gold *et al*. 2003).

1.3.2 Distribution

The banana weevil reportedly originates in the Indo-Malayian region (Zimmerman 1968c; Stover & Simmonds 1987), but Hasyim & Gold (1999) suggested the region is unsure. Dissemination is most often by infested plant material, but crawling adults also colonise nearby plantations (Feakin 1971, Franzmann 1972, Waterhouse & Norris 1987, Gowen 1995; Seshu Reddy *et al*. 1999). The weevil is currently found in Southeast Asia, Australia (East and West), the Pacific, Indian Ocean islands, tropical and South Africa and tropical America (southern U.S.A. to southern Brazil, including the Caribbean) (Simmonds 1966, Castrillon 1991, cited in Gold *et al*. 2003, Gettman *et al*. 1992, Ploetz *et al*. 1992, Robinson 1996; Bellis *et al*. 2004). The weevil has not been identified in banana growing regions of North Africa (including Egypt) (Cardenosa 1953; Cuillé & Vilardebó 1963) and Israel (Cardenosa 1953, Gettman *et al*. 1992, Castrillon 1991, cited in Gold *et al*. 2003). According to Gold & Messiaen (2000), however, the weevil is currently found in all banana and plantain growing areas in the tropics and subtropics. The cryptic nature (Gold *et al*. 2003) and the fact that infestation symptoms of the weevil resemble nematode damage and bacterial head rot (rhizome rot) (*Erwinia* spp.) (Jones 2000) has caused the time of introduction to be underestimated or even allowed the pest to remain undetected.

The banana weevil was first reported to occur in South Africa in 1924 (Cuillé 1950). According to Schoeman (1997, 2001) and Govender & Viljoen (2002), the weevil was only introduced in the 1970s, with mild infestations at individual localities. Occurrence of the weevil in South Africa has been documented in the South Coast region (KwaZulu-Natal), the Sabie River valley (Mpumalanga), Peebles (Mpumalanga), Burgershall (Mpumalanga), the Kiepersol region (Mpumalanga) (Schoeman 1996) and areas near Tzaneen (Limpopo Province) (Schoeman 2002). The banana weevil has since been identified in Tzaneen and at the North Coast of KwaZulu-Natal. Occurrence in other banana growing areas in the Limpopo province and Mpumalanga (Levubuland and Komatipoort) are currently unknown.

1.3.3 Biology and behaviour

Females oviposit their elongate, oval, white eggs singularly (Froggatt 1925, Simmonds 1966; Franzmann 1972) in small crevices chewed in the plant tissue, sealed by latex-containing plant sap and necrotic tissue (Beccari 1967). Eggs are usually laid at about ground level (Franzmann 1972) in the crown of the rhizome and pseudostem base (Abera *et al*. 1999) and flowered plants are favoured (Treverrow *et al*. 1992; Abera *et al*. 1999). Eggs are, however, also found in harvested stumps, larval tunnels, superficially in the base of roots (Koppenhöfer 1993b), well below ground level (Froggat 1925, Seshu Reddy & Koppenhöfer 1991; Seshu Reddy *et al*. 1993), more exposed positions and other parts of the plant (Froggat 1925).

Upon emergence, the legless, crescent-shaped larvae immediately tunnel into the rhizome or occasionally the pseudostem, producing distinctive circular, debris-filled tunnels (Franzmann 1972) up to 8 mm in diameter. Larvae display developmental polymorphism and pass through five to eight instars (Mesquita *et al*. 1984, Traore *et al*. 1996; Gold *et al*. 1999b), reaching approximately 10-20 mm in length (Treverrow *et al*. 1992; De Jager 1993). The pupa develops in a chamber at the corm periphery (Franzmann 1972) and eclosion produces a reddish, brown adult (teneral stage), which becomes uniformly dull black (Pinese & Elder 2004). The teneral stage is passed within the corm or pseudostem (Gold *et al*. 1999c). Mating usually occurs at night (Delattre 1980) and only mated females produce chorionated eggs (Treverrow & Bedding 1993). Weevils also reproduce in residual pseudostems (especially true stems), but prefer rhizomes (Treverrow & Maddox 1993).

Adults measure 10-15 mm (Gold & Messiaen 2000) and are found in moist environments (Hord & Flippen 1956), leaf bases and decayed corms and stems (Treverrow *et al*. 1992), feeding on plant tissues or crop debris (Franzmann 1972; Treverrow *et al*. 1992). Wings are well developed, but flight is considered rare and being negatively phototropic, adults move mainly by walking at night (Simmonds 1966, Ostmark 1974, Uzakah 1995, cited in Gold *et al*. 1999c; Gold *et al*. 1999c). Adults are gregarious and usually patchy distributed in the field (Treverrow *et al*. 1992); dispersal is slow and weevils normally move less than 10 m per month (Gold *et al*. 1999c), while only a small proportion will move more than 25 m in 6 months (Gold & Messiaen 2000). Weevils show aberrant behaviour and difficulty in walking at low humidities (Roth & Willis 1963). The beetle is highly susceptible to desiccation and commonly die within 3 to 10 days on a dry substrate (Viswanath 1977; Gold *et al*. 1999c), but survives approximately 4 to 17 months in moist soil

without food (Franzmann 1972, Viswanath 1977; Treverrow *et al*. 1992). Adults are thigmotactic (Delattre 1980) and exhibit hydrotropism; for *C. sordidus* the latter include search for higher humidity and liquid water (Cuillé 1950). Orientation in humidity gradients is by means of orthokineses, klinokineses, klinotaxis and titubant reactions (Roth & Willis 1963). Adults display thanatosis (feigning death) when disturbed (Feakin 1971). Both sexes are especially attracted to stressed or damaged plants and residual corm and pieces of freshly cut pseudostem (Froggatt 1925, Treverrow *et al*. 1992, Treverrow & Bedding 1993; Gold *et al*. 1994b).

Males aggregate at lower humidities than females (Roth & Willis 1963), but distribution patterns of males and females in the field are similar (Gold *et al*. 1999c). Males produce an aggregation pheromone that attracts both genders (Budenberg *et al*. 1993a). Females tend to be larger than males (Cuillé 1950; Gold *et al*. 1999c) and have rostrums with a more accentuated reddish colour relative to the rest of the body (Longoria 1968). As a secondary sexual character, however, the ventral margin of the last abdominal segment being more sharply curved in the male (lateral view), is a more accurate feature in distinguishing weevil sexes (Roth & Willis 1963). Punctuations on the female rostrum do not extend beyond the antennae as can be found in males (Longoria 1968). Using the latter two characters, Rukazambuga *et al*. (1998) reported that dissections confirmed >95% of predictions.

1.3.4 Population dynamics

The reproductive activity of the banana weevil is relatively low (Cuillé 1950), with high field mortality of eggs and larvae (Treverrow & Bedding 1993; Abera 1997, cited in Gold *et al*. 1999c). Field oviposition rates are a negative function of weevil density (Abera *et al*. 1999; Gold *et al*. 1999c, 2002a), but Koppenhöfer (1993b) reported that it only occurs at very high densities, which can impossibly be attained under field conditions. Egg laying activity is negatively influenced by temperature (Franzmann 1972, Parnitzki 1992; Gold *et al*. 2002a) and generally ceases during the Australian winter (Treverrow & Bedding 1993). Under tropical conditions, oviposition is reduced during the dry season (Cuillé 1950). Females oviposit further below ground level during drier periods, but will also do so on young deep-planted bananas (Koppenhöfer 1993b). Under tropical conditions, females usually lay one egg per week (Abera *et al*. 1999). In the subtropics, two eggs (Treverrow *et al*. 1992) or two to four eggs are laid per week and 50-100 eggs per annum, mostly over a 6-

month period in spring, late summer and autumn (Simmonds 1959, Treverrow *et al*. 1992; Treverrow & Bedding 1993). The developmental threshold of eggs is 12 °C with 89 degree-day thermal requirement (determined on a West African population) (Traore *et al*. 1993). The incubation period was reported to normally be a week (Treverrow *et al*. 1992), but varied from 4 to over 30 days at high (± 30 °C) and low (± 15 °C) temperatures, respectively (Franzmann 1972; Traore *et al*. 1993).

Larval development time (of a West African population) is inversely related to temperature, with a thermal threshold of 8.8 °C and 537.9 degree-days development requirement (Traore *et al*. 1996); generally lasting from 2 weeks to several months (Simmonds 1966; Franzmann 1972). Under field conditions larval populations can be positively related to rainfall and temperature (Batista Filho *et al*. 1991). The pupal stage requires 10.1 °C and 120.7 degree-days for development (Traore *et al*. 1996), and completion requires 8 days (Simmonds 1966; Franzmann 1972) at 25 °C, but up to 3 weeks at cooler temperatures (Simmonds 1966).

The teneral stage generally lasts 2 weeks under tropical conditions (Viswanath 1976). Sexual maturity of males and females is obtained after 2 to 5 and 1 to 3 weeks, respectively (Uzakah 1995, cited in Gold *et al*. 1999c). Females oviposit a week after pupal eclosion (Treverrow & Bedding 1993), but 27 to 41 days may also be required (Uzakah 1995, cited in Gold *et al*. 1999c). Fertile eggs can be laid a year after mating (Treverrow *et al*. 1992) and adults live up to 2 (Froggatt 1925, Waterhouse & Norris 1987; Treverrow & Bedding 1993) or 4 years (Rukazambuga *et al*. 1998). All post embryonic stages require a thermal threshold of 10.2 °C and 609.3 degree-days to complete development (Traore *et al*. 1996). In the tropics seasonality is mostly related to rainfall; while in the subtropics seasonality is also related to temperature. Depending on temperature, the life cycle is normally completed in 6 weeks to 6 months (Treverrow & Bedding 1993). Uganda, with a tropical climate, is at the lower end of the scale (6-8 weeks) (Gold *et al*. 1999b), while in subtropical climates, the life cycle ranges from 30 days in summer to 180 days in winter (Robinson 1996, Treverrow *et al*. 1992; Govender & Viljoen 2002), with a mean of 12 weeks in northern Queensland (Australia) (Pinese & Elder 2004). The weevil is multivoltine, with four or more and five to six generations in Australia and China, respectively (Luo *et al*. 1985, Treverrow & Bedding 1993; Maolin 1994).

The emergence and activity of adults peak during spring and autumn in Australia (Froggatt 1926, Treverrow 1985, Treverrow & Bedding 1993; Pinese &

Elder 2004). Peaks are usually more evident in Southeast Queensland, where activity almost ceases in winter (Pinese & Elder 2004). In North Queensland, where winter temperatures are higher, activity is reduced in winter but continue throughout the year (Pinese & Elder 2004). Most adults also emerge during spring and autumn in China (Luo *et al*. 1985; Maolin 1994). Activity increases shortly after rain in the tropics (Gold *et al*. 1999c) and subtropics (Treverrow *et al*. 1992, Smith 1995, Govender & Viljoen 2002; Pinese & Elder 2004). No correlation between adult catches and rainfall or sunlight was however reported in Colombian field trials (Cárdenas & Arango 1986). Brazilian field studies also showed no correlation between adult population and rainfall, relative humidity or temperature (Arleu *et al*. 1984; Batista Filho *et al*. 1991). In South Africa (Kiepersol area), catches in rhizome traps peaked in October (spring) and showed a weak positive correlation with temperature (Schoeman 1996). According to De Jager (1993), weevil numbers in South Africa tend to peak in spring and autumn. Emergence peaks during spring and late summer have also been reported (Govender & Viljoen 2002). The weevil is generally accepted to have an approximate 1:1 sex ratio (Cuillé 1950, Viswanath 1976, Delattre 1980; Gold *et al*. 1999c), but Sponagel *et al*. (1995), cited in Gold *et al*. 1999c, reported 2.2 males per female from field collected adults in Honduras. More females have been encountered in the field during the rainy season (Delattre 1980), suggesting that sexes have different behaviour patterns.

Reports of seasonal fluctuations in weevil populations depend on crop management, predators, weevil density, sampling method, weevil development rate, and/or weevil biotype. Differences in crop management (e.g. mulching material or mulching location) influence weevil distribution (Gold *et al*. 2004b), and can also change field microclimate, which alter temperatures and humidity (Seshu Reddy *et al*. 1999). Weevil numbers are also influenced and can be negatively related to predator densities (Hasyim & Harlion 1998). The size of the population between studies probably influences the rate of migration and the effect of destructive sampling. Development rate of *C. sordidus* depends on cultivar, plant stage, diet, relative humidity and population density (Mesquita *et al*. 1984, Gold *et al*. 1999b; Kiggundu 2000). Weevil biotypes may, however, have different developmental temperature requirements (Traore *et al*. 1993). The development thresholds and periods (based on temperature) of specimens from West Africa (Cotonou, Benin and

Onne, Nigeria) (Traore *et al*. 1993, 1996) and East Africa (Bombo, Luwero District) (Gold *et al*. 1999b) were, however, found to be similar.

1.3.5 Pest status

Cosmopolites sordidus is a pest specific to *Musa* (bananas and plantains) and *Ensete* (Stover & Simmonds 1987; Gold *et al*. 2003), but has also been reported as a monophagous pest of *Musa* (Simmonds 1966, Zimmerman 1968b, Gowen 1995; Pavis & Lemaire 1996). If severely starved, adults will feed on yam (*Dioscorea rotundata* Poir.) and cocoyam (*Xanthosoma sagittifolium* Poir.) (Schmitt 1993, cited in Traore *et al*. 1993) and has been found on sweet potato tubers (*Ipomoea batatas* (L.) Lam.) and canna corms (*Canna edulis* Kerr) (Froggatt 1925). Records of attacks on sugarcane (*Saccharum officinarum* L.) appear to be false (Zimmerman 1968b). According to Gold *et al*. (2003), reports of hosts other than *Musa* and *Ensete* are possibly in error.

Damage attributable to adults is relatively little (Franzmann 1972) and considered negligible (Treverrow *et al*. 1992). Larval tunnels, however, interfere with root initiation (Treverrow *et al*. 1992), plant nutrition (Chavarria-Carvajal & Irizarry 1997) and water transport (Collins *et al*. 1991), resulting in plant stunting, delayed maturation (Gold *et al*. 1998), reduced fruit size and bunch weight, and even plant snapping or toppling (Batchelder 1954, Franzmann 1972; Koppenhöfer 1993b). Larval tunnels also provide entry points for secondary pests (Gold *et al*. 1999c), but reports of spreading rhizome rot are false (Hord & Flippen 1956). Interior corm damage is speculated to affect nutrient transport and stem growth (Taylor 1991), while peripheral damage may adversely affect root development (Gold *et al*. 1994b). Morphological and physiological symptoms of infested plants include reduced vigour, leaf chlorosis (Franzmann 1972), choking of the bunch in the pseudostem (Pinese & Elder 2004), decreased vigour of followers (Rukazambuga 1996) and a different proportion of water suckers (Gold *et al*. 1999c). Infestation by banana root nematodes shows similar symptoms, including a reduction in vigour, leaf chlorosis, plant toppling and yield reduction (Bujulu *et al*. 1983, Smith 1995; Willers *et al*. 2001).

Of 470 species of insects and mites recorded as pests of bananas (Simmonds 1966; Ostmark 1974), *C. sordidus* has been reported as the major (Waterhouse & Norris 1987) and most important insect pest (Gold *et al*. 1999c) of banana and plantain in the world. The weevil is also an important pest of *Ensete* (Gold &

Messiaen 2000). Specifically, the weevil has been reported as a major production constraint in several tropical and subtropical localities (Froggatt 1926, Harris 1947, Braithwaite 1963, Sikora *et al.* 1989, Seshu Reddy 1993, Davide 1994, Maolin 1994) and even in its presumed area of origin (Vittayaruk *et al.* 1994). Yield losses of between 20 and 100% are associated with banana weevil infestations (Mitchell 1980, INIBAP 1986, Koppenhöfer & Schmutterer 1993, Peña *et al.* 1993, Rukazambuga *et al.* 1998; Gold *et al.* 2004a). Pest status appears to be related to altitude, variable plant susceptibility, crop management, weevil population density, phenological plant age, plantation age, plant stress, nematode infestation and weevil biotype.

Weevil damage is inversely related to altitude (Kehe 1988; Lescot 1988) and can therefore be based on temperature (Gold *et al.* 2003). At high elevations in East and West Africa damage is not prevalent above 1500 m altitude (Lescot 1988). At low population densities weevil activity is confined to residual rhizomes of Cavendish (AAA) (Wallace 1937, Ostmark 1974; Treverrow & Maddox 1993), while at high infestations an increasing amount of damage spread to pre-harvested plants (Smith 1995). This behaviour has been reported in north Queensland (Australia), but is not typical on Cavendish bananas in all growing areas (Vilardebó 1984), including South Africa, New South Wales and Southeast Queensland in Australia (Treverrow & Bedding 1993; Stanton 1994). Plants are mainly attacked after flowering (Treverrow *et al.* 1992, Smith 1995; Abera *et al.* 1999) and kairomones may cause preferential attraction to these plants (Cerda *et al.* 1996). In Australia, most tunnels appeared between flowering and harvest (70%), with 30% after harvest (Stanton 1994). The effect of damage is greater on bunch weight than on plant growth or rate of development (Rukazambuga *et al.* 1998). Highly variable yield loss values are complicated by plant loss (toppling/snapping) that contribute more to yield loss than reduction in bunch weight and the fact that yield loss is a positive exponential function of crop cycle (Speijer *et al.* 1993, Vittayaruk *et al.* 1994, Rukazambuga 1996, Rukazambuga *et al.* 1998; Gold *et al.* 2004a), but can also be severe in newly planted fields (Speijer *et al.* 1993; Mitchell 1980). Stressed plants are more attractive (Treverrow & Bedding 1993) and have more weevil damage (Froggatt 1925) or a lower damage threshold (Rukazambuga 1996). Suckers infested by nematodes may increase the probability of weevil infestation (Speijer *et al.* 1993). Weevil biotypes (Fogain & Price 1994; Gowen 1995) or even several weevil species have been

suggested to be involved (Zimmerman 1968a, b, Neuenschwander 1988; Gowen 1995). The parameters influencing pest status are probably interrelated.

The major insect pests of bananas in South Africa are listed in Table 1.1 (Annecke & Moran 1982). The banana weevil is currently regarded as the most important insect pest. The species is of economic importance at the South Coast of KwaZulu-Natal (Schoeman *et al.* 1999) and recently areas near Hazyview and Tzaneen reported plant losses of 30% (Schoeman 2002).

1.4 Integrated management

Pests are usually targeted at their most vulnerable stage(s). *Cosmopolites sordidus* adults have been theorised to be a more important target than larvae, because oviposition is relatively infrequent (Treverrow & Bedding 1993), population build-up is slow (Treverrow *et al.* 1992) and, especially after over-wintering, females contain a relatively high number of eggs (Treverrow pers. comm.). However, adult densities are not closely related to damage (Treverrow *et al.* 1992) and crop sanitation (targeting adults) does not appear to be very effective (Gold *et al.* 1999c; Masanza 2003). Uncertainty in the level of intrinsic mortality in egg and larval stages of the insect also exists (Gold *et al.* 1999c). The influence of density processes in oviposition and larval success also needs to be clarified (Gold *et al.* 1999c). As a result, Gold *et al.* (1999c) regard targeting larvae to have a greater effect than targeting adults.

1.4.1 Monitoring (sampling)

1.4.1.1 Adult trapping

Traps are commonly made from pseudostem and/or rhizome material, which are effective in attracting adults (Hord & Flippen 1956; Stover & Simmonds 1987). Several trap designs are known, (Hord & Flippen 1956, Castrillon 1989, 1991, cited in Gold *et al.* 2003, Batista Filho *et al.* 1990, Collins *et al.* 1991, Treverrow *et al.* 1992, Price 1993, Raga & De Oliveira 1996; Aranzazu *et al.* 2000, cited in Gold *et al.* 2003), but disk-on-stump traps, pseudostem-disk traps and split-pseudostem traps are the most common (Yaringano & van der Meer 1975, Mitchell 1978, Koppenhöfer 1992, Treverrow *et al.* 1992; Gold *et al.* 1999d). The former is constructed by using a pseudostem disk (Ostmark 1974, Mitchell 1978, 1980, Stover & Simmonds 1987;

Price 1993), rhizome slice or leaf to cover the cut surface of a plant harvested at the rhizome (Gold *et al*. 1999d). Disk traps consist of a transverse section (usually 100 mm wide) of a fresh pseudostem placed next to the base of the plant (Treverrow *et al*. 1992). A split-pseudostem trap is a pseudostem cut into a 15-100 cm (usually 30 cm) section, split longitudinally and placed next to the mat of a plant with the ventral surface facing the soil (Simmonds 1959, Bujulu *et al*. 1983, Arleu *et al*. 1984, Batista Filho *et al*. 1990, Gowen 1995; Gold *et al*. 1999d). Traps are commonly covered with mulch material to delay desiccation. Pseudostem traps are preferred due to their mobility, availability and relative ease of preparation. Recommendations on trap inspection vary, but are usually within a week of placement (Wallace 1938a, Cuillé 1950, Hord & Flippen 1956, Simmonds 1966, Mitchell 1980, Treverrow 1985, Stover & Simmonds 1987, Treverrow *et al*. 1992; Gowen 1995). Disk traps are recommended at 50 traps per hectare (Treverrow *et al*. 1992) or at the base of every plant (Mitchell 1978, Price 1995c; Pinese & Elder 2004), while split-pseudostem trap density varies from approximately 10 to 60 per hectare (Vilardebó 1960, Allen 1989, Treverrow *et al*. 1992, De Jager 1993, Sponagel *et al*. 1995, cited in Gold *et al*. 1999c; Castrillon 2000, cited in Gold *et al*. 2003).

The attraction mechanism is based on the search for food and shelter and/or kairomone attraction (Simmonds 1966, Budenberg *et al*. 1993b, Ndiege *et al*. 1996a, Braimah 1997; Braimah & van Emden 1999). Kairomones are allelochemicals that convey interspecific information to the benefit of the receiver and disadvantage of the producer (Dicke & Sabelis 1988, Gullan & Cranston 1994; Tinzaara *et al*. 2002). Whilst the chemistry of the kairomones involved is unclear, monoterpenes (alpha-pinene, beta-pinene, beta-myrecene and limonene) and sesquiterpenes (alpha-cubebene, alpha-copaene, beta-caryophyllene and alpha-humulene) have been reported as major components from pseudostem volatiles (Githumo banana) (Ndiege *et al*. 1991). Terpene compounds were also identified from substances released by pseudostems and corms (Lemaire 1996). Ndiege *et al*. (1996a) identified an attractive compound, 1, 8 Cineole, in susceptible or tolerant bananas, which was absent in resistant varieties. Specific lipophilic and annalose-11 volatiles (Valery cultivar) were also reported to be attractive (Jones 1968). A synthetic mixture of monoterpenes and sesquiterpenes have, however, been reported to elicit weak or no weevil responses, and minor components have been suggested to hold the key to attraction (Budenberg

et al. 1993b; Braimah 1997). An enzyme-mediated process potentially develops attractive odours in leaves (Braimah & van Emden 1999).

Male banana weevils produce an aggregation pheromone (conveying intraspecific information) via the intestines that attracts males and females (Budenberg *et al*. 1993a). The host plant stimulates (Lemaire 1996; Braimah 1997), while female presence inhibits pheromone production (Lemaire 1996). The major volatile component of the pheromone has been identified, named sordidin (Beauhaire *et al*. 1995) and the natural configuration determined as (1S, 3R, 5R, 7S)-(+)-1-ethyl-3.5.7-trimethyl-2.8-dioxabicyclo[3.2.1]octane (Mori *et al*. 1996; Fletcher *et al*. 1997). Large-scale synthesis of racemic sordidin has been developed (Ndiege *et al*. 1996b; Jayaraman *et al*. 1997) and sampling adults with commercially available pheromones are less labour intensive, with only one trap per hectare required (Anonymous 2004).

Pseudostem- and rhizome-based trapping systems have mostly been used for population dynamics studies (Mitchell 1980, Arleu *et al*. 1984, Price 1995c; Schoeman 1996) and were singularly used for quantifying treatment effects (Mitchell 1978; Price 1995c) before the development of damage assessments. Attractiveness of traps depends on material, size, density, placement, trap age, collection interval, cropping system and weather (Vilardebó 1973, Ostmark 1974, Delattre 1980, Pavis 1988, Ogenga-Latigo & Bakyalire 1993, Gold *et al*. 1994b; Price 1995c). Catches of traps do not necessarily provide population size or tendencies, but probably sample the activity patterns of a selected proportion of the total weevil population. Therefore, trapping may not provide accurate estimates (Seshu Reddy *et al*. 1993) or allow for between-study comparisons.

1.4.1.2 Damage assessments

The Coefficient of Infestation (CI) was developed to quantify banana weevil damage to plants and involved the superficial annular decortication of the rhizome with a coefficient value assigned based on the proportion of the rhizome circumference with weevil galleries (Vilardebó 1973). The CI was subjective and the scoring method was modified and named the Percentage Coefficient of Infestation (PCI) (Mitchell 1978, 1980). The PCI involves scoring the presence/absence of peripheral damage for ten sections, each covering 18° of the corm surface. Modifications of the method have also been used; where a 10 by 10 cm plate, divided in nine equal sections, was used to

rate damage from 0-9 (Mesquita 1985; Smith 1995). The principle of scoring specific areas on the corm periphery is dependant on tunnel distribution and can saturate quickly, underestimate clumped damage (Ogenga-Latigo & Bakyalire 1993) and/or score damage not derived from weevils (Gold *et al*. 1994b).

Bridge & Gowen (1993) suggested a 10 cm wide peripheral paring of the rhizome and then scoring the percentage of total exposed tissue occupied by tunnels, divided in four classes: no damage, slight damage (<10% tunnels), moderate damage (11-30% tunnels) and severe damage (>30% tunnels). Also by paring a fresh rhizome, damage has been divided in categories of absent (no galleries), light (1-5 galleries), medium (6-10 galleries) or heavy (>10 galleries) (Treverrow *et al*. 1992, Treverrow 1993). The latter two categories are associated with plants snapping at the base under windy conditions, but medium damage is only half as likely to snap as heavy damage (Treverrow *et al*. 1992). Tunnelling on the corm surface (CI and PCI) is generally not a good indicator of weevil damage (Taylor 1991, Rukazambuga 1996; Gold *et al*. 2005b), because the cortex is preferred (Moznette 1920; Ittyeipe 1986) and the ability to penetrate the corm is cultivar related (Speijer *et al*. 1993; Kiggundu 2000). Taylor (1991) suggested a presence/absence system for a circular grid divided in five sub-circles of equal area applied to transverse sections of the rhizome. Each sub-circle is allocated a score of 20, with circles having fewer subdivisions closer to the centre to compensate for central damage having a greater effect on fruit production (Taylor 1991). Correlations between external and internal damage are low (Gold *et al*. 1994b, 2005), but it is relatively specific between cultivars (Ogenga-Latigo & Bakyalire 1993). Damage to the central cylinder has a greater effect on bunch weight than damage to the corm surface or cortex of highland cooking bananas (Rukazambuga 1996; Gold *et al*. 2005b). The percentage of plants infested can be closely correlated to damage assessments of individual plants and has been recommended as the simplest indicator of weevil infestation (Mestre 1997). According to Gold *et al*. (1994b), using a PCI grid at different depths does not increase accuracy, and cross sectional damage assessments are more appropriate due to relative ease, low susceptibility to bias and less damage caused to the banana mat. All assessments of plant damage are usually conducted at harvest (scoring accumulated damage) and therefore do not sample the time of attack.

Damage estimates can be subjective, thresholds misleading, unique for a given banana type or cultivar and values specific to compare treatment effects (Smith 1995;

Gold *et al*. 2003). Alternatives may also be considered in quantifying damage and larval occurrence. X-ray radiographs were used to screen mango fruit for weevil tunnels (Thomas *et al*. 1995). Even though this approach is expensive and portable x-ray machines might be required to screen banana rhizomes, the method theoretically provides rapid, accurate, holistic damage estimates of any age plant without damaging the mat or the plant.

1.4.1.3 Economic thresholds

Adult monitoring is usually recommended after rain during spring and autumn in the subtropics (Treverrow *et al*. 1992). Action threshold has been set at one (Bullock & Evers 1962), two (Collins *et al*. 1991, Treverrow *et al*. 1992; Smith 1995), four (Pinese & Piper 1994) and more than five weevils per Cavendish pseudostem-disk trap (Treverrow *et al*. 1992). Poison traps are recommended at two and butt spraying or replanting at more than five weevils per trap (Treverrow *et al*. 1992). In the Windward Islands, two and in Honduras 15-20 weevils per split-pseudostem trap indicates action threshold (Vilardebó & Ostmark 1977; Mitchell 1978). Thresholds may be unique between cultivars and most studies did not relate trap catch to yield losses. According to Gold *et al*. (2003), available thresholds are questionable. Adult densities have been correlated with damage levels (Vilardebó 1973, interpreted from Mitchell 1980, Ogenga-Latigo & Bakyalire 1993, Mestre & Rhino 1997; Hasyim & Harlion 1998), but explained less than 50% of the variation observed (Speijer *et al*. 1993).

According to Vilardebó (1960), action threshold has been attained if the percentage of plants with signs of peripheral weevil damage exceeds 10%. Vilardebó's coefficient of infestation, when greater than 25%, equates to 30-60% yield loss (Vilardebó 1973). Using the CI method, action threshold in Cameroon is when one of 20 plants sampled per hectare is attacked (Fogain *et al*. 2002). By the damage rating method of Smith (1995) and Mesquita (1985), the action threshold is from two to four (Smith 1995). Treverrow *et al*. (1995) set the action threshold when 10% of plants were damaged by 10 or more tunnels after sampling approximately 1% of plants. Areas (sampling 20-40 plants per hectare) with one or more plants having six to 10 tunnels could be treated by chemical baiting, while more than 10 tunnels in two to four plants merit chemical treatment (Treverrow *et al*. 1992). No density treatment thresholds have been reported for South Africa. Threshold values are

disputed and comparisons are troublesome, since specific calculations are not revealed, pest status is variable and/or nematode damage is not partitioned. A clear relationship between adult density, rhizome damage and yield needs to be determined (Ostmark 1974, Treverrow 1993, Stanton 1994, Gowen 1995; Gold *et al*. 1998).

1.4.2 Host resistance

Plant resistance is considered a safe and long-term control strategy for the banana weevil (Seshu-Reddy & Lubega 1993) within the IPM framework (Sikora *et al*. 1989). Host plant resistance to banana weevil has recently been reviewed by Kiggundu (2000). Historically all cultivars were thought to be similarly attacked by *C. sordidus* (Jepson 1914; Cuillé 1950). Currently, however, plantains (AAB), highland cooking bananas (AAA-EA) and *Ensete* are generally regarded to be more susceptible and dessert bananas (especially AAA) less so, with other cultivars in-between (Simmonds 1966, Haddad *et al*. 1979, Jones 1986, Mesquita & Caldas 1986, Stover & Simmonds 1987, Sikora *et al*. 1989, Seshu Reddy *et al*. 1992, Speijer *et al*. 1993, Fogain & Price 1994, Gold *et al*. 1994b, Pavis & Lemaire 1996, Gold & Messiaen 2000, Fogain *et al*. 2002; Kiggundu *et al*. 2003). Susceptibility in the Eumusa varies and some reports are contradictory. *Musa acuminata* and *M. balbisiana* usually escape attack (Fogain & Price 1994), but in some areas *M. acuminata* is susceptible (Simmonds 1966; Viswanath 1981). Cavendish shows relative high tolerance in India (Viswanath 1977) and low susceptibility in Uganda, Cameroon, South and Central America (Gowen 1995; Kiggundu *et al*. 2003), while it is highly susceptible in Australia (Stanton 1994), the Philippines (Davide 1994) and South Africa (Govender & Viljoen 2002). Inter-group and even inter-subgroup susceptibility variations are also common within the AAA genome, with cooking and beer types more susceptible than sweet types (Seshu Reddy & Lubega 1993). In Australia cv. Mysore (AAB), Pisang Ramo (AAB), Kuma Kuma (AA) and Kluai Khai Bonng (AAA) are resistant and Lady Finger (AAA) is less susceptible to toppling than Williams (AAA) (Stanton 1994). In the Philippines one Cavendish cultivar (Saba) also show resistance (Davide 1994) and in Honduras, Gros Michel (AAA) is more susceptible than Lacatan (Cavendish, AAA) (Hord & Flippen 1956).

Three general resistance mechanisms of plants were originally defined by Painter (1951): antixenosis (non-preference), tolerance (normal development in

presence of the pest) and/or antibiosis (negative effect on insect biology). These terms are not always biologically discrete entities (Smith 1989).

Antixenosis has been suggested in *Musa* (Gowen 1995) and the weevil has a preference and is able to differentiate plantain from other varieties (Padmanaban *et al*. 2001). Traps of AAB plantain are more attractive than AAA genome plants (Price 1993). Budenberg *et al*. (1993b) also reported lower adult weevil responses to resistant AB than to susceptible AAA-EA clones and an attractive compound, 1,8 Cineole, has been found in susceptible or tolerant bananas but was absent in resistant varieties (Ndiege *et al*. 1996a). Resistant and susceptible bananas were also found to be equally attractive (Pavis & Minost 1993) and relatively resistant varieties were even more attractive than some susceptible types (Gold & Bagabe 1997). Resistant clones deter adult feeding (Pavis & Lemaire 1996), thereby reducing ovipositional pressure. Hence, if there is antixenosis in banana, it does not necessarily take effect during host location. Tolerance has been suggested in varieties with relatively large corms (Gros Michel AAA) (Cuillé & Vilardebó 1963) or with vigorous growth (Pisang Awak, ABB and Cavendish, AAA) (Pavis 1993, Gowen 1995, Seshu Reddy *et al*. 1999; Pinese & Elder 2004). Increased plant growth rate in northern Queensland versus Southeast Queensland (Australia) rendered weevils economically unimportant (Pinese & Elder 2004). Vilardebó (1960) reported that the AAA cultivar Gros Michel is more susceptible than Cavendish varieties because of differences in timing of attack and corm size. A negative correlation between corm hardness and infestation has been reported (Pavis 1993; Pavis & Minost 1993), but were absent in other studies (Ortiz *et al*. 1995; Kiggundu 2000). Antibiosis is considered the most important in plant resistance to the banana weevil (Fogain *et al*. 2002; Gold *et al*. 2003) and can be related to the absence of essential nutrients or compounds that inhibit weevil development (Ortiz *et al*. 1995). Resistant plants have been shown to have lower larval survival and development rates (Mesquita *et al*. 1984, Mesquita & Caldas 1986, Seshu Reddy 1992, Seshu Reddy & Lubega 1993, Lemaire 1996, Abera 1997, cited in Gold *et al*. 1999c, Abera *et al*. 2000; Kiggundu 2000). Some variation also exists, as larval growth and development on some AAA varieties were faster than on others (Mesquita *et al*. 1984; Gowen 1995). Kiggundu (2000) and Gold *et al*. (2003) suggested that cultivars with the B genome have an antibiosis mechanism, whilst resistant AA or AAA has other mechanisms of resistance. There is however

often an overlap and difficulty in separating antibioses from antixenosis (Smith 1989).

Contradictions in reports are probably caused by differences in ecology, methodology (Pavis & Lemaire 1996), management (Gold *et al.* 1994b) and weevil biotypes (Fogain & Price 1994; Gowen 1995). The perception of the modality of weevil plant resistance depends on experimental design, planting material, age and growing habits of plants. Host choice within a replicate should be reserved for antixenosis, but not for antibioses or tolerance testing (Smith 1989). *In vitro* plants are more susceptible to *C. sordidus* (Nuno & Ribeiro 2002) and more prone to high mat (Robinson 1996). Plantains are also highly susceptible to high mat (Wilson 1983; Stover & Simmonds 1987), exposing the rhizome above ground level much sooner than other varieties. Consequently, more eggs are laid in the rhizome (Abera *et al.* 1999). The cause of high mat is uncertain. In plantain in West Africa it reflects plant stress, including low soil fertility and high pest pressure (Swennen 1984). High mat is also related to the tendency of plants to produce successive shoots closer to the soil surface (Simmonds 1959) and consequently, in Uganda (Abera *et al.* 1999) and South Africa, it is most common in ageing plantations.

Primary sources of resistance are found in Yangambi Km5, FHIA-03 (or its parents) and some diploid hybrids, including Calcutta-4, TMB2x8075-7, TMB2x7197-2 and TMB2x6142-1 (Pavis & Lemaire 1996, Gold & Messiaen 2000; Kiggundu *et al.* 2003). The banana weevil has only recently been incorporated in breeding programmes (Kiggundu & Gold 2002), mainly because of difficulties in rearing the insect, in developing an infestation method and a criterion for early assessment of plant susceptibility (Pavis & Lemaire 1996).

1.4.3 Cultural control

Cultural control is an important strategy, especially for subsistence and organic farmers. It is based on the manipulation of the weevil habitat to adversely affect the pest and promote the banana plant. Cultural control practises are considered important and under certain conditions has been reported to keep weevil populations and damage at insignificant levels (Simmonds 1959).

1.4.3.1 Crop establishment

Uninfested plants are widely recommended as propagating material to prevent the spread of the weevil and reduce damage, as eggs and larvae can be disseminated in infested planting material. If suckers are used, rhizomes should be trimmed and pared (Franzmann 1972; Fogain *et al*. 2002). Hot water treatment of suckers is also recommended (Gettman *et al*. 1992), but can be problematic (Gold *et al*. 1998). In South Africa commercial growers mainly use *in vitro* planting material (Robinson 1996). Tissue culture plants are free of banana weevils and nematodes (Robinson 1996), making them ideal to 'start clean, stay clean' (Peasley & Treverrow 1986). All banana plant material should be removed from fields to be replanted and left fallow or used for annual crops for a minimum of 1 year (Seshu Reddy *et al*. 1993), but 18 months (Treverrow *et al*. 1992) or 2 years are preferred. New plantings should preferably be in virgin soil and/or removed from infested fields. Deep planting (45-60 cm) lower weevil incidence and delay infestation (Seshu Reddy *et al*. 1993). *Tephrosia* spp. and neem (*Azadirachta indica* A. Juss.) have a repellent effect (Walangululu *et al*. 1993), while the latter also negatively affects the physiology of the weevil (Musabyimana *et al*. 2001), thereby helping to prolong re-infestation rates of new plantings (Musabyimana 1999; Fogain *et al*. 2002). Intercropping with coffee has also been reported to reduce weevil numbers (Kehe 1988) and susceptible banana cultivars and residues can serve as trap crops in multi-cultivar stands (Masanza 2003). In South Africa plant crop bananas are sometimes intercropped with winter brassica crops, with no adverse effects on either crop (Robinson 1996). Intercropping with Macadamia nut trees are also practised.

Re-infestation from neighbouring plantations, inadequate fallow periods, growing habits (Robinson 1996) and susceptibility of *in vitro* plants to *C. sordidus* may, however, negate their advantage (Nuno & Ribeiro 2002). Not all plant varieties benefit from deep planting, as plantains will produce a new rhizome above the previous one (Seshu Reddy *et al*. 1993). High rates of powdered neem are phytotoxic (Musabyimana *et al*. 2000) and it is not effective as a curative treatment (Fogain *et al*. 2002). Intercropping with coffee has not been scientifically investigated and most crops will be of limited value after the first season due to the closing of the banana canopy (Seshu Reddy *et al*. 1993). Intercropping with sweet potatoes, maize or groundnut does not reduce weevil population growth and the former two crops compete for nutrients and reduce banana yield (Uronu 1992). According to Gold *et al*. (1999c), intercropping will have limited potential to control the banana weevil,

since most of the reported mechanisms by which diversified systems reduce herbivore attack, including higher efficacy of natural enemies, effects on immigration/emigration rates and modification of micro-environments are not relevant to the insect.

1.4.3.2 Crop management

Covering the base of stools with soil mounds up to 30 cm high were associated with low weevil infestations in the Ivory Coast (Kehe 1988), while covering post harvest stumps in Uganda reduced weevil oviposition (during the wet season) in Uganda (Gold *et al*. 2005a). The additional soil assists in delaying high mat formation and providing firm anchorage for the plant (Seshu Reddy *et al*. 1999). Felling pseudostems at ground level (Simmonds 1959; Annecke & Moran 1982) and diligent crop hygiene, the destruction or removal of accumulating crop trash and fallen plants, are also recommended to minimise additional sheltering and breeding sites of *C. sordidus* (Peasley & Treverrow 1986, Collins *et al*. 1991, Treverrow *et al*. 1992; Fogain *et al*. 2002). Desiccation rate is increased by cutting debris in a longitudinal fashion (Treverrow *et al* 1992). The area around plants should be free of trash and remnants placed in the inter-row (Stanton 1994). Sound horticultural practises, especially weed control (Ostmark 1974, Annecke & Moran 1982; Fogain *et al*. 2002), fertilising, mulching, desuckering, propping (Seshu Reddy *et al*. 1999; Fogain *et al*. 2002), nematode control and irrigation also reduce the impact of the banana weevil (Treverrow & Maddox 1993, Pinese & Piper 1994; McIntyre *et al*. 2003) and increase host plant vigour. Desuckering lead to more sturdy plants and propping reduce snapping and toppling (Seshu Reddy *et al*. 1999).

The efficacy of some of these methods is uncertain. The effect of a soil mound cover on weevil damage has not been scientifically evaluated and harvesting at a 2 m versus 0.1 m height in uninfested plantations increased bunch mass on the follower by 12% and decreased time to the next harvest by 5% compared to cutting low (Daniells & O'farrell 1987). Leaving most of the pseudostem standing at harvest has also been recommended; only cutting old decayed plants at ground level and splitting them longitudinally (Treverrow *et al*. 1992). The efficacy of other sanitation practises are questionable, because one of the most important sources of pest populations (residual corms) are not amendable to crop hygiene (Treverrow & Maddox 1993), since removal of the rhizome is labour intensive and will weaken

followers by reducing the support of the mat. A reduction in weevil numbers has been reported when uprooted rhizomes are cut longitudinally in four pieces to increase the rate of desiccation (Nanne & Klink 1975). Residues also serve as traps, being more attractive to egg laying females than standing plants (Waterhouse & Norris 1987, Gold *et al*. 1999c; Masanza 2003). Double the number of weevils complete development in toppled compared to standing plants because of greater ovipositional accessibility to softer corm material and an increased oviposition area (Treverrow *et al*. 1992). Immature and adult weevils are more abundant on residues of low sanitation (residues left standing or not destroyed) compared to high sanitation (residues destroyed weekly) and developmental rate is positively related to residue age in Uganda (Masanza 2003). High sanitation levels increase yield and reduce damage and adult densities after about 2 years (Masanza *et al*. 2005), but in closed systems a reduction in yield can be found, probably because of increased weevil attack on growing plants (Masanza 2003). In these closed systems more than 4 years may be required before results are evident (Masanza 2003). Movement of mulch to the inter-row and cutting-up of harvested pseudostems over 4 years do not reduce adult numbers or plant damage ratings (Smith 1995). In Uganda, recession of mulch more than 1 m from the pseudostem compared to mulching to the base of the pseudostem over 3 years, did not significantly reduce weevil density or damage to the plant (McIntyre *et al*. 2003). Mulching of plantations increase damage (Uronu 1992, Rukazambuga 1996; McIntyre *et al*. 2003), but also help with water conservation, regulation of soil temperatures, erosion prevention, weed control and provision of organic manure in decomposition that can more than compensate (especially in varieties showing tolerance) for additional damage by *C. sordidus* (Wallace 1938b, Seshu Reddy *et al*. 1999; McIntyre *et al*. 2003). However, even at low weevil damage levels, production of cooking bananas in Uganda was not economically increased through the use of mineral fertiliser and/or organic mulch (Ssali *et al*. 2003). Grass mulches increase damage (Braimah 1997), while potentially repellent green manures do not influence weevil density or damage (Gold *et al*. 1999d). Application of cultural management methods is also problematic due to labour requirements. All commercial farmers interviewed (12% of total) at the South Coast of KwaZulu-Natal (South Africa) regarded residues as weevil breeding grounds, but only 53% of those farmers were willing to remove residues (Dochez 1998). Farmers believed standing residues “feed” followers (Treverrow & Bedding

1993) and that the method was too labour intensive (Dochez 1998). Regular weed control, leaf removal, desuckering and propping of bunch bearing plants are, however, commonly practised.

1.4.3.3 Mass trapping

Trapping as a control method exclusively targets adults, relying on using the most effective trapping material and assuming that the removal of adults from a population will reduce damage to plants. Traps prepared from the basal (proximal) end of pseudostems are more attractive (Mestre & Rhino 1997). It is uncertain if rhizome or pseudostem-based traps are most attractive (Edwards 1925, cited in Schmitt 1993, Cuillé 1950, Moreira *et al*. 1986, cited in Gold *et al*. 2003, Sumani 1997; Reyes-Rivera 2000) and if fresh or decaying material should preferentially be used (Hord & Flippen 1956, Budenberg *et al*. 1993b; Koppenhöfer *et al*. 1994). Recently dead banana leaves were reported to be more attractive than pseudostem and rhizome material (Braimah 1997; Braimah & van Emden 1999), while dead leaves of yam and cocoyam were found to be more attractive than dead banana leaves (Braimah & van Emden 1999). Bulb volatiles have also been reported to be more attractive than those of pseudostems (Cerda *et al*. 1995). Traps of AAB plantain are more attractive than AAA genome plants (Price 1993; Seshu Reddy *et al*. 1993), but the latter show inter-varietal differences (Hord & Flippen 1956; Filho *et al*. 1990). Healthy corms and pseudostems were more attractive than those damaged by weevils (Cerda *et al*. 1995). Plant material trapping is labour intensive and material is not always available. In localities with tropical climates, pheromone-based trapping systems have been shown to be much more effective than plant material traps (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997; Tinzaara *et al*. 1999, 2003) and combination of pheromone and kairomone substances produce an additive response (Tinzaara *et al*. 2003). Semiochemical use has, therefore, been recommended as a weevil control method (Seshu Reddy *et al*. 1999; Tinzaara *et al*. 2002). In South Africa, split-pseudostem traps are used exclusively and the relative efficacy of pheromone traps is unknown and it possibly depends on plant trap variety, crop management, climate, season and weevil biotype.

Trapping as a control method for *C. sordidus* is disputed (Vilardebó 1950, Ostmark 1974, Arleu *et al*. 1984, Stover & Simmonds 1987, Seshu Reddy *et al*. 1993, Koppenhöfer *et al*. 1994, Seshu Reddy *et al*. 1995, Alpizar *et al*. 1998, Gold *et*

al. 1998, Fogain *et al*. 2002, Nuno & Ribeiro 2002; Tinzaara *et al*. 2005) and can be better used for monitoring (Treverrow *et al*. 1992). Only a small proportion of the population (5-15%) is attracted to traps (Mitchell 1980). Variable results and disputes over the efficacy of trapping result from most studies not utilising controls (Gold *et al*. 2003) or experimental designs being prone to pseudo-replication (particularly replication at an incorrect level). In controlled studies, intensive split-pseudostem trapping has been shown to significantly reduce *C. sordidus* damage after 1 year (Gold *et al*. 2002b). Control efficacy appears to be negatively related to population density (Seshu Reddy *et al*. 1999) and depends on trap density (Fogain *et al*. 2002; Tinzaara *et al*. 2005), crop management and immigration (Gold *et al*. 2002b, 2004b). There is also a suspected time lag between the onset of trapping, reduction in adult density and reduction in damage levels (Gold *et al*. 1999d).

1.4.4 Biological control

1.4.4.1 Classical biological control

Classical biological control involves the search for specific natural enemies in a pest's area of origin, assuming the pest to be under control by the co-evolved natural enemies in their endemic range (Hasyim & Gold 1999). It is regarded important and feasible because of the assumed shared centre of origin (Indo-Malaysian region) between the weevil and its host (Stover & Simmonds 1987; Koppenhöfer & Schmutterer 1993). The weevil appears to be less important in Malaysia (Neuenschwander 1988), but the empirical pest status of the weevil in Asia is unsure (Vittayaruk *et al*. 1994; Hasyim & Gold 1999). Nevertheless, expeditions to find natural enemies were conducted in Malaysia and Indonesia (Jepson 1914; Froggatt 1928). Most of the species identified were generalist predators found in banana residues. Four histerid, two hydrophilid and one rhagionid species were subsequently introduced into several countries (Waterhouse & Norris 1987).

From these attempts, *Plaesius javanus* Marseul (Coleoptera: Histeridae), native to Java, Borneo and Malaysia, is considered the only species to provide banana weevil control with larvae and adults predacious on several weevil species (Simmonds 1966). Since 1914, the beetle was introduced to more than 20 countries including several introductions to eastern Australia between 1915 and 1940 (Simmonds 1966). It failed to establish in Africa, Australia and most of South America, but did establish in other localities (Simmonds 1966; Waterhouse & Norris

1987). However, only in Fiji and Tahiti does it appear to provide useful weevil control (Simmonds 1966; Waterhouse & Norris 1987). In Indonesia, weevil densities were negatively related to *P. javanus* densities (Hasyim & Harlion 1998), but at no locality has a reduction in weevil abundance been critically evaluated (Koppenhöfer 1993a). Failures of classical biological control attempts are related to inadequate studies of candidates, their potential impact on the pests and use of too little material (Koppenhöfer 1992).

1.4.4.2 Arthropod natural enemies

In pot experiments, Koppenhöfer (1993b) determined that 58% of banana weevil eggs were accessible to a complex of egg predators. From different predators identified in western Kenya, *Dactylosternum abdominale* (F.) (Coleoptera: Hydrophilidae) proved promising for providing weevil control in residual stumps, but did not feed on all weevil stages, were not pest specific and did not result in reduced plant damage (Koppenhöfer & Schmutterer 1993). The species is also widespread in the tropics, but when introduced from Malaysia to Jamaica, it failed to establish (Waterhouse & Norris 1987). No parasitoids of *C. sordidus* have been found to date, probably because eggs are not easily accessible, the larval and pupal stage are secluded in the rhizome and adults have a thick cuticle and cryptic behaviour (Koppenhöfer 1992). Some tachinid flies, however, oviposit close to the mouthparts of feeding weevils (Jacobs & Renner 1988), and phorid flies attack weevil larvae and pupae (Hasyim & Gold 1999). Parasitoids are generally more effective than predators, but ants can be an exception, being very effective foragers (Hasyim & Gold 1999). *Tetramorium guinensee* (Mayr) (synonym *T. bicarinatum* (Nylander)) and *Pheidole megacephala* Fabricius reportedly contribute to weevil control in Cuba (Roche & Abreu 1983; Castineiras *et al*. 1991a), but according to Gold *et al*. (1999c), no effective natural enemies have been found.

In South Africa the occurrence of a beetle resembling *P. javanus* have been reported (Schoeman 1996) and other potential natural enemies have been identified, including monkeys (predation observed), frogs (associated with banana mat), reduviids (associated with banana mat), carabids (associated with banana mat), dermaptera (associated with banana mat), elaterids (associated with banana mat) and formicids (occupying weevil tunnels). The ants are commonly encountered in toppled plants, fresh and rotten residues. A predatory relationship has not been investigated.

1.4.4.3 Microbial control

Microbial control has been reviewed by Nankinga (1999). Strains of the entomopathogenic fungi, *Beauveria bassiana* Balsamo and *Metarhizium anisopliae* Metchnikoff cause up to 100% mortality of the banana weevil in the laboratory (Mesquita 1988, Kaaya *et al*. 1993, Hasyim & Gold 1999, Schoeman & Schoeman 1999; Gold *et al*. 2003). Some field trials reported reductions in adult numbers (Schoeman *et al*. 1999, Nankinga & Moore 2000, Khan & Gangapersad 2001; Schoeman 2002) and others the potential of a protective treatment for suckers (Godonou *et al*. 2000). Adult numbers are not regarded as a good indicator of control potential because entomopathogenic fungi are repellent or induce avoidance and/or dispersal from a treated area (Nankinga 1999; Nankinga & Moore 2000). Some positive results have been reported (Castineiras *et al*. 1991b), but the efficacy of entomopathogenic fungi under field conditions relating to damage and yield is largely uncertain, and cost effective delivery and field persistence remain troublesome (Hasyim & Gold 1999; Fogain *et al*. 2002). A strain of *B. bassiana*, registered in South Africa as a biopesticide, showed a significant reduction in adults (trapped with split-pseudostem traps) after augmentative application (Schoeman 2002). A naturally occurring white muscardine (*B. bassiana*) has been observed on dead *C. sordidus* adults in South Africa. Endophytes (non-pathogenic *Fusarium* spp.) have also been identified and shown to cause weevil larvae and egg mortality (Griesbach 1999; Sikora *et al*. 2000). It has been successfully inoculated into tissue culture plants (Griesbach 1999), but the level of control it provides in the field is unclear (Gold *et al*. 2003).

Strains of the entomopathogenic nematodes of the Heterorhabditidae and Steinernematidae have shown control potential, especially against weevil larvae (Kermarrec *et al*. 1993). *Steinernema carpocapsae* (Weiser) applied into cuts or holes made in residual rhizomes caused significant mortality of larvae (Treverrow *et al*. 1991). In laboratory studies, *Steinernema* spp. has been reported to cause 100% larval mortality and a 70% reduction in plant damage (Figueroa 1990), while larval mortality of 37% was found in greenhouse trials (Peña *et al*. 1993). Application methods to target these immatures are troublesome (Treverrow & Bedding 1993). *Heterorhabditis* sp. (HT2-Trinidad strain) and the commercial strain *S. carpocapsae* (All-Biosafe®) have proved promising against adults and larvae (Sirjusingh *et al*.

1991; Schmitt *et al*. 1992). In Australia *S. carpocapsae* BW proved most promising to control adults, while other strains (*H. zealandica* Poinar and *Heterorhabditis* D1) performed much better in Tonga (Parniski *et al*. 1990; Treverrow & Bedding 1993). Field studies with *S. carpocapsae* BW in New South Wales (Australia), applied in cone shaped holes made in residual corms, showed it reduced damage to a similar extent as chemicals (prothiophos) (Treverrow & Bedding 1993), even though *H. zealandica* and *Steinernema carpocapsae* BW did not prove effective in Queensland (Australia) field trials utilising a spike-hole application method (Smith 1995).

More effective entomopathogen delivery systems need to be developed and the use of semiochemicals have been suggested (Budenberg *et al*. 1993a; Tinzaara *et al*. 2002). Field transmission of entomopathogens between weevils has been suggested (Schoeman 2002), but it needs to be clarified to validate the development of semiochemical infection traps instead of pitfall traps (Gold *et al*. 2003). Field efficacy of biopesticides still needs to be improved and chemical pesticides are currently considered more economical and more efficient than microbial control for high weevil infestations (Treverrow 1994; Smith 1995).

1.4.5 Chemical control

Initially, chemical control of the weevil consisted mainly of Paris Green, followed by the use of the organochlorines BHC, DDT and others (Froggatt 1925, Cuillé 1950, Simmonds 1966; Treverrow *et al*. 1992). The chemicals were usually applied with flour or other substances as baits (Froggatt 1925, Cuillé 1950, Simmonds 1966; Treverrow *et al*. 1992). The method was not very effective (Simmonds 1966) and the persistent cyclodienes, dieldrin and aldrin, showed high efficacy as a soil treatment against the banana weevil (Braithwaite 1958). The former was used extensively around the world from the mid 1950's (Edge 1974) and was found to be effective up to 2 years after application (Braithwaite 1967). Before 1970, however, resistance in cyclodienes was widely diagnosed (Anonymous 1969, Vilardebó 1967; Shanahan & Goodyer 1974). Investigations into alternative chemicals (mainly organophosphates and carbamates) showed chlordecone (organochlorine), pirimiphos-ethyl, chlorpyrifos, prothiophos and ethoprophos as viable at biannual applications, but diazinon was unsuitable because of its short residual action (Wright 1977, Collins *et al*. 1991; Smith 1995). Aldicarb, terbufos, carbofuran, carbosulfan, oxamyl,

fenamiphos (Román *et al*. 1979, Cárdenas 1984, De Jager *et al*. 1991, Vittayaruk *et al*. 1994, Chavarria-Carvajal & Irizarry 1997; Fogain *et al*. 2002), isofenphos, isazofos (Bujulu *et al*. 1983), phoxim (Nuno & Ribeiro 2002) tebupirimiphos, cadusafos (Quilici 1993), phorate, disulfoton, quinalphos (Viswanath 1977), fosthiazate (Chabrier *et al*. 2002), acephate, diethyl, pada, monocrotophos, deltamethrin (pyrethroid) (Maolin 1994), fipronil (phenyl pyrazole) (Price 1995c; Fogain *et al*. 2002) and bifenthrin (pyrethroid) (Smith 1995) were also found to be effective. Less than 10 years after widespread organophosphate use in Australia, resistance to pirimiphos-ethyl, prothiophos, chlorpyrifos and ethoprophos were reported in Queensland and New South Wales with evidence of cross resistance to oxamyl but not to carbofuran, isazofos or isofenphos (Collins *et al*. 1991). Subsequently soil applications of bifenthrin were found to be effective, but fipronil, carbosulfan and furathiocarb were similar to untreated controls in Southeast Queensland (Smith 1995). Resistance to carbofuran has not been found in Uganda or Australia (Collins *et al*. 1991; Gold *et al*. 1999a). The high rate of resistance development was attributed to widespread, regular applications with no population monitoring (Collins *et al*. 1991).

Chemical control with mostly non-systemic pesticides is mainly directed against adults (Simmonds 1966, Wright 1977; Collins *et al*. 1991). Dipping corms in insecticide solution were significantly more effective than hot water treatment (Cardenas Murillo *et al*. 1986). Chemical application is commonly recommended in planting holes (Franzmann 1972, Anitha *et al*. 1992; Fogain *et al*. 2002), to plant traps (bait spraying) (Treverrow *et al*. 1992) and to the bases of banana plants (butt sprays) (Braithwaite 1958, Bujulu *et al*. 1983, Collins *et al*. 1991, Smith 1995; Fogain *et al*. 2002). In the subtropics, these treatments are applied in spring and autumn (Froggatt 1926, Franzmann 1972, Treverrow 1985; Treverrow *et al*. 1992). Poison traps save on insecticide, but are regarded as being relatively ineffective (Simmonds 1959), especially at high infestation levels (Treverrow *et al*. 1992). Butt sprays are especially detrimental to beneficial insects and only target adults in close vicinity of plants (Collins *et al*. 1991). Soil application of systemic chemicals (dimethoate, omethoate, aldicarb, carbofuran, carbosulfan, fenamiphos, fosthiazate, isazofos, monocrotophos, oxamyl, phorate, terbufos (Gold *et al*. 2003)) can potentially also control larvae. These chemicals provide a protective treatment for plants, but have relatively shorter residual actions (Treverrow *et al*. 1992) and do not

prevent attacks on plant residues after harvest (Treverrow pers. comm.). Dual action insecticide-nematicides with systemic action will be of value to treat moderate weevil infestations when nematode densities also require treatment (Treverrow *et al*. 1992). Application strategies in Australia currently consist of butt spraying during spring and autumn (Treverrow *et al*. 1992). Bait sprays are applied to fresh residues every 2nd or 4th week in spring and autumn, and chemicals are injected into residual pseudostems during winter (Stanton 1994, Treverrow *et al*. 1992; Treverrow pers. comm.).

In South Africa, late summer and early spring butt application of pirimiphos-ethyl and aldicarb has been recommended (Jones & Dieckmann 1982). Pirimiphos-ethyl was used until the mid 1990's (Schoeman 1996) and imidacloprid and prothiofos were likely used in 1999 (Schoeman *et al*. 1999). Locally the pesticides aldicarb, terbufos and oxamyl were also reported to be effective in controlling the banana weevil and the pratylenchid nematode, *Radopholus similis* (Cobb) (Burrowing nematode) (De Jager *et al*. 1991). Schoeman (1998) reported that fenamiphos and cadusafos showed promise to control the weevil in a field trial. Results of Dochez (1998) showed that neither terbufos, fosthiazate, aldicarb nor cadusafos reduced weevil damage locally. Only aldicarb is registered for control of the banana weevil and nematodes in South Africa (Nel *et al*. 2002; Anonymous 2005b). Soil around the plants is treated and application is recommended at planting, during November (late spring) and March (late summer/early autumn). According to Quilici (1993) and Schoeman (1998), aldicarb does not provide sufficient control of the weevil and growers have also reported treatment failures. Some desperate growers have even resorted to illegal and unregistered chemical usage (Dochez 1998).

Chemical control needs to be linked to monitoring programmes and other control methods to delay resistance development. Fipronil and carbofuran have been shown not to affect the viability of *B. bassiana* (Batista Filho *et al*. 1996) and *Steinernema* species are relatively tolerant to organophosphates and carbamates (Sirjusingh *et al*. 1991). Chemical control can, therefore, form part of an IPM system for *C. sordidus*.

1.5 Conclusions

Banana weevil research can generally be divided in two categories, correlating with the food production systems of *Musa*: Studies conducted in areas with a tropical climate on locally consumed bananas and plantains, and studies in the tropics (and subtropics) on Cavendish bananas produced for sale or export. In the former, producers are commonly poor subsistence farmers with minimal investment in crop management. In these systems, researchers investigate control strategies that are mainly preventative and concentrate on low cost, long-term approaches such as host resistance, cultural and biological control. In contrast, Cavendish production is usually associated with commercial growers that invest heavily in crop management. Weevil control in these systems is mainly of a curative nature, concentrating on short-term approaches, especially chemical control.

Certain biological and behavioural aspects of the weevil appear to be clear, including nocturnal activity, long life span, low reproductive rate, limited mobility, rare flight, dissemination by infested plant material, interaction with kairomones and production of pheromones (Gold *et al*. 2003). Findings concerning different biotic and abiotic factors affecting the population processes of the banana weevil are, however, variable. The inconsistency in research reports between studies may reflect on banana clones, management and production systems, ecological conditions, weevil biotypes and research methodologies (Gold *et al*. 2003).

South Africa is one of only a few countries where Cavendish bananas are considered very susceptible to *C. sordidus* (Govender & Viljoen 2002). Research under local conditions, which represent a subtropical climate, specific management and production systems and possibly unique weevil biotypes is, therefore, required. To develop a successful IPM protocol, the genetic variability of *C. sordidus* needs to be assessed between and within local and international populations. The method needs to be accurate and reliable to allow for adoption in and comparison with future studies. Reports on the population dynamics of the insect are variable; it needs to be researched and the dependence on abiotic factors should be quantified. The empirical pest status of the insect is uncertain and has not been studied in South Africa. In elucidating the former locally and contribute to its global understanding, standardised assessment methods are required to allow for comparison with different areas and studies. From a management perspective, cultural control in the form of crop

management and mass trapping are best applied to local production systems, where farm land and fallow periods are limited and *in vitro* plants are mainly used for propagation. Basic field sanitation and practises promoting host vigour with low labour intensity and optimal relative efficacy are in need of research. The control potential of semiochemical mass trapping to conventional trapping methods should also be addressed under local conditions to determine the relative potential of mass trapping. Currently the applicability of biological control will be in the form of arthropod natural enemies, with formicids deserving attention in long-term future studies. Microbial control is also considered as a long-term research priority and should address the ecological impact, host specificity, delivery systems and field efficacy of inoculative and inundative application of entomopathogens. Chemicals can be the most effective means of controlling the weevil. Application of current pesticides are not proving effective and alternative application methods and chemicals with a positive environmental profile, that can function in an integrated control approach, are effective, more pest-specific, less laborious and more economical are urgently required.

In the future, for all banana systems, host resistance will aid in providing economical and sustainable management of the weevil. A better understanding of the mechanisms of host resistance are needed to lead to accurate selection criteria, which can be applied before the harvest stage to speed up breeding experiments (Gold & Messiaen 2000). Genetic transformation of bananas using foreign genes or resistance genes from *Musa* may facilitate the development of resistant clones that retain locally desirable fruit characteristics (Gold *et al*. 2003). Conventional and non-conventional breeding programmes should standardise susceptibility measures to allow for direct comparisons (Fogain & Price 1994). As a cultural control in the crop establishment phase, neem applications for weevil control merits further research (Gold *et al*. 2003). Biological control attempts should focus on parasitoids, which have proven successful in several biological control programmes and tend to have narrower host ranges than predators (Greathead 1986, Neuenschwander 1988, Herren & Neuenschwander 1991; Hasyim & Gold 1999). The efficacy of formicids as natural enemies around the world and endophytes as control agents are in need of research (Gold *et al*. 2003).

Despite the economic and environmental advantages of IPM, implementation of IPM programmes in general has been slow due to the lack of sufficient data on the

ecology of pests, knowledge required of economic injury levels for each pest of each crop and the interdisciplinary approach required to elucidate the former and latter (Gullan & Cranston 1994). Risks of damage to crops associated with IPM protocols, the apparent simplicity of regular widespread chemical applications and the necessity of training farmers and extension officers in new principles and methods also delayed the acceptance of IPM (Gullan & Cranston 1994).

1.6 References

ABERA, A.M.K. 1997. *Oviposition Preferences and Timing of Attack by the Banana Weevil (*Cosmopolites sordidus *Germar) in East African Highland Banana (*Musa *spp.)*. M.Sc. Thesis, Makerere University, Uganda.

ABERA, A.M.K., GOLD, C.S. & KYAMANYWA, S. 1999. Timing and distribution of attack by the banana weevil (Coleoptera: Curculionidae) in East African highland banana (*Musa* spp.). *Florida Entomologist* 82: 631-641.

ABERA, A.M.K., GOLD, C.S., KYAMANYWA, S. & KARAMURA, E.B. 2000. Banana weevil, *Cosmopolites sordidus* (Germar), ovipositional preferences, timing of attack and larval survivorship in a mixed cultivar trial in Uganda. *Acta Horticulturae* 487-495.

ALLEN, R.N. 1989. *Control of Major Pests and Diseases of Bananas*. Department of Agriculture, New South Wales.

ALPIZAR, D., FALLAS, M., OEHLSCHLAGER, A.C., GONZALEZ, L. & JAYARAMAN, S. 1998. Pheromone-based mass-trapping of the banana weevil, *Cosmopolites sordidus* (Germar) and the West Indian sugarcane weevil *Metamasius hemipterus* L. (Coleoptera: Curculionidae) in plantain and banana. In: *Memorias XIII Reunion ACORBAT, Guayaquil, Ecuador*. November 1998: 515-538.

ANITHA, N., CHARLES, J.S.K. & RAJAMONY, L. 1992. Effect of sucker treatment with insecticides on incidence on banana rhizome weevil (*Cosmopolites sordidus*). *Indian Journal of Agricultural Sciences* 62: 572-573.

ANNECKE, D.P. & MORAN, V.C. 1982. *Insects and Mites of Cultivated Plants in South Africa*. 67-68. Butterworths, Durban.

ANONYMOUS. 1969. Beetle borer studies. *Banana Bulletin* 33: 4.

ANONYMOUS. 1973. *Report of the Fourth Session of the FAO Panel of Experts on Integrated Pest Control. December 1972*. FAO, Rome.

ANONYMOUS. 2004. *Pheromone trapping system,* Cosmopolites sordidus *and* Metamasius hemipterus. Information pamphlet, CTI IPM products. ChemTica Internacional, S.A., Costa Rica.

ANONYMOUS. 2005a. *Abstract of Agricultural Statistics*. The Directorate: Agricultural Statistics of the National Department of Agriculture. World Wide Web: http://www.nda.agric.za/docs/abstract_2005.pdf

ANONYMOUS. 2005b. *Agricultural remedies*. National Department of Agriculture. World Wide Web: http://www.nda.agric.za/act36/AR/Insecticides.htm

ANONYMOUS. 2005c. *Banana: History of Banana Production in South Africa.* Agricultural Research Council - Institute for Tropical and Subtropical Crops. World Wide Web: http://www.arc.agric.za/institutes/itsc/main/banana/history.htm

ANONYMOUS. 2005d. *FAOSTAT,* © FAO 2004. Food and Agricultural Organization of the United Nations. World Wide Web: http://apps.fao.org/faostat/servlet/XteServlet3?Areas=202&Items=486&Elements=31&Years=2004&Format=Table&Xaxis=Years&Yaxis=Countries&Aggregate=&Calculate=&Domain=SUA&ItemTypes=Production.Crops.Primary&language=EN

ANONYMOUS. 2005e. *Major Food and Agricultural Commodities and Producers, Commodities by Country*. Food and Agricultural Organization of the United Nations, Economic and Social Department, Statistics Division. World Wide Web: http://www.fao.org/es/ess/top/country.jsp?lang=EN&country=202&pays=South+Africa&iso3=ZAF&CountryList=202&year=2004&yearLyst=2004

ANONYMOUS. 2005f. *Major Food and Agricultural Commodities and Producers, Countries by Commodities*. Food and Agricultural Organization of the United Nations, Economic and Social Department, Statistics Division. World Wide Web: http://www.fao.org/es/ess/top/commodity.jsp?commodity=486&lang=EN&year=2004

ANONYMOUS. 2005g. *Statistics on Bananas and Plantains*, *FAO 2000*. World Wide Web: http://www.inibap.org/network/statistics_eng.htm

ANONYMOUS. 2005h. *WordNet, a lexical database for the English language. Cognitive science laboratory, Princeton University, NJ*. World Wide Web: http://www.cogsci.princeton.edu/cgi-bin/webwn?stage=1&word=biotype

ARANZAZU, L.F., ARCILA, M.I., BOLANOS, M.M., CASTELLANOS, P.A., CASTRILLON, C., PEREZ, J.C., RODRIGUEZ, J.L., & BALENCIA, J.A. 2000. *Manejo Integrado del Cultivo de Plátano. Manual Tecnico*. CORPOICA, Manizales, Columbia.

ARIAS, P., DANKERS, C. LIU, P. & PILKAUSKAS, P. 2003. *The World Banana Economy, 1985-2002*. Commodity Studies 1, FAO, Rome.

ARLEU, R.J., NETO, S.S., GOMES, J.A., NOBREGA, A.C. & SARDINI, D.M. 1984. Dinamica populacional do *Cosmopolites sordidus* (Germ. 1824) (Col:

Curculionidae) em bananais da cv. Prata (Grupo AAB), em Alfredo Chaves, Espirito Santo. *Turrialba* 34: 473-480.

BATCHELDER, C.H. 1954. Experimentos con insecticidas para combater el picudo negro, *Cosmopolites sordidus* (Germar), en plantaciones de abaca. *Turrialba* 4: 88-93.

BATISTA FILHO, A., LEITE, L.G., ALVES, E.B. & AGUIAR, J.C. 1996. Control of *Cosmopolites sordidus* by fipronil and it's effect on *Beauveria bassiana*. *Arquivos do Instituto Biologico (Sao Paulo)* 63: 47-51.

BATISTA FILHO, A., LEITE, L.G., RAGA, A. & SATO, M.E. 1990. Atracao de *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) por iscas do tipo "sanduiche" e "telha". *Arquivos do Instituto Biologico (Sao Paulo)* 57: 9-13.

BATISTA FILHO, A., SATO, M.E., RAGA, A., LEITE, L.G. & PRADA, A. 1991. Flutuacao populacional da broca da bananeira (*Cosmopolites sordidus* Germar) em Miracatu, SP. *Ecossistema* 16: 46-53.

BEAUHAIRE, J., DUCROT, P.H., MALOSSE, C., ROCHAT, D., NDIEGE, I.O. & OTIENO, D.O. 1995. Identification and synthesis of sordidin, a male pheromone emitted by *Cosmopolites sordidus*. *Tetrahedron Letters* 36: 1043-1046.

BECCARI, F. 1967. Contributo alla conoscenza del *Cosmopolites sordidus* (Germ.) (Coleopt., Curcul.). *Rivista di Agricultura Subtropicale e Tropicale, Firenze* 61: 131-150.

BELLIS, G.A., DONALDSON, J.F., CARVERS, M., HANCOCK, D.L. & FLETCHER, M.J. 2004. Records of insect pests on Christmas Island and the Cocos (Keeling) Islands, Indian Ocean. *Australian Entomologist* 31: 93-102.

BRAIMAH, H. 1997. *Laboratory Studies on the Host Plant Searching Behaviour and Chemical Ecology of the Banana Weevil,* Cosmopolites sordidus *(Germar 1824) (Coleoptera: Curculionidae)*. Ph.D. Thesis, University of Reading, UK.

BRAIMAH, H. & VAN EMDEN, H.F. 1999. Evidence for the presence of chemicals attractive to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in dead banana leaves. *Bulletin of Entomological Research* 89: 485-491.

BRAITHWAITE, B.M. 1958. Ground sprayed treatments for control of the banana beetle borer (*Cosmopolites sordidus*) (Germar). *Journal of the Australian Institute for Agricultural Science* 24: 27-34.

BRAITHWAITE, B.M. 1963. The banana beetle borer. *The Agricultural Gazette* 7: 396-399, 419.

BRAITHWAITE, B.M. 1967. Banana beetle borer control investigations on the north coast of New South Wales. *The Agricultural Gazette of New South Wales* 78: 359-365.

BRIDGE, J & GOWEN, S.R. 1993. Visual assessment of plant parasitic nematode and weevil damage on bananas and plantain. In: Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 140-146.

BUDENBERG, W.J., NDIEGE, J.O. & KARAGO, F.W. 1993a. Evidence for volatile male produced pheromone in banana weevil *Cosmopolites sordidus*. *Journal of Chemical Ecology* 19: 1905-1916.

BUDENBERG, W.J., NDIEGE, J.O., KARAGO, F.W. & HANSSON, B.S. 1993b. Behavioral and electro-physiological responses of the banana weevil *Cosmopolites sordidus* to host plant volatiles. *Journal of Chemical Ecology* 19: 267-277.

BUJULU, J., URONU, B. & CUMMING, C.N.C. 1983. The control of banana weevils and parasitic nematodes in Tanzania. *East African Agricultural and Forestry Journal* 49: 1-13.

BULLOCK, R.C. & EVERS, C. 1962. Control of the banana root borer (*Cosmopolites sordidus* Germar) with granular insecticides. *Tropical Agriculture (Trinidad)* 39: 109.

CÁRDENAS R. 1984. El picudo negro del plátano *Cosmopolites sordidus* (Germar). *Cenicafé* 120: 12.

CARDENAS, R. & ARANGO, L.G. 1986. Fluctuacion poblacional y dispersion del picudo negro del plátano *Cosmopolites sordidus* (Germar 1824). *Revista Colombiana de Entomologia* 12: 37-45.

CARDENAS MURILLO, R., ARROYAVE, R.F.P. & ARANGO BERNAL, L.G. 1986. Treatment of plantain (*Musa* AAB Simmonds) against the banana borer weevil (*Cosmopolites sordidus* Germar). *Cenicafé* 37: 61-71 (Abstract cited).

CARDENOSA, R. 1953. El genero *Musa* en Columbia. *Notas Agronomia* 6: 1-368.

CASTINEIRAS, A., CABRERA, T., CALDERON, A., LOPEZ, M. & LUJAN, M. 1991a. Lucha biologica contra *Cosmopolites sordidus* (Germar). In: Pavis, C. &

Kermarrec, A. (Eds.) *Rencontres Caraibes en Lutte Biologique, Proceedings of a Symposium, Les Colloques de l'INRA, Guadeloupe*. November 1990, 58: 423-428.

CASTINEIRAS, A., CALDERON, A. & PONCE, E. 1991b. Biological control of *Cosmopolites sordidus* (Germ.) with *Metarhizium anisopliae* (Metsch.). *Revista de Proteccion Vegetal* 6: 102-106.

CASTRILLON, C. 1989. Plagas del cultivo del plátano. In: *Curso de Actualizacion sobre Problemas Sanitarios en Plátano*. La Dorada. Columbia: ICA.

CASTRILLON, C. 1991. Manejo del picudo negro (*Cosmopolites sordidus* Germar) en plátano y banano de la zona cafetera de Colombia. In: *Memorias* IX *ACORBAT*. 349-362.

CASTRILLON, C. 2000. *Distribucion de las Especies de Picudo del Plátano Evaluacion de sus Entomopatogenos Nativos en el Departemento de Risaralda*. CORPOICA, Manizales, Columbia.

CERDA, H., LOPEZ, A., FERNANDEZ, G., SANCHEZ, P. & JAFFE, K. 1995. Etude de la response olfactive du charancon des bananiers a des stimuli degages par differentes plantes. *Fruits* 50: 323-331.

CERDA, H., LOPEZ, A., SANOJA, O., SANCEZ, P. & JAFFE, K. 1996. Attraccion olfativa de *Cosmopolites sordidus* Germar (1824) (Coleoptera: Curculionidae) estimulado por volatiles originados en Musaceas de destintas edades y variedades genomicas. *Agronomia Tropical (Maracay)* 46: 413-429.

CHABRIER, C., HUBERVIC, J. & QUENEHERVE, P. 2002. Evaluation of fosthiazate (Nemathorin® 10G) for the control of nematodes in banana fields in Martinique. *Nematropica* 32: 137-147.

CHAVARRIA-CARVAJAL, J.A. & IRIZARRY, H. 1997. Rates, application intervals and rotation of four granular pesticides to control nematodes and the corm-weevil (*Cosmopolites sordidus* Germar) in plantain. *Journal of Agriculture of the University of Puerto Rico* 81: 43-52.

COLLINS, P.J., TREVERROW, N.L. & LAMBKIN, T.M. 1991. Organophosphorus insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Australia. *Crop Protection* 10: 215-221.

CSIKI, E. 1936. Rhynchophorinae, Cossoninae. *Coleopterorum Catalogus* 149: 1-212.

CUILLÉ, J. 1950. *Recherches sur le Charancon du Bananier*. Institut des Fruits Agrumes Coloniaux; Serie Technique No 4, Paris.

CUILLE, J. & VILARDEBO, A. 1963. Les calandrini nuisibles au bananier. In: Balachowsky (Ed.) *Entomologie Appliquee a l'Agriculture*. 1099-1114. Masson et Cie Ed., Paris.

DANIELLS, J.W. & O'FARREL, P.J. 1987. Effect of cutting height of the parent pseudostem on yield and time of production of the following sucker in banana. *Scientia Horticulturae* 31: 89-94.

DAVIDE, R.G. 1994. Status of nematode and weevil borer problems affecting banana in the Philippines. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 79-88.

DE JAGER, K. 1993. Banana weevil borer. In: Robinson, J.C. (Ed.) *Handbook of Banana Growing in South Africa*. 119-120. Institute for Tropical and Subtropical Crops, Nelspruit.

DE JAGER, K., RABIE, E.C. & ANDERSON, S.H. 1991. Chemiese beheer van die piesangwortelboorder, *Cosmopolites sordidus* en aalwurms, veral die booraalwurm, *Radopholus similis*. *Inligtingsbulletin - Navorsingsinstituut vir Sitrus en Subtropiese Vrugte* 228: 17-20.

DELATTRE, P. 1980. Recherche d'une methode d'estimation des populations du charancon du bananier, *Cosmopolites sordidus* Germar (Col., Curc.). *Acta Oecologia* 1: 83-92.

DENT, D. 1991. *Insect Pest Management*. CAB International, Wallingford.

DICKE, M. & SABELIS, M.W. 1988. Infochemical terminology: Based on cost-benefit analysis rather than origin of compounds. *Functional Ecology* 2: 131-139.

DOCHEZ, C. 1998. *Study on Pest Status and Control of* Cosmopolites sordidus *(Germar) in South Africa*. M.Sc. Thesis, Heriot-Watt University, Scotland.

EDGE, V.E. 1974. Cyclodiene-BHC resistance in *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae) in New South Wales, Australia. *Bulletin of Entomological Research* 64: 1-7.

EDWARDS, W.H. 1925. La charancon du bananier *Cosmopolites sordidus* Germar. *Revue Agricole et Sucriere del l' Ile Maurice (Mauritius)* 7-8: 513-514.

ENDRÖDY-YOUNGA, S. 1985. Coleoptera, introduction. In: Scholtz, C.H. & Holm, E. (Eds.) *Insects of Southern Africa*. 188. Butterworths, Durban.

FEAKIN, S.D. 1971. *Pest Control in Bananas*. 2nd Edition. London, PANS.

FIGUEROA, W. 1990. Biocontrol of the banana root borer weevil *Cosmopolites sordidus* (Germar) with steinermatid nematodes. *Journal of Agriculture of the University of Puerto Rico* 74: 15-19.

FILHO, A.B., LEITE, L.G., RAGA, A., & SATO, M.E. 1990. Atraçao de *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) por iscas do tipo "Sanduiche" e "Telha". *Arquivos do Instituto Biologico (Sao Paulo)* 57:9-13.

FLETCHER, T.M., MOORE, J.C. & KITCHING, W. 1997. Absolute configuration of sordidin and 7-episordidin emitted by the banana weevil, *Cosmopolites sordidus*. *Tetrahedron Letters* 38: 3475-3476.

FOGAIN, R., MESSIAEN, S. & FOURÉ, E. 2002. Studies on the banana borer weevil in Cameroon. *Infomusa* 11: 8-9.

FOGAIN, R. & PRICE, N.S. 1994. Varietal screening of some *Musa* cultivars for susceptibility to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Fruits* 49: 247-251.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

FROGGATT, J.L. 1925. The banana weevil borer (*Cosmopolites sordidus*). *Queensland Agricultural Journal* 24: 558-593.

FROGGATT, J.L. 1926. *The Banana Weevil Borer*. Bulletin No. 4. Queensland Department of Agriculture and Stock, Brisbane, Australia.

FROGGATT, J.L. 1928. The banana weevil borer in Java, with notes on other crop pests. *Queensland Agricultural Journal* 6: 530-541.

GALLUN, R.L. & KHUSH, G.S. 1980. Genetic factors effecting expression and stability of resistance. In: Maxwell, F.G. & Jennings, P.R. (Eds.) *Breeding Plants Resistant to Insects*. 64-85. Wiley, New York.

GETTMAN, A.D., MITCHELL, W.C., LI, P. & MAU, R.F.L. 1992. A hot water treatment for control of the banana root borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in banana planting stock. *Proceedings of the Hawaiian Entomological Society* 31: 59-63.

GODONOU, I., GREEN, K.R., ODURO, K.A., LOMER, C.J. & AFREH-NUAMAH, K. 2000. Field evaluation of selected formulations of *Beauveria bassiana* for the management of the banana weevil (*Cosmopolites sordidus*) on

plantain (*Musa* spp., AAB group). *Biocontrol Science and Technology* 10: 779-788.

GOLD, C.S. & BAGABE, M.I. 1997. Banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), infestation of cooking and beer bananas in adjacent stands in Uganda. *African Entomology* 5: 103-108.

GOLD, C.S., BAGABE, M.I. & SSENDEGE, R. 1999a. Banana weevil (*Cosmopolites sordidus*) (Germar) (Coleoptera: Curculionidae) tests for suspected resistance to carbofuran and dieldrin in Masaka district, Uganda. *African Entomology* 7: 189-196.

GOLD, C.S., KAGEZI, G., NEMEYE, P. & RAGAMA, P. 2002a. Density effects of the banana weevil *Cosmopolites sordidus* (Germar) on its oviposition performance and egg and larval survivorship. *Insect Science and its Application* 22: 205-213.

GOLD, C.S., KAGEZI, G.H., NIGHT, G. & RAGAMA, P.E. 2004a. The effects of banana weevil, *Cosmopolites sordidus*, damage on highland banana growth, yield and stand duration in Uganda. *Annals of Applied Biology* 145: 263-269.

GOLD, C.S., MASANZA, M., VAN HUIS, A. & RAGAMA, P.E. 2005a. Effects of covering highland banana stumps with soil on banana weevil *Cosmopolites sordidus* (Coleoptera: Curculionidae) oviposition. *International Journal of Tropical Insect Science* 25: 19-24.

GOLD, C.S. & MESSIAEN, S. 2000. *The Banana Weevil,* Cosmopolites sordidus. Musa Pest Fact Sheet No. 4, INIBAP.

GOLD, C.S., NEMEYE, P.S. & COE, R. 1999b. Recognition and duration of the larval instars of banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 7: 49-62.

GOLD, C.S., NIGHT, G., ABERA, A. & SPEIJER, P.R. 1998. Hot-water treatment for the control of the banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 6: 215-221.

GOLD, C.S., NIGHT, G., RAGAMA, P.E., KAGEZI, G.H., TINZAARA, W. & ABERA, A.M.K. 2004b. Field distribution of banana weevil *Cosmopolites sordidus* (Germar) adults in cooking banana stands in Uganda. *International Journal of Tropical Insect Science* 24: 242-248.

GOLD, C.S., OKECH, S.H. & NOKOE, S. 2002b. Evaluation of pseudostem trapping as a control measure against banana weevil, *Cosmopolites sordidus*

(Coleoptera: Curculionidae) in Uganda. *Bulletin of Entomological Research* 92: 35-44.

GOLD, C.S., PEÑA, J.E. & KARAMURA, E.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews* 6: 79-155.

GOLD, C.S., RAGAMA, P.E., COE, R. & RUKAZAMBUGA, N.D.T.M. 2005b. Selection of assessment methods for evaluating banana weevil *Cosmopolites sordidus* (Coleoptera: Curculionidae) damage on highland cooking banana (*Musa* spp., genome group AAA-EA. *Bulletin of Entomological Research* 95: 115-123.

GOLD, C.S., RUKAZAMBUGA, N.D.T.R., KARAMURA, E.B., NEMEYE, P. & NIGHT, G. 1999c. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 33-50.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., & RUKAZAMBUGA, N.D. 1994a. Assessment of banana weevils in East African highland banana systems and strategies for control. In: Valmayor, R.V., Davide, R.G., Stanton, J.M., Treverrow, N.L. & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference, Los Banos, Philippines*. April 1994: 170-190.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., TUSHEMEREIRWE, W.K. & KASHAIJA, I.N. 1994b. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2: 309-321.

GOLD, C.S., SSENNYONGA, J., OKECH, S.H., BAGAMBA, F., KIGGUNDU, A., TINZAARA, W., MASANZA, M. & NAMPALA, P. 1999d. Cultural control of banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in Uganda. *African Crop Science Conference Proceedings* 4: 555-562.

GOUSSELAND, J. 1983. Etude de l'enracinement et de l'emission racinaire du bananier "Giant Cavendish" (*Musa acuminata* AAA, sous groupe Cavendish) dans les andosols de la Guadeloupe. *Fruits* 38: 611-628.

GOVENDER, P. & VILJOEN, A. 2002. The biology and management of the banana weevil, *Cosmopolites sordidus* in South Africa. *Infomusa* 11: 10.

GOWEN, S.R. 1995. Pests. In: Gowen, S.R. (Ed.) *Bananas and Plantains*. 382-402. Chapman & Hall, London.

GREATHEAD, D.J. 1986. Parasitoids in classical biological control. In: Waage, J.D. & Greathead, D.J. (Eds.) *Insect Parasitoids*. 289-318. Academic Press, London.

GRIESBACH, M. 1999. *Occurrence of Mutualistic Endophytes in Bananas* (Musa *spp.) and their Potential as Biocontrol Agents of the Banana Weevil,* Cosmopolites sordidus *(Germar) (Coleoptera: Curculionidae) in Uganda*. Ph.D. Thesis, University of Bonn, Germany.

GULLAN, P.J. & CRANSTON, P.S. 1994. Sensory systems and behaviour. In: Gullan, P.J. & Cranston, P.S. (Eds.) *The Insects: An Outline of Entomology*. 96-121. Chapman & Hall, London.

HADDAD, O., SURGA, J.R. & WAGNER, M. 1979. Relacion de la composicion genomica de las musaceas con el grado de atraccion de adultos y de larvas de *Cosmopolites sordidus* G. (Coleoptera: Curculionidae). *Agronomia Tropical* 24: 429-438.

HALLAM, D. 1995. The world banana economy. In: Gowen, S. (Ed.) *Bananas and Plantains*. 509-533. Chapman & Hall, London.

HARRIS, W.V. 1947. The banana borer. *East African Agricultural and Forestry Journal* 13: 15-18.

HASYIM, A. & GOLD, C.S. 1999. Potential of classical biological control for banana weevil, *Cosmopolites sordidus* Germar, with natural enemies from Asia (with emphasis on Indonesia). In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 59-71.

HASYIM, A. & HARLION, D. 1998. *Dinamika Populasi Hama Penggerek Bonggol Pisang di Sitiung, Sumatera Barat*. Laporan tahunan Anggaran tahunan, APBN 1997-1998.

HERREN, H.R. & NEUENSCHWANDER, P. 1991. Biological control of cassava pests in Africa. *Annual Review of Entomology* 36: 257-283.

HORD, H.Y. & FLIPPEN, R.S. 1956. Studies of banana borer in the Honduras. *Journal of Economic Entomology* 49: 296-300.

INIBAP, 1986. *Banana Research in East Africa. Proposal for a Regional Research and Development Network*. INIBAP, Montpellier, France.

ITTYEIPE, K. 1986. Studies on host preference of banana weevil borer, *Cosmopolites sordidus* Germ. (Curculionidae – Coleoptera). *Fruits* 41: 375-379.

JACOBS, W. & RENNER, M. 1988. *Biologie und Ökologie der Insekten*. 2nd Edition. Stuttgart, Gustav Fischer Verlag.

JAYARAMAN, S., NDIEGE, I.O., OEHLSCHLAGER, A.C., GONZALEZ, L.M., ALPIZAR, D., FALLAS, M., BUDENBERG, W.J. AND AHUYA, P. 1997.

Synthesis, analysis, and field activity of sordidin, a male produced aggregation pheromone of the banana weevil, *Cosmopolites sordidus*. *Journal of Chemical Ecology* 23: 1145-1161.

JEPSON, F.P. 1914. *A Mission to Java in Quest of Natural Enemies for a Coleopterous Pest of Bananas (*Cosmopolites sordidus*, Chev.)*. Fiji Department of Agriculture. Bulletin 7.

JONES, D.E. 1968. *Attraction of Banana Rhizome Volatiles to the Banana Root Borer,* Cosmopolites sordidus *Germar*. Unpublished manuscript. United Fruit Company, La Lima, Honduras.

JONES, D.R. 2000. Introduction to banana, abacá and enset. In: Jones, D.R. (Ed.) *Diseases of Banana, Abacá and Enset*. 1-36. CAB International, Wallingford.

JONES, M.T. 1986. Pests and diseases of bananas and plantains of Trinidad and Tobago. *Journal of the Agricultural Society of Trinidad and Tobago* 86: 18-33.

JONES, R.K. & DIECKMANN, F. 1982. Control of the banana root borer, *Cosmopolites sordidus* Germar. *Information Bulletin, Citrus and Subtropical Fruit Research Institute* 13-17.

KAAYA, G.P., SESHU REDDY, K.V., KOKWARO, E.D. & MUNYINYI, D.M. 1993. Pathogenicity of *Beauveria bassiana*, *Metarhizium anisopliae* and *Serratiamarcescens* to the banana weevil, *Cosmopolites sordidus*. *Biocontrol Science and Technology* 3: 177-187.

KARAMURA, E.B. & KARAMURA, D.A. 1995. Banana morphology – part II: the aerial shoot. In: Gowen, S. (Ed.) *Bananas and Plantains*. 190-205. Chapman & Hall, London.

KEHE, M. 1988. Le charançon du bananier (*Cosmopolites sordidus*), les aquis et les perspectives de la recherché: contribution de L'IRFA-CIRAD/Cote d'Ivoire. In: INIBAP (Ed.) *Nematodes and the Borer weevil in Bananas: Present Status of Research and Outlook. Proceedings of a Workshop in Bujumbura, Burundi*. December 1987: 47-51.

KERMARREC, A., SIRJUSINGH, C., MAULÉON, H. & SARAH, J.L. 1993. Biological control of weevils and whitegrubs on bananas in the Caribbean: A review. In: Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 155-170.

KHAN, A. & GANGAPERSAD, G. 2001. Comparison of three entomopathogenic fungi in the management of the banana borer weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *International Pest Control* 43: 208-213.

KIGGUNDU, A. 2000. *Host Plant Reactions and Resistance Mechanisms to Banana Weevil, Cosmopolites sordidus (Germar) in Ugandan Musa Germplasm*. M.Sc. Thesis, Orange Free State University, South Africa.

KIGGUNDU, A. & GOLD, C.S. 2002. Aspects of banana weevil resistance in *Musa* and prospects for genetic engineering against the banana weevil. *Infomusa* 11: 13.

KIGUNDU, A., GOLD, C.S., LABUSCHAGNE, M.T., VUYLSTEKE, D. & LOUW, S. 2003. Levels of host plant resistance to banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Ugandan *Musa* germplasm. *Euphytica* 133: 267-277.

KOPPENHÖFER, A.M. 1992. Predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Col., Curculionidae) in western Kenya. *Journal of Applied Entomology* 114: 530-533.

KOPPENHÖFER, A.M. 1993a. Egg predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in western Kenya. *Journal of Applied Entomology* 116: 352-357.

KOPPENHÖFER, A.M. 1993b. Observation on egg laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata* 68: 187-192.

KOPPENHÖFER, A.M. & SCHMUTTERER, H. 1993. *Dactylosternum abdominale* (F.) (Coleoptera: Hydrophilidae): A predator of the banana weevil. *Biocontrol Science and Technology* 3: 141-147.

KOPPENHÖFER, A.M. & SESHU REDDY, K.V. & SIKORA, R.A. 1994. Reduction of banana weevil populations with pseudostem traps. *International Journal of Pest Management* 40: 300-304.

LEMAIRE, L. 1996. *Les Relations Semiochimiques chez le Charancon* Cosmopolites sordidus *(Germar) (Coleoptera: Curculionidae) et la Resistance de sa Plante-hote, le Bananier*. Ph.D. Thesis. University of Montpellier, France.

LESCOT, T. 1988. Influence de l'altitude sur des populations du charançon des bananiers (*Cosmopolites sordidus* Germar). *Fruits* 43: 433-437.

LONGORIA, A. 1968. Diferencias sexuales en la morfologia externa de *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae). *Ciencia Biologica la Habana* 1: 1-11.

LUO, L.Y., LUO, Q.C., YAO, X. & LIU, Z.L. 1985. Weevils injurious to banana in Guizhou and their biological features. *Insect Knowledge (Kunchong Zhishi)* 22: 265-267.

MAOLIN, S. 1994. Status of nematode and weevil borer problems affecting banana in China. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines, INIBAP*. 57-62.

MASANZA, M. 2003. *Effect of Crop Sanitation on Banana Weevil* Cosmopolites sordidus *(Germar) Populations and Associated Damage*. Ph.D. Thesis. Wageningen University, Wageningen, The Netherlands.

MASANZA, M., GOLD, C.S., VAN HUIS, A., RAGAMA, P.E. & OKECH, S.H.O. 2005. Effect of crop sanitation on banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) populations and crop damage in farmers' fields in Uganda. *Crop Protection* 24: 275-283.

MAXWELL, F.G. & JENNINGS, P.R. 1980. *Breeding Plants Resistant to Insects*. Wiley & Sons, New York.

MCINTYRE, B.D., GOLD, C.S., SSALI, H. & RIHA, S.J. 2003. Effects of mulch location on banana weevil, soil and plant nutrients, soil water and biomass in banana fields. *Biology and Fertility of Soils* 39: 74-79.

MCNICOLL, A. (ed.) 1989. *Annual Report 1988*. INIBAP, Montpellier, France.

MESQUITA, A.L.M. 1985. *Avaliacao do Ataque do* Cosmopolites sordidus *(Germar, 1824) (Col.: Curculionidae) em Rizoma de Bananeira*. Pesquisa em Andamento. CNPMF, EMBRAPA (NO. 21).

MESQUITA, A.L.M. 1988. Controle biologico das brocas da bananeira *Cosmopolites sordidus* (Germar 1824) e *Metamasius hemipterus* (Linne 1764) com fungos entomogenos. In: *Memorias VIII Reunion ACORBAT, Santa Marta, Colombia*. 311-324.

MESQUITA, A.L.M., ALVES, E.J. & CALDAS, R.C. 1984. Resistance of banana cultivars to *Cosmopolites sordidus* (Germar 1824). *Fruits* 39: 254-257.

MESQUITA, A.L.M & CALDAS, R.C. 1986. Efeito da idade e da cultivar de bananeira sobre a biologia e preferencia do *Cosmopolites sordidus* (Germar, 1824) (Coleoptera, Curculionidae). *Fruits* 41: 245-249.

MESTRE, J. 1997. A coefficient to evaluate infestations of banana weevils, *Cosmopolites sordidus*. *Fruits* 52: 135-140.

MESTRE, J. & RHINO, B. 1997. *Les Etudes sur le Charancon des Bananiers,* Cosmopolites sordidus *(Germar 1824): Bilan Sommaire – Neufchateau 1995-1997*. CIRAD-FLHOR document JM-97-04, Neufchateau.

MITCHELL, G. 1978. *The Estimation of Banana Borer Population and Resistance levels*. Technical Bulletin 2, Windward Island Banana Growers Association (WINBAN), St. Lucia.

MITCHELL, G. 1980. *Banana Entomology in the Windward Islands. Final report 1974-1978*. Centre for Overseas Pest Research, London.

MOREIRA, R.S., LAURENCAO, A.L. & SAES, L.A. 1986. Comparacao entre o queijo e a telha como iscas na atratividade do moleque das bananeiras. In: *Congresso Brasileiro de Fruticultura, 8, Brasilia, SBF 87-92*. 26-31.

MORI, K., NAKAYAMA, T. & TAKIKAWA, H. 1996. Synthesis and absolute configuration of sordidin, the male-produced aggregation pheromone of the banana weevil, *Cosmopolites sordidus*. *Tetrahedron Letters* 37: 3741-3744.

MOZNETTE, G.F. 1920. Banana root-borer. *Journal of Agricultural Research* 19: 39-46.

MUSABYIMANA, T. 1999. *Neem Seed for the management of the Banana Weevil*, Cosmopolites sordidus *Germar (Coleoptera: Curculionidae) and Banana Parasitic Nematode Complex*. Ph.D. Thesis, Kenyatta University, Kenya.

MUSABYIMANA, T., SAXENA, R.C., KAIRU, E.W., OGOL, C.K.P.O., KHAN, Z.R. 2000. Powdered neem seed and cake for management of the banana weevil, *Cosmopolites sordidus*, and parasitic nematodes. *Phytoparasitica* 28: 321-330.

MUSABYIMANA, T., SAXENA, R.C., KAIRU, E.W., OGOL, C.K.P.O. & KHAN, Z.R. 2001. Effects of neem seed derivatives on behavioural and physiological responses of the *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Journal of Economic Entomology* 94: 449-454.

NANKINGA, C.M. 1999. *Characterisation of Entomopathogenic Fungi and Evaluation of Delivery Systems of* Beauveria bassiana *for the Biological Control*

of the Banana Weevil, Cosmopolites sordidus. Ph.D. Thesis, University of Reading, UK.

NANKINGA, C.M. & MOORE, D. 2000. Reduction of banana weevil populations using different formulations of the entomopathogenic fungus *Beauveria bassiana*. *Biocontrol Science and Technology* 10: 645-657.

NANNE, H.W. & KLINK, J.W. 1975. Reducing banana root weevil adults from an established banana plantation. *Turrialba* 25: 177-178.

NDIEGE, I.O., BUDENBERG, W.J., LWANDE, W. & HASSANALI, A. 1991. Volatile components of banana pseudostem of a cultivar susceptible to the banana weevil. *Phytochemistry* 30: 3929-3930.

NDIEGE, I.O., BUDENBERG, W.J., OTIENO, D.O. & HASSANALI, A. 1996a. 1, 8-Cineole: An attractant for the banana weevil, *Cosmopolites sordidus*. *Phytochemistry* 42: 369-371.

NDIEGE, I.O., JAYARAMAN, S., OEHLSCHLAGER, A.C., GONZALEZ, L., ALPIZAR, D. & FALLAS, M. 1996b. Convenient synthesis and field activity of a male-produced aggregation pheromone of *Cosmopolites sordidus*. *Naturwissenschaften* 83: 280-282.

NEL, A., KRAUSE, M. & KHELAWANLALL, N. 2002. *A Guide for the Control of Plant Pests*. 39th Edition. Directorate, Agricultural Production Inputs, Department of Agriculture, South Africa.

NEUENSCHWANDER, P. 1988. Prospects and proposals for biological control of *Cosmopolites sordidus* (Germar) (Coleoptera Curculionidae) in Africa. In: INIBAP (Ed.) *Nematodes and the Borer weevil in Bananas: Present Status of Research and Outlook. Proceedings of a Workshop in Bujumbura, Burundi*. December 1987: 54-57.

NUNO, L. & RIBEIRO, V.P. 2002. *Cosmopolites sordidus* in the autonomous region of Madeira. *Infomusa* 11: 10.

OBERPRIELER, R.G. & LOUW, S. 1985. Curculionoidea. In: Scholtz, C.H. & Holm, E. (Eds.) *Insects of Southern Africa*. 270, 276-280. Butterworths, Durban.

OCHIENG, V. 2002. Genetic biodiversity in banana weevil (*Cosmopolites sordidus*) from different banana growing regions. *Infomusa* 11: 13-14.

OGENGA-LATIGO, M.W. & BAKYALIRE, R. 1993. Use of pseudostem traps and coefficient of infestation (PCI) for assessing banana infestation and damage by *Cosmopolites sordidus* Germar. *African Crop Science Journal* 1: 39-48.

ORTIZ, R., VUYLSTEKE, D., DUMPE, B. & FERRIS, R.S.B. 1995. Banana weevil resistance and corm hardness in *Musa* germplasm. *Euphytica* 86: 95-102.

OSTMARK, H.E. 1974. Economic insect pests of bananas. *Annual Review of Entomology* 19: 161-176.

PADMANABAN, B., SUNDARARAJU, P., VELAYUDHAN, K.C. & SATHIAMOORTHY, S. 2001. Evaluation of *Musa* germplasm against banana weevil borers. *Infomusa* 10: 26-28.

PAINTER, R.H. 1951. *Insect Resistance in Crop Plants*. New York, The MacMillan Co.

PARNISKI, P.F., TREVERROW, N.L., BEDDING, R.A. & SIKORA, R.A. 1990. Susceptibility of adults of the banana weevil borer *Cosmopolites sordidus* to 32 species and strains of *Heterorhabditis* and *Neoaplectana*. In: *Abstracts from the Second International Nematology Congress*. 121-122.

PARNITZKI, P. 1992. *Biologische Bekämpfung des Rüsselkäfers* Cosmopolites sordidus *(Germar) mit entomopathogenen Nematoden der Gattungen* Heterorhabditis *und* Steinernema *sowie Untersuchungen zur Biologie de Schädlings*. Ph.D. Thesis, University of Bonn, Germany.

PAVIS, C. 1993. Etude des relations plante-insecte chez le charancon du bananier *Cosmopolites sordidus*. In: Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 171-181.

PAVIS, M. 1988. Quelques aspects comportamentaux chez le charançon du bananier *Cosmopolites sordidus* (Germar) (Col., Curc.). In INIBAP (Ed.) *Nematodes and the Borer weevil in Bananas: Present Status of Research and Outlook. Proceedings of a Workshop in Bujumbura, Burundi*. December 1987: 58-61.

PAVIS, C. & LEMAIRE, L. 1996. Resistance of *Musa* germplasm to the banana borer weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) *Infomusa* 5: 3-9.

PAVIS, C. & MINOST, C. 1993. Banana resistance to the banana weevil borer *Cosmopolites sordidus*: Role of pseudostem attractivity and physical properties of the rhizome. In Ganry, J. (Ed.) *Breeding Banana and Plantain for Resistance to Diseases and Pests, Montpellier, France: CIRAD*. 129-142.

PEASLEY, D. & TREVERROW, N. 1986. *Count, Cut and Dry: Management of Banana Weevil Borer in Bananas. Agdex 231/62Z.* NSW Agriculture and Fisheries, Australia.

PEÑA, J.E., DUNCAN, R. & MARTIN, R. 1993. Biological control of *Cosmopolites sordidus* in Florida. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 124-139.

PICKER, M., GRIFFITHS, C. & WEAVING, A. 2002. *Field Guide to Insects of South Africa*. Struik Publishers, Cape Town.

PINESE, B. & ELDER, R. 2004. *Banana Weevil Borer*. Queensland Government, Department of Primary Industries and Fisheries, Horticulture and Fresh Produce. World Wide Web: http://www.dpi.qld.gov.au/horticulture/2507.html

PINESE, B. & PIPER, R. 1994. *Bananas - Insect and Mite Management*. Queensland Department of Primary Industries: Brisbane.

PLOETZ, R.C., CHANNER, A.G., CHIZALA, C.T., BANDA, D.L.N., MAKINA, D.W. & BRAUNWORTH, W.S.JR. 1992. A current appraisal of banana and plantain diseases in Malawi. *Tropical Pest Management* 38: 36-42.

PRICE, N.S. 1993. Preliminary weevil trapping studies in Cameroon. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 57-67.

PRICE, N.S. 1995a. Banana morphology – part I: roots and rhizomes. In: Gowen, S. (Ed.) *Bananas and Plantains*. 179-189. Chapman & Hall, London.

PRICE, N.S. 1995b. Origin and development of banana and plantain cultivation. In: Gowen, S. (Ed.) *Bananas and Plantains*. 1-13. Chapman & Hall, London.

PRICE, N.S. 1995c. The use of a modified pseudostem trapping technique for assessing the efficacy of insecticides against the banana borer weevil. *Fruits* 50: 23-26.

QUILICI, S. 1993. Insect pests of banana. *Fruits* 48: 29-31.

RAGA, A. & DE OLIVEIRA, J.A. 1996. Insecticidal efficacy against the banana borer (*Cosmopolites sordidus*) (Coleoptera: Curculionidae) in Vale do Ribeira region, State of Sao Paulo. *Arquivos do Instituto Biologico (Sao Paulo)* 63: 81-84.

REYES-RIVERA, H. 2000. *Volatile Semiochemicals for Biological Control of* Cosmopolites sordidus. Progress reports of special grants: Tropical Agriculture. University of Puerto Rico. Rio Piedras.

ROBINSON, J.C. 1993. Foreword. In: Robinson, J.C. (Ed.) *Handbook of Banana Growing in South Africa*. Ad Dynamics, Nelspruit.

ROBINSON, J.C. 1996. *Bananas and Plantains*. CAB International, Wallingford.

ROCHE, R. & ABREU, S. 1983. Control of the banana weevil (*Cosmopolites sordidus*) by the ant *Tetramorium guinensee*. *Ciencia de la Agricultura* 17: 41-49.

ROMÁN, J., ORAMAS, D. & GREEN, J. 1979. Effect of rate and frequency of application of nematicides in plantain production. *Nematrópica* 9: 107-117.

ROTH, L.M. & WILLIS, E.R. 1963. The humidity behavior of *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Annals of the Entomological Society of America* 56: 41-52.

ROYER, M.H., DOWLER, W.M. & HUBER, D.M. 1990. *Major Diseases of the Tropics and Sub-tropics of Bananas, Cacao, Cassava*. United States Department of Agriculture Agricultural Research Service.

RUKAZAMBUGA, N.D.T.M. 1996. *The Effects of Banana Weevil* (Cosmopolites sordidus *Germar) on the Growth and Productivity of Bananas* (Musa *AAA EA) and the Influence of Host Vigour on Weevil Attack*. Ph.D. Thesis, University of Reading, UK.

RUKAZAMBUGA, N.D.T.M., GOLD, C.S. & GOWEN, S.R. 1998. Yield loss in East African highland banana (*Musa* spp., AAA-EA group) caused by the banana weevil, *Cosmopolites sordidus* Germar. *Crop Protection* 17: 581-589.

SAXENA, R.C. & RUEDA, L.M. 1982. Morphological variations among three biotypes of the brown planthopper, *Nilaparvata lugens* in the Philippines. *Insect Science and its Application* 3: 193-210.

SCHMITT, A.T. 1993. *Biological Control of the Banana Weevil (Cosmopolites sordidus (Germar)) with Entomopathogenic Nematodes*. Ph.D. Thesis, University of Reading, UK.

SCHMITT, A.T., GOWEN, S.R., HAGUE, N.G.M. 1992. Baiting techniques for the control of *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) by *Steinernema carpocapsae* (Nematoda: Steinernematidae). *Nematrópica* 22: 159-162.

SCHOEMAN, P.S. 1996. Control of the banana weevil *Cosmopolites sordidus*

(Germar) (Coleoptera: Curculionidae). In: Robinson, J.C. (Ed.) *Banana Growers Association of South Africa* 1: 83-87.

SCHOEMAN, P.S. 1997. Further studies on the control of the banana weevil. In: Robinson, J.C. (Ed.) *Banana Growers Association of South Africa* 2: 69-73.

SCHOEMAN, P.S. 1998. Chemical control of the banana root borer. *Neltropika* July: 28-30.

SCHOEMAN, P.S. 2001. Family Curculionidae, *Cosmopolites sordidus* (Germar), banana weevil. In: Van den Berg, M.A., De Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. 275-278. ARC – Institute for Tropical and Subtropical Crops. Ad Dynamics, Nelspruit.

SCHOEMAN, P.S. 2002. Field management of the banana weevil with the parasitic fungus *Beauveria bassiana*. *Vegetables & Fruit* August/September: 38-39.

SCHOEMAN, P.S. & SCHOEMAN, M.H. 1999. Transmission of *Beauveria bassiana* from infected to uninfected adults of the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae). *African Plant Protection* 5: 53-54.

SCHOEMAN, P.S., SCHOEMAN, M.H. & DOCHEZ, C. 1999. Novel techniques for the control of the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in South Africa. *Yearbook of the Banana Growers Association of South Africa* 3: 78-82.

SESHU REDDY, K.V. 1992. Development of the weevil, *Cosmopolites sordidus* on certain banana cultivars. *Nineteenth annual report, International Centre of Insect Physiology and Ecology (ICIPE)* 34.

SESHU REDDY, K.V. 1993. An overview of the ICIPE'S project on the development of integrated pest management strategies for the control of the banana weevil/nematode complex. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 350-353.

SESHU REDDY, K.V., GOLD, C.S. & NGODE, L. 1999. Cultural control strategies for the banana weevil, *Cosmopolites sordidus* Germar. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 51-57.

SESHU REDDY, K.V. & KOPPENHÖFER, A.M. 1991. Effect of depth of planting on weevil incidence. *ICIPE Annual Report* 1990, 11.

SESHU REDDY, K.V., KOPPENHÖFER, A.M. & URONU, B. 1993. Cultural practises for the control of the banana weevil. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 140-146.

SESHU REDDY, K.V. & LUBEGA, M.C. 1993. Evaluation of banana cultivars for resistance to/tolerance of the banana weevil *Cosmopolites sordidus* Germar. In: Ganry, J. (Ed.) *Breeding Banana and Plantain for Resistance to Diseases and Pests, Montpellier, France: CIRAD/INIBAP*. 143-148.

SESHU REDDY, K.V., LUBEGA, M.C., MAYOGA, I.O. & OCHANJO, P.O. 1992. Evaluation of banana cultivars for resistance/tolerance to the banana weevil, *Cosmopolites sordidus*. *Annual report, International Centre of Insect Physiology and Ecology (ICIPE)* 61.

SESHU REDDY, K.V., PRASAD, J.S., NGODE, L. & SIKORA, R.A. 1995. Influence of trapping of the banana weevil, *Cosmopolites sordidus* (Germar 1824) on root-lesion nematode (*Pratylenchus goodeyi* (Sher & Allan 1953) population densities and subsequent banana yield. *Acta Oecologia* 16: 593-598.

SHANAHAN, G.J. & GOODYER, G.J. 1974. Dieldrin resistance in *Cosmopolites sordidus* in New South Wales, Australia. *Journal of Economic Entomology* 67: 446.

SIKORA, R.A., BAFOKUZARA, N.D., MBWANA, A.S.S., OLOO, G.W., URONU, B. & SESHU-REDDY, K.V. 1989. Interrelationship between banana weevil, root lesion nematode and agronomic practises and their importance for banana decline in the United Republic of Tanzania. *FAO Plant Protection Bulletin* 37: 151-157.

SIKORA, R.A., SCHUSTER, R.P. & GRIESBACH, M. 2000. Improved plant health through biological enhancement of banana planting material with mutualistic endophytes. *Acta Horticulturae* 409-413.

SIMMONDS, N.W. 1959. *Bananas*. 1st Edition. Longmans Press, London.

SIMMONDS, N.W. 1962. *The Evolution of Bananas*. Longmans Press, London.

SIMMONDS, N.W. 1966. *Bananas*. 2nd Edition. Longmans Press, London.

SIMMONDS, N.W. 1976. Bananas, *Musa* (Musaceae). In: Simmonds, N.W. (Ed.) *Evolution of Crop Plants*. 211-215. Longman, London.

SIMMONDS, N.W. & SHEPHARD, K. 1955. The taxonomy and origin of the cultivated bananas. *Journal of the Linnean Society – Botany* 55: 302-312.

SIRJUSINGH, C., MAULÉON, H. & KERMARREC, A. 1991. Compatibility and synergism between entomopathogenic nematodes and pesticides for control of *Cosmopolites sordidus* Germar. In: Pavis, C. & Kermarrec, A. (Eds.) *Rencontres Caraibes en Lutte Biologique, Proceedings of a Symposium in Les Colloques de l'INRA, Guadeloupe*. November 1990, 58: 183-192.

SKUTCH, A.F. 1932. Anatomy of the axis of the banana. *Botany Gazette* 93: 233-258.

SMITH, C.M. 1989. *Plant Resistance to Insects: A Fundamental Approach*. John Wiley & Sons, New York.

SMITH, D. 1995. Banana weevil borer control in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 35: 1165-1172.

SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. W.H. Freeman and Company, New York.

SPEIJER, P.R., BUDENBERG, W.J. & SIKORA, R.A. 1993. Relationships between nematodes, weevils, banana and plantain cultivars and damage. *Annals of Applied Biology* 123: 517-525.

SPONAGEL, K.W., DIAZ, F.J. & CRIBAS, A. 1995. *El Picudo Negro del Plátano,* Cosmopolites sordidus *Germar*. La Lima, Honduras: FHIA.

SSALI, H., MCINTYRE, B.D., GOLD, C.S., KASHAIJA, I.N. & KIZITO, F. 2003. Effects of mulch and mineral fertiliser on crop, weevil and soil quality parameters in highland banana. *Nutrient Cycling in Agroecosystems* 65: 141-150.

STANTON, J.M. 1994. Status of nematode and weevil borer problems affecting banana in Australia. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 48-56.

STARKS, K.J. & BURTON, R.L. 1972. *Greenbugs: Determining Biotypes, Culturing and Screening for Plant Resistance*. Technical Bulletin, USDA-ARS. No 1556, 12pp.

STATSOFT INCORPORATED. 2004. *Statistica*. Version 7.

STOVER, R.H. & SIMMONDS, N.W. 1987. *Bananas*. Third Edition. 469. John Wiley and Sons, New York.

SUMANI, A.J. 1997. *Patterns of Relationship Between Banana* (Musa spp.) *Types and the Banana Weevil,* Cosmopolites sordidus *Germar (Coleoptera: Curculionidae)*. Ph.D. Thesis, University of Zambia, Lusaka, Zambia.

SUMMERVILLE, W.A.T. 1939. Root distribution of the banana. *Queensland Agricultural Journal* 52: 376-392.

SWENNEN, R. 1984. *A Physiological Study of Suckering Behavior in Plantain (*Musa *AAB)*. Dessertationes de Agricultura. Faculty of Agriculture, Catholic University of Louvain.

TAYLOR, B. 1991. Research field work on upland bananas, *Musa* spp., principally *acuminata* triploid AAA types, in the Kangera region of Tanzania with observations on growth and on the causes of decline in crop yield. *Revista di Agricultura Subtropicale e Tropicale* 85: 349-392.

THOMAS, P., KANNAN, A., DEGWEKAR, V.H. & RAMAMURTHY, M.S. 1995. Non-destructive detection of seed weevil-infested mango fruits by X-ray imaging. *Postharvest Biology and Technology* 5: 161-165.

TINZAARA, W., DICKE, M., VAN HUIS, A. & GOLD, C.S. 2002. Use of infochemicals in pest management with special reference to the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Insect Science and its Application* 22: 241-261.

TINZAARA, W., DICKE, M., VAN HUIS, A., VAN LOON, J.J.A. & GOLD, C.S. 2003. Different bioassays for investigating orientation responses of the banana weevil, *Cosmopolites sordidus*, show additive effects of host plant volatiles and a synthetic male-produced aggregation pheromone. *Entomologia Experimentalis et Applicata* 106: 169-175.

TINZAARA, W., GOLD, C.S., KAGEZI, G.H., DICKE, M., VAN HUIS, A., NANKINGA, C.M., TUSHEMEREIRWE, W. & RAGAMA, P.E. 2005. Effects of two pheromone trap densities against banana weevil, *Cosmopolites sordidus*, populations and their impact on plant damage in Uganda. *Journal of Applied Entomology* 129: 265-271.

TINZAARA, W., TUSHEMEREIRWE, W. & KASHAIJA, I. 1999. The potential of using pheromone traps for the control of the banana weevil *Cosmopolites sordidus* Germar in Uganda. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 23-28.

TRAORE, L., GOLD, C.S., BOIVIN, G. & PILON, J.G. 1996. Developpement postembryonnaire du charancon du bananier. *Fruits* 51: 105-113.

TRAORE, L., GOLD, C.S., PILON, J.G. & BOIVIN, G. 1993. Effects of temperature on embryonic development of banana weevil *Cosmopolites sordidus* Germar. *African Crop Science Journal* 1: 111-116.

TREVERROW, N.L. 1985. *Banana Weevil Borer*. Agfact H6.AE.1, 2nd edition. NSW Agriculture and Fisheries, Australia.

TREVERROW, N.L. 1993. *An Integrated Management Programme for Banana Weevil Borer*. Horticultural Research and Development Corporation. Final report, FR/0012/RO.

TREVERROW, N.L. 1994. Control of the banana weevil borer, *Cosmopolites sordidus* (Germar) with entomopathogenic nematodes. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 124-138.

TREVERROW, N., AKEHURST, A., IRELAND, G. & NEWLY, P. 1995. *Reducing Insecticide Use in Bananas: Monitoring Banana Weevil Borer Populations*. Agnote – New South Wales Agriculture.

TREVERROW, N.L. & BEDDING, R.A. 1993. Development of a system for the control of the banana weevil borer, *Cosmopolites sordidus* with entomopathogenic nematodes. In: Bedding, R.A., Akhurst, R. & Kaya, H. (Eds.) *Nematodes and the Biological Control of Insect Pests, Melbourne, CSIRO*. 41-47.

TREVERROW, N.L., BEDDING, R.A., DETTMANN, E.B. & MADDOX, C. 1991. Evaluation of entomopathogenic nematodes for control of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), a pest of bananas in Australia. *Annals of Applied Biology* 119: 139-145.

TREVERROW, N. & MADDOX, C. 1993. The distribution of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) between various types of banana plant material in relation to crop hygiene. *General and Applied Entomology* 23: 15-20.

TREVERROW, N., PEASLEY, D. & IRELAND, G. 1992. *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*. Banana Industry Committee, New South Wales Agriculture.

URONU, B.E.M.A. 1992. *The Effect of Plant Resistance and Cultural Practises on the Population Densities of Banana Weevil* Cosmopolites sordidus *(Germar) and on banana yield*. Ph.D. Thesis, Kenyatta University, Kenya.

UZAKAH, R.P. 1995. *The Reproductive Biology, Behaviour, and Pheromones of the Banana Weevil,* Cosmopolites sordidus *Germar (Coleoptera: Curculionidae).* Ph.D. Thesis, University of Ibadan, Nigeria.

VALMAYOR, R.V., SALAYOI, B., JAMALUDDIN, S.H., KUSUMO, S., ESPINO, R.R.C. & PASCUA, O.C. 1991. *Banana Classification and Commercial Cultivars in Southeast Asia*. Information Bulletin no. 24/1991, Los Baños, Laguna: PCARRD.

VILARDEBÓ, A. 1950. Conditions d'un bon rendement du peigeage de *Cosmopolites sordidus*. *Fruits* 5: 399-404.

VILARDEBÓ, A. 1960. *Los Insectos y Nematodos de las Bananeras del Ecuador*. Instituto Franco-Euaotiano de Investigaciones Agromicas, Paris.

VILARDEBÓ, A. 1967. Resistance of the banana tree weevil *Cosmopolites sordidus* (Germar) to chlorinated hydrocarbon insecticides. *International Congress of Plant Protection* 586.

VILARDEBÓ, A. 1973. Le coefficient d'infestation, critere d' evaluation du degre d'attaques des bananeraies par *Cosmopolites sordidus* Germ. Le charancon noir du bananier. *Fruits* 28: 417-431.

VILARDEBÓ, A. 1984. Problèmes scientifiques poses par *Radopholus similis* et *Cosmopolites sordidus* en cultures bananières des zones francophones de production. *Fruits* 39: 227-233.

VILARDEBÓ, A. & OSTMARK, H.E. 1977. *Crop Loss Assessments*. Supplement 2, FAO, Rome.

VILJOEN, A. & ROBINSON, J.C. 2002. *Leaf Diseases and Disorders of Banana in South Africa. Identification and Management Guide*. Forestry and Agricultural Biotechnology Institute (FABI), University of Pretoria, Pretoria.

VISWANATH, B.N. 1976. *Studies on the Biology, Varietal Response and Control of Banana Rhizome Weevil,* Cosmopolites sordidus *(Germar) (Coleoptera: Curculionidae)*. Ph.D. Thesis, University of Bangalore, Bangalore, India.

VISWANATH, B.N. 1977. Studies on the biology, varietal response and control of banana rhizome weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Mysore Journal of Agricultural Sciences* 11: 597-598.

VISWANATH, B.N. 1981. Development of *Cosmopolites sordidus* (Coleoptera: Curculionidae) on banana varieties in South India. *Colemania* 1:57-58.

VITTAYARUK, W., WATTANACHAIYINGCHAROEN, W., CHUAYCHAROEN, T. & WATTANACHAIYINGCHAROEN, D. 1994. Status of weevil borer problems affecting banana in Thailand. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in, Los Banos, Philippines: INIBAP*. 106-114.

WALANGULULU, M., LITUCHA, B.M. & MUSASA, M. 1993. Potential for the control of the banana weevil *Cosmopolites sordidus* Germar with plants reputed to have an insecticidal effect. *Infomusa* 2: 9.

WALLACE, C.R. 1937. The banana beetle borer. Investigations and control measures. *Agricultural Gazette of New South Wales* 48: 621-623.

WALLACE, C.R. 1938a. Effect of cultivation on susceptibility of bananas to weevil borer. *Journal of the Australian Institute for Agricultural Science* 4: 220-225.

WALLACE, C.R. 1938b. Measurement of beetle borer migration in banana plantations. *Journal of the Australian Institute for Agricultural Science* 4: 215-219.

WARDLAW, C.W. 1961. *Banana Diseases Including Plantains and Abaca.* Longmans Press, London.

WATERHOUSE, D.F. & NORRIS, K.R. 1987. *Cosmopolites sordidus* (Germar). In: Waterhouse, D.F. & Norris, K.R. (Eds.) *Biological Control: Pacific Prospects*. 152-158, 454. Inkata Press, Melbourne.

WILLERS, P., DANEEL, M.S. & DE JAGER, K. 2001. Banana. In: Van den Berg, M.A., De Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. 36. ARC – Institute for Tropical and Subtropical Crops. Ad Dynamics, Nelspruit.

WILSON, G.F. 1983. Production de plantains: Perspectives pour améliorer la situation alimentaire sous les tropiques. *Fruits* 38: 229-239.

WRIGHT, W.E. 1977. Insecticides for the control of dieldrin resistant banana weevil borer *Cosmopolites sordidus* Germar. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17: 499-504.

YARINGANO, C. & VAN DER MEER, F. 1975. Control del gorgojo del plátano, *Cosmopolites sordidus* Germar, mediante trampas diversas y pesticidas granulados. *Revista Peruana de Entomologia* 18: 112-116.

ZIMMERMAN, E.C. 1968a. *Cosmopolites pruinosus*, a new pest of banana. *Journal of Economic Entomology* 61: 870-871.

ZIMMERMAN, E.C. 1968b. Rhynchophorinae of southeastern Polynesia. *Pacific Insects* 10: 47-77.

ZIMMERMAN, E.C. 1968c. The *Cosmopolites* banana weevils (Coleoptera: Curculionidae: Rhynchophorinae). *Pacific Insects* 10: 295-299.

TABLE 1.1. Insects reported as the main pests of bananas in South Africa (Annecke & Moran 1982).

Species name	**Order & Family**	**Common name**
Chrysomphalus aonidum (L.)	Hemiptera Diaspididae	Circular purple scale
Cosmopolites sordidus (Germar)	Coleoptera Curculionidae	Banana weevil
Hercinothrips bicinctus (Bagnall)	Thysanoptera Thripidae	Banana thrips
Pentalonia nigronervosa (Coquerel)	Hemiptera Aphididae	Banana aphid

Chapter 2

Genetic relationships among populations of *Cosmopolites sordidus* based on AFLP analysis

Abstract

The banana weevil, *Cosmopolites sordidus*, is a serious pest of banana and plantain (*Musa*) and has been distributed to most areas where the crops are grown. Pest status is variable around the world, and may be influenced by genetically distinct populations of weevil. The limited mobility of banana weevils suggests restricted gene flow and the evolution of biotypes within areas. The aim of the study was to quantify the genetic relatedness within and among geographically separated populations of *C. sordidus*. Six populations from four countries were sampled: Australia, Costa Rica, South Africa (South Coast, North Coast and Tzaneen) and Uganda. DNA was isolated from 12 individuals per population and subjected to amplified fragment length polymorphism (AFLP) analysis. The AFLP analysis involved DNA restriction with *Eco*RI and *Pst*I enzymes, ligation of adapters, and a pre-selective and five selective PCR amplifications. Empirical analysis of the AFLP fingerprints showed that, within populations, genetic diversity varied from 16-53% (the proportion of polymorphic loci), with the South Coast and Tzaneen/Australian populations the least and most variable, respectively. The coefficient of gene differentiation showed that the Tzaneen population were the most differentiated from the South Coast population, while the South and North Coast populations were the most similar. All the populations showed statistically distinct marker frequencies, except for the Costa Rican and South and North Coast populations, which were similar. Based on the simple mismatch coefficient, a neighbour-joining tree showed the Australian, Ugandan and South African coastal populations produced monophyletic groups, while the South African Tzaneen population were removed from the other populations and presented an ancestral state.

Keywords: AFLP, insect, population genetics, *Cosmopolites*

2.1 Introduction

The banana weevil borer, *Cosmopolites sordidus* (Germar), has been recorded as the most important insect pest of banana and plantain in the world (Waterhouse & Norris 1987; Gold *et al*. 1999). The weevil is found in almost all banana growing areas, with only regions of North Africa and Israel apparently free of the pest (Cardenosa 1953, Cuillé & Vilardebó 1963, Simmonds 1966, Castrillon 1991, Gettman *et al*. 1992; Robinson 1996). Damage results from larvae tunnelling in the rhizome, thereby causing a reduction in yield and lodging of plants. Yield losses of between 20 and 100% have been associated with banana weevil infestations (Mitchell 1980, Anonymous 1986, Koppenhöfer & Schmutterer 1993, Peña *et al*. 1993; Rukazambuga *et al*. 1998). Dissemination most often takes place by means of infested plant material, but crawling adults also colonise nearby plantations (Feakin 1971, Franzmann 1972, Waterhouse & Norris 1987; Seshu Reddy *et al*. 1999). The cryptic nature of the banana weevil, and the fact that infestation symptoms of the weevil resemble nematode and bacterial head rot (rhizome rot) (*Erwinia* spp.) damage (Jones 2000) has caused the time of its introduction(s) to be underestimated, and allowed the pest to remain undetected in certain areas (Gold *et al*. 2003).

The weevil has been reported as a major production constraint in several tropical and subtropical localities (Froggatt 1926, Harris 1947, Braithwaite 1963, Sikora *et al*. 1989, Seshu Reddy 1993, Davide 1994; Maolin 1994), including the Indo-Malayian region, its presumed area of origin (Zimmerman 1968c, Stover & Simmonds 1987; Vittayaruk *et al*. 1994). Empirical pest status, however, is unsure (Ostmark 1974), and appears to be related to several factors, including weevil biotypes (Fogain & Price 1994; Gowen 1995). Biotypes have been defined as organisms that share a specified genotype or the genotype (or peculiarities) so shared (Anonymous 2005), and as a population within an insect species that differs in their ability to utilise a crop plant (Gallun & Khush 1980). Maxwell & Jennings (1980) described a biotype as an individual or a population that is distinguished from the rest of its species by criteria other than morphology, e.g. a difference in parasite ability. The latter definition should be applied with caution, as dimorphic biotypes have been reported (Starks & Burton 1972; Saxena & Rueda 1982).

The *Cosmopolites* genus (Coleoptera: Curculionidae: Rhynchophorinae) comprise only two species, the banana weevil, *C. sordidus* and *C. pruinosus* Heller

(Zimmerman 1968a, b, c). *Cosmopolites pruinosus* is morphologically very similar to *C. sordidus*, but differs externally in the nature of pruinosity on the dorsum and the character of the elytral striae (Zimmerman 1968a, c). The former is associated with bananas in Borneo, Philippines and the Caroline Islands (Zimmerman 1968a, b) and considered to be a secondary pest species (Masanza 2003). Zimmerman (1968c) provided taxonomic keys for the species. The limited mobility of banana weevils suggests the existence of isolated populations with restricted gene flow, and also the evolution of new biotypes (Gold *et al*. 2003). The occurrence of weevil biotypes has been postulated after pathogenicity of an entomopathogenic nematode strain varied between geographically different populations of *C. sordidus* (Parniski *et al*. 1990; Kermarrec *et al*. 1993). Traore *et al*. (1993) also suggested that weevil biotypes exist with different developmental temperature requirements. Studies on banana tolerance or resistance were cautioned to consider possible geographical differences between weevil populations (Fogain & Price 1994). Different biotypes could also have contributed to variable weevil responses to semiochemical trapping in different countries (De Graaf *et al*. 2005). Genetic research using random amplified polymorphic DNA (RAPD)-PCR produced variable results, but generally supported the existence of weevil biotypes (Ochieng 2001; Gold *et al*. 2003). The applicability of the method, however, is limited (Vos *et al*. 1995; Zhu-Salzman *et al*. 2003), because of extreme sensitivity to variations in experimental conditions (Ellsworth *et al*. 1993, Muralidharan & Wakeland 1993, Vos *et al*. 1995; Mueller & Wolfenbarger 1999).

Amplified fragment length polymorphism (AFLP) analysis is considered to be the ideal marker system for resolving genetic relatedness among individual organisms, populations and species (Mueller & Wolfenbarger 1999). The technique, developed by Vos *et al*. (1995), and originally known as selective restriction fragment amplification (SRFA) (Zabeau & Vos 1993), is a high-throughput, highly reproducible genome wide DNA fingerprinting technique. AFLP generates a large number of potential markers across the genome that may counteract the low information content of its dominant markers. The identity of same sized fragments is unknown, but the possibility that products of different loci have the same molecular weight is probably very small for closely related species (Yan *et al*. 1999; Kosman & Leonard 2005). It has proven to be a powerful method for characterising infraspecific polymorphism among insects (Reineke *et al*. 1999, Yan *et al*. 1999, Parsons & Shaw

2001, Ravel *et al*. 2001, Garcia *et al*. 2002; Carisio *et al*. 2004) and distinguishing known insect biotypes (Cervera *et al*. 2000; Zhu-Salzman *et al*. 2003). Restriction fragment length polymorphism (RFLP) and sequencing require more development time with greater costs, and the number of independent loci assayed is often low (Parsons & Shaw 2001).

The aim of the study was to determine the genetic relatedness within and among populations of *C. sordidus* from different geographic origins using AFLPs. The study will help to clarify the role of biotypes in host plant susceptibility, weevil development and behaviour. In future it might provide useful information before the implementation of integrated pest management strategies for countries affected by the pest.

2.2 Material and methods

2.2.1 Sample collection and DNA extraction

Banana weevils, identified as *C. sordidus* according to the key provided in Zimmerman (1968c), were collected from three geographical areas in South Africa during 2004, and also from Australia, Costa Rica and Uganda (Table 2.1). Dissection of residual pseudostems (Australian samples), split pseudostem traps (Ugandan and South African South Coast samples) and pheromone (Cosmolure®) trapping (Costa Rican and South African North Coast and Tzaneen samples) were used to collect weevils. Before DNA extraction, all the weevils were preserved in absolute ethanol. For molecular analysis, a total of 12 individuals (six females, six males) were randomly selected per locality. *Sitophilus orizae* (L.) (Coleoptera: Curculionidae: Rhynchophorinae), a weevil pest of stored grain, was used to serve as outgroup in this study (Table 2.1).

Total genomic DNA was isolated from beetles with the abdomen, elytra and wings removed. Weevils were first placed in a heat block at 55 °C for 10 minutes to evaporate the ethanol and then re-hydrated in distilled water for 10 minutes. Samples were frozen in liquid nitrogen and ground with Eppendorf micro-pestles in 1.5 ml Eppendorf tubes (Hamburg, Germany). DNA extractions followed a commercial protocol (High pure PCR template preparation kit, Roche Diagnostics, Mannheim, Germany) and were stored at -20 °C.

2.2.2 AFLP procedure

The method described by Vos *et al*. (1995) was followed with minor modifications. Isolated DNA (100 ng) was restricted with two six-base recognition restriction enzymes, *Eco*RI (Roche Molecular Biochemicals, Manheim, Germany) and *Pst*I (Fermentas International Inc., Ontario, Canada). The corresponding double stranded adapters (Table 2.2) (Inqaba Biotechnical Industries (Pty) Ltd.) were subsequently ligated to the sticky ends of fragments. *Eco*RI and *Pst*I primers (Inqaba Biotechnical Industries (Pty) Ltd.) with no selective nucleotides were used for preselective PCR amplification (Table 2.2). An initial screening using 12 selective primer pair combinations was performed on a randomly selected individual of each population. Combinations providing clear and reproducible electrophoretic patterns with the highest levels of polymorphisms between individuals were determined. Five *Eco*RI (Biolegio BV Nijmegen/ Malden, The Netherlands) and *Pst*I (Inqaba Biotechnical Industries (Pty) Ltd.) primer combinations were selected for further analysis (Table 2.2).

Selective amplification products were analysed with a LI-COR® model 4200S Automated DNA Analyser (LI-COR® Biotechnology Inc., Nebraska, USA). Fragments were scored with the automated programme AFLP-Quantar Pro 1.0 (Key Gene Products 2000) and confirmed by a visual check. Loci showing clear and unambiguous banding patterns were scored and uncertain fragments were considered as missing data. Band sizes were estimated with a standard size (50-700 bp) IRD-labelled marker (LI-COR® Biotechnology Inc.).

2.2.3 Statistical analysis

To estimate the genetic diversity in and among *C. sordidus* populations, the following assumptions were made: AFLP markers behave as diploid, dominant markers with alleles either present (amplified, dominant alleles) or absent (not amplified, recessive alleles), co-migrating fragments and fragments not amplified were identical among and within populations; AFLP fragments segregated according to Mendelian expectations, and genotypes at all AFLP loci were assumed to be in Hardy-Weinberg equilibrium (Yan *et al*. 1999; Despres *et al*. 2002).

All the loci obtained with the five primer combinations were used in the analyses. Genetic diversity within weevil populations was estimated from the percentage of polymorphic loci out of all polymorphic loci (*%PL*), Shannon's

Information Index (*I*) (Lewontin 1972) and Nei's (1973) gene diversity (*h*), using POPGENE version 1.31 (Yeh *et al*. 1997). Pair-wise Product-moment correlations of the different indices were conducted in STATISTICA version 7 (Statsoft Inc. 2004). To evaluate population structure in terms of among-population and among-group differentiation, total genetic diversity was partitioned among groups, among populations within groups, and within populations by conducting a hierarchical analysis of molecular variance (AMOVA) on (the required) squared Euclidian pair-wise distances (1000 permutations) (Excoffier *et al*. 1992, Huff *et al*. 1993, Peakall *et al*. 1995; Despres *et al*. 2002) using ARLEQUIN version 2.000 (Schneider *et al*. 2000). Genetic differentiation among populations was assessed by calculating Nei's coefficient of gene differentiation, G_{st} (equivalent to Wright's F_{st}) (Nei 1973) and estimating gene flow, N_m (Slatkin & Barton 1989) from G_{st} (POPGENE version 1.31). Interpopulation differentiation was scrutinised by using TFPGA version 1.3 (Miller 1997) to perform Monte Carlo approximations of Fisher's exact (*RxC*) test (Raymond & Rousset 1995) on marker frequencies at each locus between all pairs of populations. To determine the phylogenic relationships among individuals, a neighbour-joining dendrogram (Saitou & Nei 1987), based on the simple mismatch coefficient (squared Euclidian distance), was constructed with 5000 bootstrap (Felsenstein 1985) replications, using the program MEGA version 3.1 (Kumar *et al*. 2004) (Kosman & Leonard 2005). A correlation between Nei's unbiased genetic distance (Nei 1978) and simple mismatch coefficients and geographic distance (in km) among populations (Garcia *et al*. 2002; Carisio *et al*. 2004) was investigated with a Mantel test (Mantel 1967) using TFPGA version 1.3. The distance matrices were transformed (ln (x+1)) and 10 000 random permutations used in the analysis (TFPGA version 1.3).

2.3 Results

2.3.1 AFLP patterns

Each primer combination produced approximately 100 to 150 amplified fragments between 50-700 bp (Fig. 2.1), to give a total of 659 fragments, with 604 loci polymorphic for *C. sordidus*. Visual assessment of all the raw data suggested that, within banana weevil populations, the Tzaneen and Australian individuals showed relatively high marker variability (Fig. 2.1). Unique bands were identified most

frequently for these populations, especially for Tzaneen, where bands were often specific to individual level (Fig. 2.1). The Costa Rican and North and South Coast populations from South Africa appeared to share relatively high levels of marker homogeneity, with differences essentially based on band frequency. Similarities of the Australian and Ugandan populations were also evident with the Costa Rican and South African North and South Coast populations, while the South African samples from Tzaneen showed a more distinct fingerprint. The outgroup demonstrated little conformity with the other samples, and displayed the highest proportion of population specific bands (Fig. 2.1).

2.3.2 Intra population genetic diversity

Empirical analysis of the loci showed that the Tzaneen (South Africa) and Australian populations were the most variable, with 53.48% and 45.03% polymorphic loci, respectively (Table 2.3). The South African South Coast population was the most uniform (16.06 *%PL*), while the diversity of the remaining populations was close to the overall mean of 35.02% polymorphic loci. The indices of Shannon (*I*) and Nei (*h*) peaked at 0.169 and 0.101 for Tzaneen and 0.2 and 0.132 for Australia. The two indices also supported the South Coast (South Africa) population as the least variable (*I*=0.075, *h*=0.05). The three measures of intra population diversity were correlated (*I* vs. *h*: R^2=0.982; *%PL* vs. *I*: R^2=0.787; *%PL* vs. *h*: R^2=0.668, all P<0.001). Among all the South African populations the percentage polymorphic loci, Shannon (*I*) and Nei (*h*) diversity measures were (mean ± SD) 34.33 ± 18.73%, 0.126 ± 0.048 and 0.079 ± 0.026, respectively (data not shown).

2.3.3 Population structure

The AMOVA revealed that the genetic variation within *C. sordidus* was, in general, equally divided among and within the populations studied (Table 2.4). Genetic differences between populations were highly significant. Grouping of populations showed significant structure when the South African coastal populations and the Costa Rican population were combined and compared to the other populations. As a group, the three South African populations were also significantly differentiated from the other populations, but the proportion of variance contained in the former grouping was higher (10.85%) than the latter (3.19%). In both groupings, the most variation was contained within populations, while variation amongst populations was also high

(>40%) and showed significant differentiation. Amongst the South Coast, North Coast and Tzaneen populations in South Africa, significant differences existed (P<0.001), with 51.59% and 48.41% of genetic variation contained amongst and within the populations, respectively (Table 2.4).

The global G_{st} value among all populations and among South African populations was 0.4744 and 0.4316, respectively, while associated gene flow (N_m) for all the populations and for South African populations was 0.5540 and 0.6586 (data not shown). The coefficient of gene differentiation and gene flow calculated for pair-wise population comparisons indicated that, among all the populations, the greatest differentiation occurred between the South African South Coast and Tzaneen populations, with about 47% difference between the populations, equating to a mean of 0.57 migrants per generation (Table 2.5). The populations sharing the most genetic similarity were the South and North Coast populations from South Africa, with a G_{st} and N_m value of 0.13 and 3.35 respectively (Table 2.5). Based on the Monte Carlo approximation of Fisher's exact test (through 1000 dememorisation steps, in 10 batches with 2000 permutations per batch), most population pairs were significantly different (P<0.001) (data not shown). Only the Costa Rican population was not significantly (P>0.999) differentiated from the two South African coastal populations, whom also showed no significant (P=1.000) among population differences (Table 2.5).

2.3.4 Phylogeny

The neighbour-joining phenogram showed high bootstrap support for the partitioning of banana weevil populations (Fig. 2.2). The outgroup provided an alternative root. The Tzaneen population from South Africa was separated (bootstrap value 99%), and the basal divergent population of the other *C. sordidus* individuals (Fig. 2.2). Monophyletic clusters of the South African South and North Coast, Australian and Ugandan populations were supported by high bootstrap values (≥90%) (Fig. 2.2). The node grouping the South African coastal populations with Costa Rican individuals was not very robust (bootstrap value 43%) (data not shown). A recent common ancestor between Australia and Uganda was supported by a 99% bootstrap value (Fig 2.2). The Australian and the Tzaneen populations showed relatively low levels of similarity between individuals, whilst the highest level of similarity between samples was found in the South Coast population from South Africa (Fig. 2.2).

2.3.5 Isolation by distance

The correlation between Nei's unbiased genetic distance and geographic distance for all pair-wise comparisons among the six banana weevil populations, indicated an overall non-significant pattern of isolation by distance (R=0.053, P=0.849). The Costa Rican and Tzaneen (South Africa) samples generally showed a negative relation between genetic and geographic distance (data not shown). Removal of these populations from the data matrix improved the fit of the isolation pattern, but not significantly so (R=0.935, P=0.083). Correlation between the simple mismatch coefficient and geographic distance supported a non significant pattern of isolation by distance (R=-0.201, P=0.737).

2.4 Discussion

Diversity in *C. sordidus*, collected from four countries in three continents revealed that, within all populations, the percentage of polymorphic loci ranged from 16-53%, with an average diversity of 35%. Among the South African populations, within-population diversity was slightly lower. These results are in contrast to a mean of 92% polymorphic loci (percentage of all loci), ranging from 78-98%, reported for the species following RAPD analysis of a worldwide population (Ochieng 2001). The diversity reported within a region (Uganda) ranged from 78-100%, with a mean of 94% polymorphic loci. RAPD analysis of *C. sordidus* (Ochieng 2001) was based on 46 loci and 15 worldwide populations, while 37 loci and 15 populations were studied in Uganda. The present study is based on 659 loci (91% polymorphic loci) and the information content is, therefore, more than 14 times higher. The proportion of polymorphic loci in the present study is comparable to recent AFLP studies in termites (8-39%) (Garcia *et al*. 2002), crickets (28-43%) (Parsons & Shaw 2001) and three species of dung beetles (44.2-79.7%) (Carisio *et al*. 2004).

The low within-population diversity of the South Coast population in South Africa suggests a founder effect, where the current population was introduced as a small number of genetically related individuals. Alternatively, or in combination with a founder effect, strong selection pressures (including chemical control) may have contributed to the lower levels of diversity. In turn, the higher genetic diversity observed for the Australian and Tzaneen (in South Africa) populations suggests a

relatively large establishment population and/or lower selection pressures. The unique bands observed within these populations suggested intra-populational sub-structuring, or pooling of populations that differed in genetic composition.

Genetic variation among banana weevil populations was significantly genealogically and spatially clumped, despite relatively high levels of variation within populations. Molecular variance analysis indicated that the South African coastal populations grouped more closely with the Costa Rican population than with the Tzaneen population. Nevertheless, even for the former grouping, 89% of genetic variance was still partitioned (almost equally) among and within the populations. Among all the populations and the South African populations, most variation was equally divided or between, and not within populations, as reported by Ochieng (2001).

The coefficient of gene differentiation (G_{st}) can be interpreted according to Wright's (1978) suggestions for F_{st} (= G_{st}): The range 0 to 0.05 may be considered as little, 0.05 to 0.15 as moderate, 0.15 to 0.25 as great and values above 0.25 as very great genetic differentiation. Similarly, gene flow (N_m) values of less than one can indicate little or no gene flow (Crow & Aoki 1984). The overall genetic differentiation of *C. sordidus* populations, and also the populations from South Africa was, therefore, very great, with migration between populations very rare. Pair-wise comparisons indicated a very great differentiation between most populations, with a great separation between the South African coastal and Costa Rican populations, and with moderate genetic differences between the North and South Coast population from South Africa. As expected, results on gene differentiation were supported by the dependent gene flow parameter. Some degree of gene flow was suggested between populations of great genetic differentiation i.e. the South African coastal populations and Costa Rica. According to the Monte Carlo approximation of Fisher's exact test, most populations were separate entities, except for the Costa Rican and South African South and North Coast populations, which were similar. The significance should be interpreted with caution, as the approximation for diploid dominant data sets can only be performed on marker frequencies (Miller 1997) and thus may lead to an overestimate of population differentiation (Arafeh *et al.* 2002). The neighbour-joining dendrogram of *C. sordidus* showed that the South African coastal, Australian and Ugandan populations were distinct groupings, while the South African Tzaneen population presented the

ancestral state of the banana weevils. Phylogenetically, a recent common ancestor between the Costa Rican and South African coastal populations was not strongly supported.

Most of the data suggested that, under similar ecological and agronomical conditions, the most robust comparisons can be made between local coastal populations and studies conducted in Costa Rica. All the data suggested that the South African coastal, Australian, Ugandan, and Tzaneen populations could be classified as separate taxonomic units. Especially the Tzaneen population had a relatively unique AFLP fingerprint, but then also showed high within population diversity. Results were relative to a low number of *C. sordidus* populations sampled and even though three continents were included, analysis of additional populations is required to test the hypothesis. Biotype status of the different *C. sordidus* populations should be quantified under controlled studies in relation to host plant susceptibility, development and behaviour.

Genetic inter-populational differences are assumed to depend on genetic drift and gene flow (Carisio *et al*. 2004). Based on a model of population structure among organisms whose dispersal ability is constrained by distance (Kimura 1953; Kimura & Weis 1964), a positive correlation between geographical and genetic distances suggests a basic equilibrium between drift and gene flow, while no correlation indicates drift prevalence (Hutchison & Templeton 1999; Despres *et al*. 2002). No correlation between genetic and geographical distance for *C. sordidus* was found in the present study. Genetic drift could, therefore, be most important in shaping present day genetic diversity patterns of the banana weevil. Nevertheless, the data indicated that *C. sordidus* probably does not strictly conform to the model. The relative close genetic relationship and geographic distance between the North and South Coast populations in South Africa suggests gene flow or recent separation. The genetic disparity between the coastal populations and the Tzaneen population, in turn, can support isolation and genetic drift. However, the underlying genetic data (high genetic differentiation, high within population diversity and unique bands) of the Tzaneen population suggested that it could be the result of random dissemination from a number of populations rather than extreme genetic drift from a common or local ancestor. The species was first reported in South Africa in the 1920s (Cuille 1950; Simmonds 1966), but the original timing and source of the introductions are unknown. The current and future population genetics of the species may, therefore,

be complicated by the past and future dissemination of infested plant material within and between areas, of which no reliable records exist.

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2.6 References

ANONYMOUS. 1986. *Banana Research in East Africa. Proposal for a Regional Research and Development Network*. INIBAP, Montpellier, France.

ANONYMOUS. 2005. *WordNet, a lexical database for the English language. Cognitive science laboratory, Princeton University, NJ*. World Wide Web: http://www.cogsci.princeton.edu/cgi-bin/webwn?stage=1&word=biotype.

ARAFEH, R.M.H., SAPIR, Y., SHMIDA, A., IRAKI, N., FRAGMAN, O. & COMES, H.P. 2002. Patterns of genetic and phenotypic variation in *Iris haynei* and *I. atrofusca* (*Iris* sect. *Oncocyclus* = the royal irises) along an ecogeographical gradient in Israel and the West Bank. *Molecular Ecology* 11: 39-53.

BRAITHWAITE, B.M. 1963. The banana beetle borer. *The Agricultural Gazette* 7: 396-419.

CARDENOSA, R. 1953. El genero *Musa* en Columbia. *Notas Agronomia* 6: 1-368.

CARISIO, L., CERVELLA, P., PALESTRINI, C., DELPERO, M. & ROLANDO, A. 2004. Biogeographical patterns of genetic differentiation in dung beetles of the genus *Trypocopris* (Coleoptera, Geotrupidae) inferred from mtDNA and AFLP analysis. *Journal of Biogeography* 31: 1149-1162.

CASTRILLON, C. 1991. Manejo del picudo negro (*Cosmopolites sordidus* Germar) en plátano y banano de la zona cafetera de Colombia. In: *Memorias* IX *ACORBAT*. 349-362.

CERVERA, M.T., CABEZAS, J.A., SIMÓN, B., MARTINEZ-ZAPATER, J.M., BEITIA, F. & CENIS, J.L. 2000. Genetic relationships among biotypes of *Bemisia tabaci* (Hemiptera: Aleyrodidae) based on AFLP analysis. *Bulletin of Entomological Research* 90: 391-396.

CROW, J.F. & AOKI, K. 1984. Group selection for polygenic behavioral trait: Estimating the degree of population subdivision. *Proceedings of the National Academy of Sciences of the United States of America* 81: 6073-6077.

CUILLÉ, J. 1950. *Recherches sur le Charancon du Bananier*. Institut des Fruits Agrumes Coloniaux; Serie Technique No 4, Paris.

CUILLE, J. & VILARDEBO, A. 1963. Les calandrini nuisibles au bananier. In: Balachowsky (Ed.) *Entomologie Appliquee a l'Agriculture*. 1099-1114. Masson et Cie Ed., Paris.

DAVIDE, R.G. 1994. Status of nematode and weevil borer problems affecting banana in the Philippines. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 79-88.

DE GRAAF, J., GOVENDER, P., SCHOEMAN, A.S. & VILJOEN, A. 2005. Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa. *International Journal of Pest Management* (*In Press*).

DESPRES, L., LORIOT, S. & GAUDEUL, M. 2002. Geographic pattern of genetic variation in the European globeflower *Trollius europaeus* L. (Ranunculaceae) inferred from amplified fragment length polymorphism markers. *Molecular Ecology* 11: 2337-2347.

ELLSWORTH, D.L., RITTENHOUSE, K.D. & HONEYCUTT, R.L. 1993. Artifactual variation in randomly amplified polymorphic DNA banding-patterns. *Biotechniques* 14: 214-217.

EXCOFFIER, L., SMOUSE, P.E. & QUATTRO, J.M. 1992. Analysis of molecular variance inferred from metric distances among DNA haplotypes: Application to human mitochondrial DNA restriction sites. *Genetics* 131: 479-491.

FEAKIN, S.D. 1971. *Pest Control in Bananas*. 2nd Edition. London, PANS.

FELSENSTEIN, J. 1985. Confidence limits on phylogenies: an approach using the bootstrap. *Evolution* 39: 783-791.

FOGAIN, R. & PRICE, N.S. 1994. Varietal screening of some *Musa* cultivars for susceptibility to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Fruits* 49: 247-251.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

FROGGATT, J.L. 1926. *The Banana Weevil Borer*. Bulletin No. 4. Queensland Department of Agriculture and Stock, Brisbane, Australia.

GALLUN, R.L. & KHUSH, G.S. 1980. Genetic factors effecting expression and stability of resistance. In: Maxwell, F.G. & Jennings, P.R. (Eds.) *Breeding Plants Resistant to Insects*. 64-85. Wiley, New York.

GARCIA, J., MAEKAWA, K., MIURA, T & MATSUMOTO, T. 2002. Population structure and genetic diversity in insular populations of *Nasutitermes*

takasagoensis (Ispotera: Termitidae) analysed by AFLP markers. *Zoological Science* 19: 1141-1146.

GETTMAN, A.D., MITCHELL, W.C., LI, P. & MAU, R.F.L. 1992. A hot water treatment for control of the banana root borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in banana planting stock. *Proceedings of the Hawaiian Entomological Society* 31: 59-63.

GOLD, C.S., PEÑA, J.E. & KARAMURA, E.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews* 6: 79-155.

GOLD, C.S., RUKAZAMBUGA, N.D.T.R., KARAMURA, E.B., NEMEYE, P. & NIGHT, G. 1999. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 33-50.

GOWEN, S.R. 1995. Pests. In: Gowen, S.R. (Ed.) *Bananas and Plantains*. 382-402. Chapman & Hall, London.

HARRIS, W.V. 1947. The banana borer. *East African Agricultural and Forestry Journal* 13: 15-18.

HUFF, D.R., PEAKALL, R. & SMOUSE, P.E. 1993. RAPD variation within and among natural populations of outcrossing buffalograss *Buchloe dactyloides* (Nutt) Engelm. *Theoretical and Applied Genetics* 86: 927-934.

HUTCHISON, D.W. & TEMPLETON, A.R. 1999. Correlation of pairwise genetic and geographic distance measures: inferring the relative influences of gene flow and drift on the distribution of genetic variability. *Evolution* 53: 1898-1914.

JONES, D.R. 2000. Introduction to banana, abacá and enset. In: Jones, D.R. (Ed.) *Diseases of Banana, Abacá and Enset*. 1-36. CAB International, Wallingford.

KERMARREC, A., SIRJUSINGH, C., MAULÉON, H. & SARAH, J.L. 1993. Biological control of weevils and whitegrubs on bananas in the Caribbean: A review. In: Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 155-170.

KEY GENE PRODUCTS. 2000. *AFLP-Quantar Pro 1.0*. Wageningen, The Netherlands.

KIMURA, M. 1953. Stepping-stone model of population. *Annual Report of the National Institute of Genetics* 3: 62-63.

KIMURA, M. & WEIS, G.H. 1964. The stepping-stone model of population structure and the decrease of genetic correlation with distance. *Genetics* 49: 561-576.

KOPPENHÖFER, A.M. & SCHMUTTERER, H. 1993. *Dactylosternum abdominale* (F.) (Coleoptera: Hydrophilidae): A predator of the banana weevil. *Biocontrol Science and Technology* 3: 141-147.

KOSMAN, E. & LEONARD, K.J. 2005. Similarity coefficients for molecular markers in studies of genetic relationships between individuals for haploid, diploid and polyploid species. *Molecular Ecology* 14: 415-424.

KUMAR, S., TAMURA, K. & NEI, M. 2004. MEGA3: Integrated software for molecular evolutionary genetics analysis and sequence alignment. *Briefings in Bioinformatics* 5:150-163.

LEWONTIN, R.C. 1972. The apportionment of human diversity. *Evolutionary Biology* 6: 381-394.

MANTEL, N. 1967. The detection of disease clustering and a generalized regression approach. *Cancer Research* 27: 209-220.

MAOLIN, S. 1994. Status of nematode and weevil borer problems affecting banana in China. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines, INIBAP*. 57-62.

MASANZA, M. 2003. *Effect of Crop Sanitation on Banana Weevil* Cosmopolites sordidus *(Germar) Populations and Associated Damage*. Ph.D. Thesis. Wageningen University, Wageningen, The Netherlands.

MAXWELL, F.G. & JENNINGS, P.R. 1980. *Breeding Plants Resistant to Insects*. Wiley & Sons, New York.

MILLER, M.P. 1997. *Tools for population genetic analysis (TFPGA) 1.3: A Windows program for the analysis of allozyme and molecular population genetic data*. Northern Arizona University, U.S.A.

MITCHELL, G. 1980. *Banana Entomology in the Windward Islands. Final report 1974-1978*. Centre for Overseas Pest Research, London.

MUELLER, U.G. & WOLFENBARGER, L.L. 1999. AFLP genotyping and fingerprinting. *Trends in Ecology and Evolution* 14: 389-394.

MURALIDHARAN, K. & WAKELAND, E.K. 1993. Concentration of primer and template qualitatively affects products in random-amplified polymorphic DNA PCR. *Biotechniques* 14: 362-364.

NEI, M. 1973. Analysis of gene diversity in subdivided populations. *Proceedings of the National Academy of Science of the United States of America* 70: 3321-3323.

NEI, M. 1978. Estimation of average heterozygosity and genetic distance from a small number of individuals. *Genetics* 89: 583-590.

OCHIENG, V.O. 2001. *Genetic Biodiversity in Banana Weevil* Cosmopolites sordidus *Populations in Banana Growing Regions of the World*. Ph.D. Thesis, University of Nairobi, Kenya.

OSTMARK, H.E. 1974. Economic insect pests of bananas. *Annual Review of Entomology* 19: 161-176.

PARNISKI, P.F., TREVERROW, N.L., BEDDING, R.A. & SIKORA, R.A. 1990. Susceptibility of adults of the banana weevil borer *Cosmopolites sordidus* to 32 species and strains of *Heterorhabditis* and *Neoaplectana*. In: *Abstracts from the Second International Nematology Congress*. 121-122.

PARSONS, Y.M. & SHAW, K.L. 2001. Species boundaries and genetic diversity among Hawaiian crickets of the genus *Laupala* identified using amplified fragment length polymorphism. *Molecular Ecology* 10: 1765-1772.

PEAKALL, R., SMOUSE, P.E. & HUFF, D.R. 1995. Evolutionary implications of allozyme and RAPD variation in diploid populations of dioecious buffalograss *Buchloe dactyloides*. *Molecular Ecology* 4: 135-147.

PEÑA, J.E., DUNCAN, R. & MARTIN, R. 1993. Biological control of *Cosmopolites sordidus* in Florida. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 124-139.

RAVEL, S., MONTENY, N., OLMOS, D.V., VERDUGO, J.E. & CUNY, G. 2001. A preliminary study of the population genetics of *Aedes aegypti* (Diptera: Culicidae) from Mexico using microsatellite and AFLP markers. *Acta Tropica* 78: 241-250.

RAYMOND, M.L. & ROUSSET, F. 1995. An exact test for population differentiation. *Evolution* 49: 1280-1283.

REINEKE, A., KARLOVSKI, P. & ZEBITZ, C.P.W. 1999. Amplified fragment length polymorphism analysis of different geographical populations of the gypsy

moth, *Lymantria dispar* (Lepidoptera: Lymantriidae). *Bulletin of Entomological Research* 89: 79-88.

ROBINSON, J.C. 1996. *Bananas and Plantains*. CAB International, Wallingford.

RUKAZAMBUGA, N.D.T.M., GOLD, C.S. & GOWEN, S.R. 1998. Yield loss in East African highland banana (*Musa* spp., AAA-EA group) caused by the banana weevil, *Cosmopolites sordidus* Germar. *Crop Protection* 17: 581-589.

SAITOU, N. & NEI, M. 1987. The neighbour-joining method: a new method for reconstructing phylogenetic trees. *Molecular Biology and Evolution* 4: 406-425.

SAXENA, R.C. & RUEDA, L.M. 1982. Morphological variations among three biotypes of the brown planthopper, *Nilaparvata lugens* in the Philippines. *Insect Science and its Application* 3: 193-210.

SCHNEIDER, S., ROESSLI, D. & EXCOFFIER, L. 2000. *Arlequin ver. 2.000. A software for population genetics data analysis*. Genetics and Biometry Laboratory, University of Geneva, Switzerland.

SESHU REDDY, K.V. 1993. An overview of the ICIPE'S project on the development of integrated pest management strategies for the control of the banana weevil/nematode complex. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 350-353.

SESHU REDDY, K.V., GOLD, C.S. & NGODE, L. 1999. Cultural control strategies for the banana weevil, *Cosmopolites sordidus* Germar. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 51-57.

SIKORA, R.A., BAFOKUZARA, N.D., MBWANA, A.S.S., OLOO, G.W., URONU, B. & SESHU-REDDY, K.V. 1989. Interrelationship between banana weevil, root lesion nematode and agronomic practises and their importance for banana decline in the United Republic of Tanzania. *FAO Plant Protection Bulletin* 37: 151-157.

SIMMONDS, N.W. 1966. *Bananas*. 2nd Edition. Longmans Press, London.

SLATKIN, M. & BARTON, N.H. 1989. A comparison of three indirect methods for estimating average levels of gene flow. *Evolution* 43: 1349-1368.

STARKS, K.J. & BURTON, R.L. 1972. *Greenbugs: Determining Biotypes, Culturing and Screening for Plant Resistance*. Technical Bulletin, USDA-ARS. No 1556, 12pp.

STATSOFT INCORPORATED. 2004. *Statistica, version 7*. Tulsa, U.S.A.

STOVER, R.H. & SIMMONDS, N.W. 1987. *Bananas*. Third Edition. 469. John Wiley and Sons, New York.

TRAORE, L., GOLD, C.S., PILON, J.G. & BOIVIN, G. 1993. Effects of temperature on embryonic development of banana weevil *Cosmopolites sordidus* Germar. *African Crop Science Journal* 1: 111-116.

VITTAYARUK, W., WATTANACHAIYINGCHAROEN, W., CHUAYCHAROEN, T. & WATTANACHAIYINGCHAROEN, D. 1994. Status of weevil borer problems affecting banana in Thailand. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in, Los Banos, Philippines: INIBAP*. 106-114.

VOS, P., HOGERS, R., BLEEKER, M., REIJANS, M. VAN DER LEE, T., HORNES, M., FRIJTERS, A., POT, J., PELEMAN, J., KUIPER, M. & ZABEAU, M. 1995. AFLP: a new technique for DNA fingerprinting. *Nucleic Acids Research* 23: 4407-4414.

WATERHOUSE, D.F. & NORRIS, K.R. 1987. *Cosmopolites sordidus* (Germar). In: Waterhouse, D.F. & Norris, K.R. (Eds.) *Biological Control: Pacific Prospects*. 152-158, 454. Inkata Press, Melbourne.

WRIGHT, S. 1978. *Evolution and the Genetics of Populations. Variability Within and Among Natural Populations*. University of Chicago Press, Chicago.

YAN, G., ROMERO-SEVERSON, J., WALTON, M., CHADEE, D.D. & SEVERSON, D.W. 1999. Population genetics of the yellow fewer mosquito in Trinidad: comparisons of amplified fragment length polymorphism (AFLP) and restriction fragment length polymorphism (RFLP) markers. *Molecular Ecology* 8: 951-963.

YEH, F.C., YANG, R. & BOYLE, T. 1997. *Popgene, version 1.31. Microsoft windows-based freeware for population genetic analysis*. Joint Project Development by University of Alberta and the Centre for International Forestry Research.

ZABEAU, M. & VOS, P. 1993. Selective restriction fragment amplification: a general method for DNA fingerprinting. *European patent application, publication no. EP 0534858-A1, No. 92402629.7*.

ZHU-SALZMAN, K., LI, H., KLEIN, P.E., GORENA, R.L. & SALZMAN, R.A. 2003. Using high-throughput amplified fragment length polymorphism to distinguish sorghum greenbug (Homoptera: Aphididae) biotypes. *Agricultural and Forest Entomology* 5: 311-315.

ZIMMERMAN, E.C. 1968a. *Cosmopolites pruinosus*, a new pest of banana. *Journal of Economic Entomology* 61: 870-871.

ZIMMERMAN, E.C. 1968b. Rhynchophorinae of southeastern Polynesia. *Pacific Insects* 10: 47-77.

ZIMMERMAN, E.C. 1968c. The *Cosmopolites* banana weevils (Coleoptera: Curculionidae: Rhynchophorinae). *Pacific Insects* 10: 295-299.

Table 2.1. The geographical origin and global positioning system (GPS) co-ordinates of *Cosmopolites sordidus* populations and *Sitophilus orizae* (outgroup) sampled in 2004 for genetic analysis.

Species	Geographic origin	GPS co-ordinates	
		Latitude	**Longitude**
C. sordidus	Australia (New South Wales, Tweed Shire)	28º22'15''S	153º29'15''E
C. sordidus	Costa Rica (Limón, Guapiles)	10º36'10''N	84º17'11''W
C. sordidus	South Africa (KwaZulu-Natal, North Coast)	29º28'52''S	31º07'18''E
C. sordidus	South Africa (KwaZulu-Natal, South Coast)	30º58'14''S	30º15'33''E
C. sordidus	South Africa (Limpopo Province, Tzaneen)	23º48'09''S	30º07'41''E
C. sordidus	Uganda (Busoga Province, Kawanda)	0º25'05''N	32º31'54''E
S. orizae	South Africa (Gauteng, Pretoria)	25º39'00''S	28º22'30''E

Table 2.2. The sequences of adapters, primers and primer combinations used for amplified fragment length polymorphism (AFLP) analysis of different *Cosmopolites sordidus* populations.

Description	Sequence
*Eco*RI adapter	5´ CTCGTAGACTGCGTACC CTGACGCATGGTTAA 5´
*Pst*I adapter	5´ TGTACGCAGTCTAC ACGTACATGCGTCAGATGCTC 5´
*Pst*I primer	5´ GACTGCGTACATGCAG
*Eco*RI primer	5´ GACTGCGTACCAATTC
Preselective amplification primers	*Pst*I (+0) and *Eco*RI (+0)
Selective amplification primers (combination 1)	*Pst*I (+ACA) and *Eco*RI (+AT) [1]
Selective amplification primers (combination 2)	*Pst*I (+ACC) and *Eco*RI (+AT) [1]
Selective amplification primers (combination 3)	*Pst*I (+AGG) and *Eco*RI (+AT) [1]
Selective amplification primers (combination 4)	*Pst*I (+AGG) and *Eco*RI (+TC) [1]
Selective amplification primers (combination 5)	*Pst*I (+ACC) and *Eco*RI (+CC) [2]

[1] IRD-labelled *Eco*RI primer (800 nm) (LI-COR® Biotechnology Inc., Nebraska, USA).

[2] IRD-labelled *Eco*RI primer (700 nm) (LI-COR® Biotechnology Inc., Nebraska, USA).

Table 2.3. Intra population genetic diversity of *Cosmopolites sordidus* expressed as the percentage of polymorphic loci (*%PL*), Shannon's Information Index (*I*) and Nei's gene diversity (*h*). Standard deviations are in parenthesis.

Geographical population	Genetic diversity parameter			
	Polymorphic loci	*%PL*	*I*	*H*
Australia	272	45.03	0.200 (0.2666)	0.132 (0.1848)
Costa Rica	190	31.46	0.122 (0.2209)	0.078 (0.1518)
SA (NC) [1]	202	33.44	0.134 (0.2307)	0.087 (0.1584)
SA (SC) [2]	97	16.06	0.075 (0.1942)	0.050 (0.1342)
SA (TZ) [3]	323	53.48	0.169 (0.2117)	0.101 (0.1424)
Uganda	185	30.63	0.142 (0.2476)	0.095 (0.1715)
Mean	**211.5 (78.05)**	**35.02 (12.92)**	**0.142 (0.0425)**	**0.091 (0.0270)**

[1] South Africa (North Coast).

[2] South African (South Coast).

[3] South Africa (Tzaneen).

Table 2.4. Analysis of molecular variance (AMOVA) of *Cosmopolites sordidus* populations from six geographical areas. Analysis is indicated for all banana weevil populations with no hierarchical structure and for groupings of different populations.

Grouping **Source of variation**	**d.f.**	**AMOVA parameter** **Sum of squares**	**Variance components**	**Percentage of variation**	***P*-value**
Cosmopolites sordidus					
Among populations	5	748.792	11.50238	49.51	<0.001
Within populations	66	774.167	11.72980	50.49	
Total	71	1522.958	23.23218	100	
SA (SC), SA (NC), CR vs. AUS, UG, SA (TZ) [1]					
Among groups	1	225.625	2.63426	10.85	<0.001
Among populations within groups	4	523.167	9.92182	40.85	<0.001
Within populations	66	774.167	11.72980	48.30	
Total	71	1522.958	24.28588	100	
SA vs. AUS, CR, UG [2]					
Among groups	1	171.375	0.75058	3.19	<0.05
Among populations within groups	4	577.417	11.05203	46.97	<0.001
Within populations	66	774.167	11.72980	49.85	
Total	71	1522.958	23.53241	100	
South Africa [3]					
Among populations in S.A.	2	367.333	14.19571	51.60	<0.001
Within populations in S.A.	33	439.500	13.31818	48.41	
Total	35	806.833	27.51389	100	

[1] A grouping of the South African North Coast, South African South Coast and the Costa Rican populations compared to a grouping of the Australian, Ugandan and South African Tzaneen populations.

[2] A grouping of the three South African populations (North Coast, South Coast and Tzaneen) compared to a grouping of the Australian, Costa Rican and Ugandan populations.

[3] Considering only the South African populations with no grouping.

Table 2.5. The coefficient of gene differentiation (G_{st}) and gene flow (N_m) among *Cosmopolites sordidus* populations from six different geographical areas.

Population		**Population**					
		AUS [1]	CR [2]	SA (NC) [3]	SA (SC) [4]	SA (TZ) [5]	UG [6]
		G_{st}					
AUS [1]		-	0.3553	0.3174	0.3856	0.3554	0.2969
CR [2]		0.9071	-	[a] 0.2311	[b] 0.2177	0.4004	0.3054
SA (NC) [3]		1.0755	[a] 1.6636	-	[c] 0.1299	0.4045	0.3163
SA (SC) [4]	N_m	0.7966	[b] 1.7970	[c] 3.3489	-	0.4675	0.3586
SA (TZ) [5]		0.9067	0.7488	0.7362	0.5696	-	0.4003
UG [6]		1.1841	1.1374	1.0807	0.8941	0.7491	-

[1] Australia.

[2] Costa Rica.

[3] South Africa (North Coast).

[4] South Africa (South Coast).

[5] South Africa (Tzaneen).

[6] Uganda.

[a] Exact test: X^2=1130.44, P=0.9999.

[b] Exact test: X^2=1030.81, P=1.0000.

[c] Exact test: X^2=579.60, P=1.0000.

Figure legends

Figure 2.1. Amplified fragment length polymorphism (AFLP) fingerprint of selectively amplified DNA fragments from different *Cosmopolites sordidus* populations and *Sitophilus orizae* (outgroup). Molecular weight markers (M) and their sizes (in bp) are indicated. The inverted gel image of the selective primers *Pst*I (+ACC) and *Eco*RI (+AT) is presented for 12 individuals per population (six females and six males, respectively) between approximately 800 and 50 bp. Arrows mark selected polymorphisms. Not all polymorphisms are marked. [1] Australia, [2] Costa Rica, [3] South Africa (South Coast), [4] South Africa (North Coast), [5] Outgroup, [6] South Africa (Tzaneen) and [7] Uganda.

Figure 2.2. Neighbour-joining phylogram of *Cosmopolites sordidus* individuals from six populations and the outgroup population (*Sitophilus orizae*), based on the simple mismatch coefficient. Bootstrap values (5000 replications) are indicated on the branch nodes (only >70%) and a scale bar at the bottom of the graph indicates branch lengths.

Figure 2.1

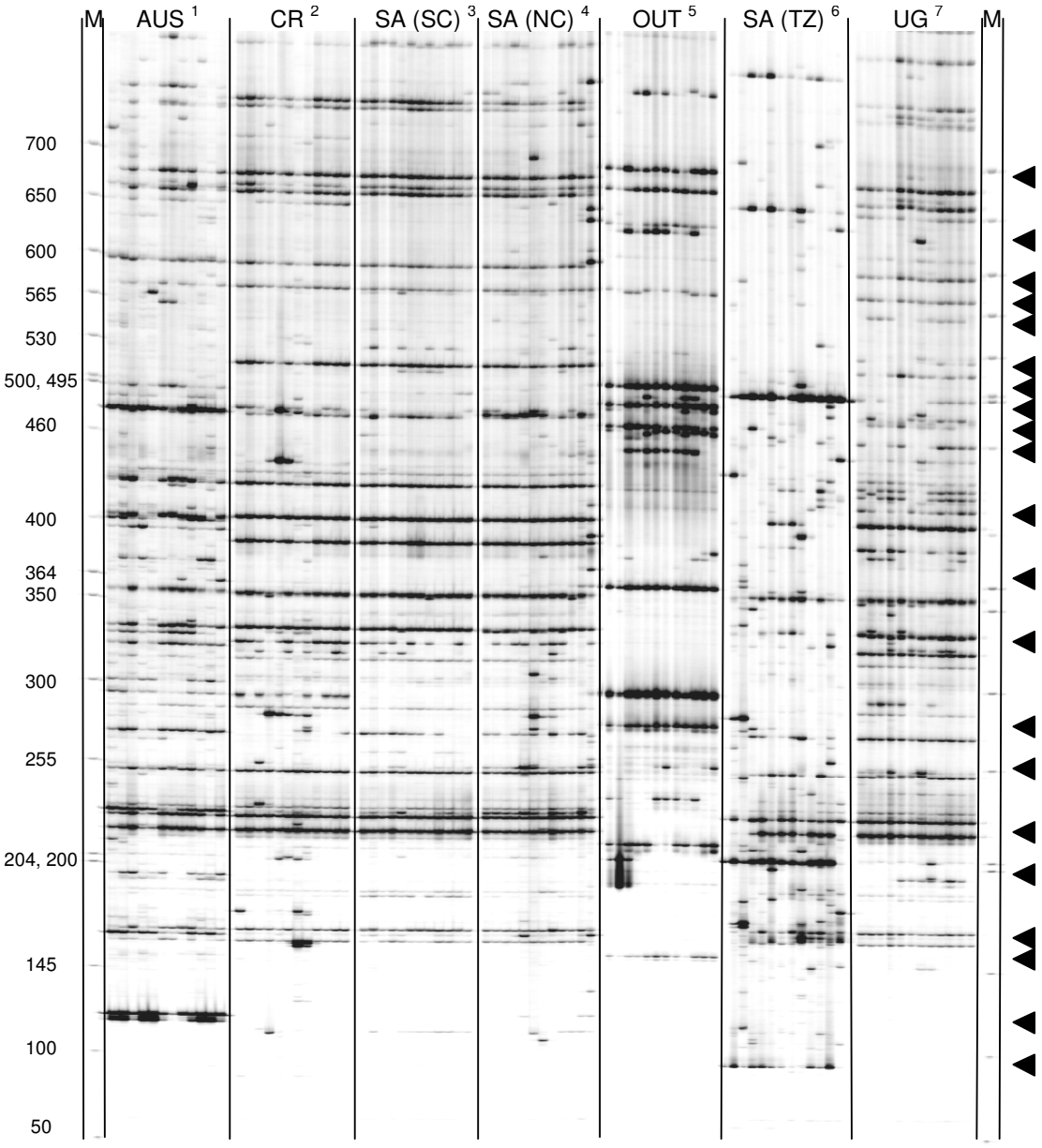
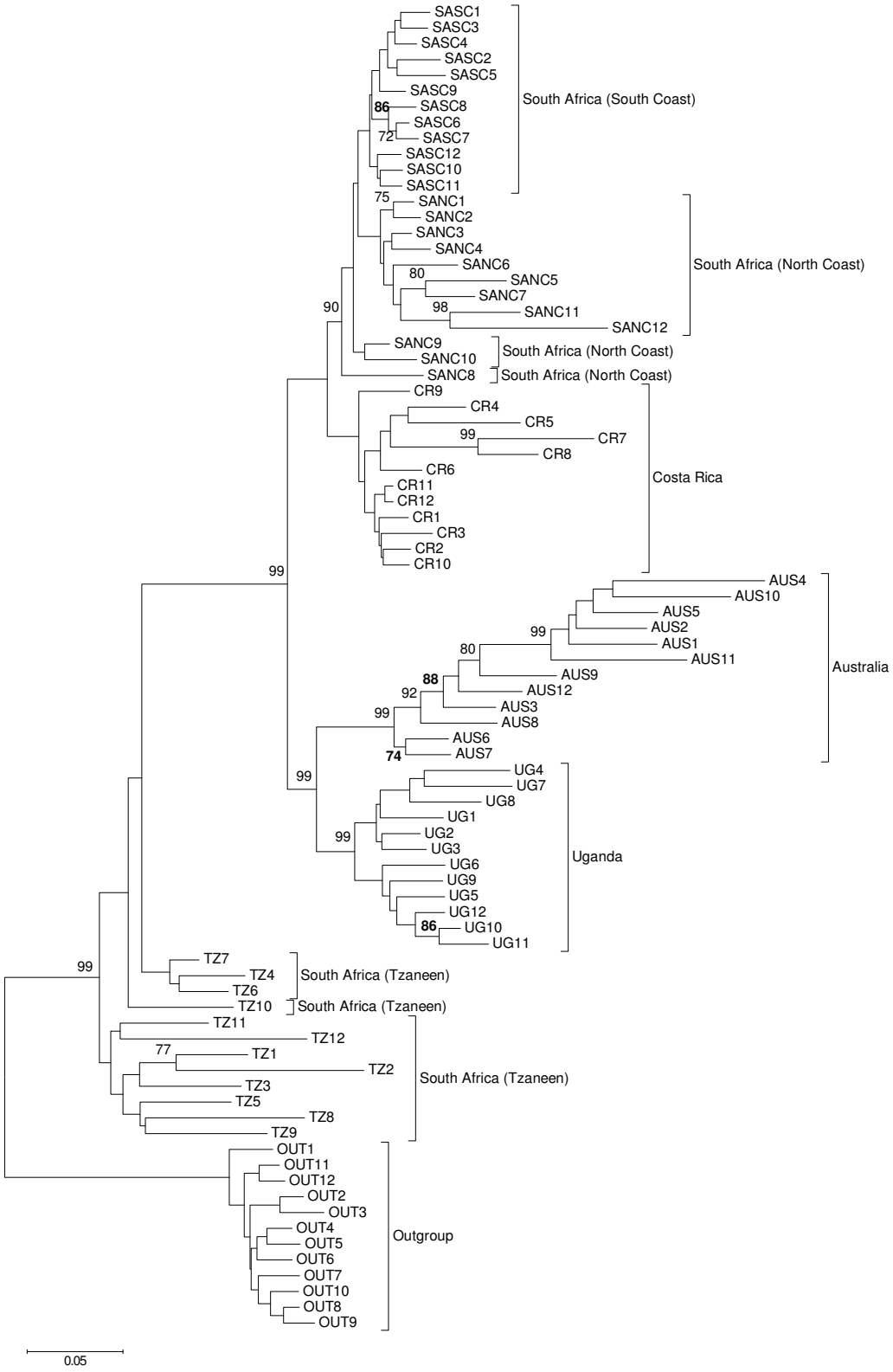

M
AUS 1
CR 2
SA (SC) 3
SA (NC) 4
OUT 5
SA (TZ) 6
UG 7
M
700
650
600
565
530
500, 495
460
400
364
350
300
255
204, 200
145
100
50

Figure 2.2


SASC1
SASC3
SASC4
SASC2
SASC5
SASC9
86
SASC8
SASC6
72
SASC7
SASC12
SASC10
SASC11
South Africa (South Coast)
75
SANC1
SANC2
SANC3
SANC4
SANC6
80
SANC5
SANC7
90
98
SANC11
SANC12
South Africa (North Coast)
SANC9
SANC10
South Africa (North Coast)
SANC8
South Africa (North Coast)
CR9
CR4
CR5
99
CR7
CR8
CR6
CR11
CR12
CR1
CR3
CR2
CR10
Costa Rica
99
AUS4
AUS10
AUS5
AUS2
99
AUS1
AUS11
80
AUS9
88
AUS12
92
AUS3
99
AUS8
AUS6
74
AUS7
Australia
99
UG4
UG7
UG8
UG1
99
UG2
UG3
UG6
UG9
UG5
UG12
86
UG10
UG11
Uganda
99
TZ7
TZ4
TZ6
South Africa (Tzaneen)
TZ10
South Africa (Tzaneen)
TZ11
TZ12
77
TZ1
TZ2
TZ3
TZ5
TZ8
TZ9
South Africa (Tzaneen)
OUT1
OUT11
OUT12
OUT2
OUT3
OUT4
OUT5
OUT6
OUT7
OUT10
OUT8
OUT9
Outgroup
0.05

Chapter 3

Ecology of *Cosmopolites sordidus* in South Africa

Abstract

The banana weevil, *Cosmopolites sordidus*, is an important pest of bananas (Musaceae: *Musa* species) in South Africa. To develop an integrated pest management strategy, the population dynamics of the insect was investigated over two seasons and at three locations in the South Coast of KwaZulu-Natal. Adult activity was monitored with semiochemical (Cosmolure®) baited pitfall traps. Traps were moved monthly to a random independent location, or left *in situ* for the duration of the experiment. The ontogeny was determined by dissecting felled plants and toppled plants (up to 2-week-old fresh residues), and harvested plants visually classified as an early and a late rotting stage (decayed residues). Replicated, randomised block designs were used in the experiments. The adult beetles were sexed and the percentage females with eggs and the number of eggs per female were recorded. Larval head capsule widths were measured with an electronic caliper. Ambient temperature and precipitation (rainfall + irrigation) were measured on site. Weevils were active throughout the year and mainly collected in stationary traps, with a collection peak in May and high numbers in early spring and late autumn/early winter. The activity was usually a negative and a positive function of ambient temperature and corrected rainfall, respectively. Eggs per female and percentage females with eggs were reduced during winter and a positive function of ambient temperature. The beetles sampled from plant material represented an equal sex ratio, while the pheromone traps collected a female biased sex ratio during spring and autumn/early winter. The beetle had overlapping generations with a peak of adults and larvae in autumn and late summer, respectively. Adults were mainly associated with decayed residues while larvae were mostly found in freshly toppled plants. Adults were the main over-wintering stage. The earliest larval instars were usually sampled during autumn. The data suggested that the beetle is multivoltine in the study areas and provided valuable information for the optimal management of the insect pest.

Keywords: Seasonal development, activity, adults, larvae

3.1 Introduction

The banana weevil, *Cosmopolites sordidus* (Germar), is an important world-wide pest of *Musa* and *Ensete* (Stover & Simmonds 1987, Gold & Messiaen 2000; Gold *et al*. 2003) and the dominant insect pest of bananas in South Africa. To develop an integrated pest management (IPM) system, a thorough knowledge of the biology and ecology of a pest insect is required to allow the rational use of cultivation and control techniques under different circumstances.

Females oviposit their eggs singularly (Froggatt 1925; Simmonds 1966) in small crevices chewed in the plant tissue, sealed by latex-containing plant sap and necrotic tissue (Beccari 1967). Eggs are usually laid at about ground level in the crown of the rhizome and pseudostem base (Abera *et al*. 1999) and flowered plants are favoured (Treverrow *et al*. 1992; Abera *et al*. 1999). Upon emergence, the larvae immediately tunnel into the rhizome or occasionally the pseudostem, producing distinctive circular, debris-filled tunnels (Franzmann 1972). Larvae display developmental polymorphism and pass through five to eight instars (Mesquita *et al*. 1984, Traore *et al*. 1996; Gold *et al*. 1999a). The pupa develops in a chamber at the corm periphery and eclosion produces a reddish, brown adult (teneral stage), which later becomes uniformly dull black (Pinese & Elder 2004). Mating usually occurs at night (Delattre 1980) and only mated females produce chorionated eggs (Treverrow & Bedding 1993). Weevils breed in residual pseudostems, but prefer rhizomes (Treverrow & Maddox 1993).

Adults are found in moist environments (Hord & Flippen 1956), leaf bases and decayed corms and stems (Treverrow *et al*. 1992), feeding on plant tissues or crop debris (Franzmann 1972; Treverrow *et al*. 1992). Wings are well developed, but flight is very rare and being negatively phototropic, adults move mainly by walking at night (Simmonds 1966, Ostmark 1974, Uzakah 1995; Gold *et al*. 1999b). Adults are gregarious and usually have a patchy distribution in the field (Treverrow *et al*. 1992). Dispersal is slow and weevils normally move less than 10 m per month (Gold *et al*. 1999b). Weevils show aberrant behaviour and experience difficulty in walking at low humidities (Roth & Willis 1963). The beetle is highly susceptible to desiccation and commonly die within 3 to 10 days on a dry substrate (Viswanath 1977; Gold *et al*. 1999b), but can survive approximately 4 to 17 months in moist soil without food (Franzmann 1972, Viswanath 1977; Treverrow *et al*. 1992). Adults are

thigmotactic (Delattre 1980), exhibit hydrotropism (Cuillé 1950) and display thanatosis (Feakin 1971). Both sexes are attracted to stressed or damaged plants and residual corm and pieces of freshly cut pseudostem (Froggatt 1925, Treverrow *et al*. 1992, Treverrow & Bedding 1993; Gold *et al*. 1994). Males aggregate at lower humidities than females (Roth & Willis 1963), but distribution patterns of males and females in the field are similar (Gold *et al*. 1999b). Sexes can be morphologically distinguished (Cuillé 1950, Roth & Willis 1963, Longoria 1968; Gold *et al*. 1999b) and males produce an aggregation pheromone that attracts both genders (Budenberg *et al*. 1993).

The reproductive activity of the banana weevil is relatively low (Cuillé 1950), with high field mortality of eggs and larvae (Treverrow & Bedding 1993; Abera 1997). Field oviposition rates are a negative function of weevil density (Abera *et al*. 1999; Gold *et al*. 1999b), but Koppenhöfer (1993) reported that it only occurs at very high densities, which can impossibly be attained under field conditions. Egg laying activity is negatively influenced by temperature (Franzmann 1972; Parnitzki 1992). Under tropical conditions, females usually lay one egg per week (Abera *et al*. 1999). In the subtropics, two to four eggs are laid per week and 50-100 eggs per annum, mostly over a 6-month period (Simmonds 1959, Treverrow *et al*. 1992; Treverrow & Bedding 1993). The developmental temperature threshold of eggs is 12°C with an 89 degree-days thermal requirement (a West African population) (Traore *et al*. 1993). Larval development time (a West African population) is inversely related to temperature, with a thermal threshold of 8.8°C and 537.9 degree-days development requirement (Traore *et al*. 1996). The pupal stage requires 10.1°C and 120.7 degree-days for development (Traore *et al*. 1996).

Sexual maturity of males and females is obtained after 2 to 5 and 1 to 3 weeks, respectively (Uzakah 1995). Females oviposit a week after pupal eclosion (Treverrow & Bedding 1993), but 27 to 41 days may also be required (Uzakah 1995). Fertile eggs can be laid a year after mating (Treverrow *et al*. 1992) and adults live up to 2 (Froggatt 1925, Waterhouse & Norris 1987; Treverrow & Bedding 1993) or 4 years (Rukazambuga *et al*. 1998). All post embryonic stages require a thermal threshold of 10.2°C and 609.3 degree-days to complete development (Traore *et al*. 1996). Depending on temperature, the life cycle is normally completed in 6 weeks to 6 months (Treverrow & Bedding 1993).

Reports of seasonal fluctuations in weevil populations depend on climate, crop

management, predators, weevil density, sampling method, weevil development rate, and/or weevil biotype. Tropical and subtropical climates greatly affect the seasonal development of the weevil. Differences in crop management, e.g. mulching material or mulching location, influence field microclimate, which can alter temperatures and humidity (Seshu Reddy *et al*. 1999). Weevil numbers are also influenced and can be negatively related to predator densities (Hasyim & Harlion 1998). Adult density variation can affect ovipositioning rates and probably influences the rate of migration and the effect of destructive sampling. Different adult traps attract specific proportions of the population in terms of density and physiology (De Graaf *et al*. 2005). Development rate of *C. sordidus* depends on cultivar, plant stage, diet, relative humidity and population density (Mesquita *et al*. 1984; Gold *et al*. 1999a). Weevil biotypes may, however, also have different developmental temperature requirements (Traore *et al*. 1993). The aim of the study was to quantify the population dynamics of the banana weevil under field conditions in South Africa. Adult activity was measured by pheromone traps and plants dissected to elucidate life stage occurrences. The outcome would be used to eventually develop an IPM programme for the weevil in South Africa.

3.2 Material and methods

3.2.1 Research sites

Three trials were conducted on commercial farms in the South Coast of KwaZulu-Natal, South Africa. Soil in the area is a Glenrosa form, with an orthic A and lithocutanic B zone. It is a sandy loam soil with 16% clay, 30% loam and 53.75% sand (Dochez 1998). Trial sites were located in Munster (30º59'40''S; 30º14'60''E), Ramsgate (30º54'27''S; 30º18'58''E) and Leisure Bay (31º00'52''S; 30º14'33''E) and ranged from 46 to 60 meters above sea level. Experiments at the respective localities were conducted from May 2003 to April 2004, May 2003 to April 2005 and June 2004 to May 2005. The locations were all in a summer rainfall area (750-1000 mm per year), and during the trials the ambient temperature ranged from 12 to 25 °C.

The Cavendish subgroup of banana cultivars (AAA group, *Musa acuminata*) was grown at all the trial localities. The Williams cultivar was cultivated at all sites (2222 plants per hectare), planted during November 1996, November 1993 and November 1995 at the Munster, Ramsgate and Leisure Bay location, respectively.

Plantations were irrigated with 20 mm water/week, a practise only suspended if rainfall exceeded that value in the particular week. Experimental fields were representative for South African plantations (see Chapter 1) and no sanitation practises were employed. The Munster and Leisure Bay sites utilized sprinkler irrigation, whilst dripper irrigation was used at the Ramsgate site. All the banana stands were treated (for nematode control) with the oxime carbamate, aldicarb (15% GR), at the registered dosage of 2.025 g.a.i./mat, at planting. Each trial site was approximately two hectares in size. Pre-trial plant inspections at all sites revealed rhizome tunnel damage by *C. sordidus*.

3.2.2 Experimental design

Treatments comprised of adult traps, moved monthly or left *in situ*, and dissections of fresh and decayed plant residues. The layout of all the trials followed a randomised block design with three replicates. Fields were divided in three blocks, each containing 12 plots (for each month of the year). To standardise for abiotic influences, replicates were orientated perpendicular to the sea/land breeze and moisture gradient in the field.

Adult activity was monitored with an aggregation pheromone, individually suspended above a pitfall trap. The commercially available aggregation pheromone (Cosmolure®) containing kairomone and four sordidin diastereoisomers, were imported from the producers, ChemTica Internacional S.A. (San José, Costa Rica). Pitfall traps were prepared by cutting four windows (200 × 200 mm) at the sides of rectangular prism-shaped containers (width: 250 mm, length: 300 mm, height: 350 mm) and suspending the pheromone with wire cable in the middle of the openings from the top end of the trap. Pitfall traps were filled with a mixture of water and ethylene glycol to drown attracted beetles. Ethylene glycol was used to reduce evaporation and lower the surface tension of the solution. The traps were placed in-line with the planting row at a constant direction to the mat. Pitfall traps were buried 150 mm in the soil at a distance of 300 mm from the pseudostem of the plant. In each replicate, one trap was moved monthly to a random independent location and one trap left *in situ* for the duration of the experiment. Traps were separated by 24 m and considered independent, as the attractive radius of pheromone pitfall traps have been determined to range from 2.5 to 7.5 m (Alpizar *et al.* 1998) and the former value falls within the range recommended and used in previous studies (Ndiege *et al.* 1996,

Jayaraman *et al.* 1997, Alpizar *et al.* 1998, Tinzaara *et al.* 1999; Anonymous 2004). The weevils were collected weekly and the pheromone lures were replaced monthly.

The seasonal field prevalence of life stages (eggs were excluded) was determined by monthly plant dissections. Plant material was divided in two classes: plants felled and plants toppled within 2 weeks (fresh residues), and harvested plants visually classified as an early and a late rotting stage (decayed residues). Early decay remnants were represented by plants where only the distal 20 cm of the erect harvested pseudostem could be totally compressed by hand. The late rotting residues included plants with prostrate harvested pseudostems which could be totally compressed by hand. Only decayed residues attached to the mother plant were selected. The rhizome and pseudostem of residues were dissected. Residues were randomly selected in each replicate (but each matt was sampled only once) and their frequencies in the field assumed to be equal. Larval head capsule widths (dorsal side) were measured with an electronic calliper (accuracy: ±0.02 mm).

Adults collected in both sampling regimes were dissected, the sex determined by examining internal genitalia, and the percentage females with eggs and the number of eggs per female were recorded. To prevent bias from repetitive monthly sampling, adults collected in the stationary pitfall traps were not included.

Ambient temperature at each trial site was measured using a waterproof WatchDog 100-Temp 2K data logger (Spectrum Technologies, Inc., Plainfield, Illinois, U.S.A.) suspended next to a pheromone lure and set to record hourly temperature. Rainfall was measured on site and corrected for irrigation quantities.

3.2.3 Statistical analysis

A factorial ANOVA (Sokal & Rohlf 1997) was used to quantify differences between the number of beetles attracted in the two trapping regimes (treatments) and over collection dates (time). Multiple regression (model II) (Sokal & Rohlf 1997) was used to quantify the relationship between beetle number in traps and mean ambient temperature, corrected rainfall, adult and larval density in the field. The proportion of females with eggs and the number of eggs per female were compared between pitfall traps and decayed and fresh residues (treatments) over time using repeated measures ANOVA. The two fecundity variables were regressed with mean ambient temperature and corrected rainfall using multiple regression (model II). Occurrence of the respective adult and larval stage in fresh and decayed residues over time was

evaluated with repeated measures ANOVA. The Tukey HSD test (Sokal & Rohlf 1997) was used for all *post hoc* analysis. Multiple regression (model II) was used to determine the correlation of adult and larval density in the field with mean ambient temperature and corrected rainfall. Deviation from an equal sex ratio was investigated using the binomial distribution (two-tailed) (Sokal & Rohlf 1997). The Bonferroni method was used to lower the type one error probability for each comparison, resulting in an overall significance level not exceeding 0.05 in the entire series of tests (Sokal & Rohlf 1997). When necessary, data were transformed to show a normal distribution and homogeneity of variances. The data transformation showing the best fit to a normal distribution was selected. The STATISTICA Version 7 (Statsoft Inc. 2004) software program was used for analysis.

3.3 Results

3.3.1 Munster trial

3.3.1.1 Adult activity

The respective adult densities were ln (x+1) transformed to comply with the assumptions of factorial ANOVA (Sokal & Rohlf 1997). The data showed a significant difference over time ($F_{39, 156}$ = 3.04, P<0.001) and between treatments ($F_{1, 156}$ = 4.79, P=0.030), but no interaction between the independent variables ($F_{39, 156}$ = 0.56, P=0.983). *Post hoc* testing revealed significant differences between sampling weeks, divided in three overlapping groups (data not shown). The stationary traps collected significantly more weevils than the traps that were moved every month, amounting to respective (back-transformed) means of 3.77 and 3.09 adults per week. Multiple regression showed a significant relationship between ambient temperature (weekly data not available for May and winter months, range: 16.40 to 25.02 °C) and corrected rainfall (range: 20 to 125 mm) with adults in stationary traps ($F_{2, 23}$ = 7.75, P<0.003, R^2=0.403, m = -0.603 and 0.027, respectively) and overall mean number of adults in traps ($F_{2, 23}$ = 7.59, P<0.003, R^2=0.397, m = -0.395 and 0.021, respectively). Averaging adult trapping densities per month and multiple regression with monthly adult and larval densities in the field, air temperature and/or rainfall produced no significant interaction (data not shown).

One-way ANOVA of mean adult activity between months also showed a significant temporal effect ($F_{10, 51}$ = 3.78, P<0.001). The post ANOVA test revealed a

significant difference between the activity in June (early winter) compared to July (mid winter), August (late winter) and February (late summer), while the remaining months was similar among themselves and to all the other months (Fig. 3.1).

3.3.1.2 Fecundity and sex ratio

The number of eggs per female, and the proportion of females with eggs, was determined by considering adult weevils collected in pheromone traps only, since insufficient adult numbers were collected following plant dissections. The number of eggs per female varied significantly over time ($F_{10, 21}$ = 2.34, P=0.049), while no temporal effect was revealed in the percentage of females with eggs ($F_{10, 21}$ = 1.24, P=0.321). *Post hoc* testing, however, did not separate the number of eggs per female found for each month (Table 3.1), because the Tukey HSD test adopts a conservative approach by employing experimentwise error rates (based on the number of comparisons) for the type I error (Sokal & Rohlf 1997). Eggs per female peaked in January (mid summer) and March (early autumn), and were minimal in April (mid autumn) and June, while the proportion of females containing eggs was highest in January and December (early summer) and lowest in April (Table 3.1). Multiple regression only showed a significant relationship between ambient temperature (range: 15.00 to 23.90 °C) and eggs per female ($F_{2, 98}$ = 3.50, P<0.081 (ambient temperature P=0.036), R^2=0.467, m = 0.150). The data showed that the potential oviposition (percentage females with eggs × eggs/female) was highest in summer and spring and lowest in winter.

The sample size of adult weevils collected in plant residues was low and did not show a biased sex ratio (two-tailed binomial distribution, Bonferroni corrected), with the percentage of males varying from 37.50 to 100%. The sex ratio of beetles collected in the pheromone traps ranged from 12.77% males in September (early spring) to 35.71% males in February, with values significantly female biased (two-tailed binomial distribution, Bonferroni corrected) in May (late autumn), June and September (data not shown).

3.3.1.3 Ontogenic field occurrence

The respective adult and larval densities in the field were square root (x+0.5) transformed to comply with the assumptions of repeated measures ANOVA (Sokal & Rohlf 1997). ANOVA showed adult numbers varied significantly over time ($F_{11, 96}$ =

2.25, P=0.018), between treatments ($F_{3, 96}$ = 4.47, P=0.006) and interacted between the independent variables ($F_{33, 96}$ = 2.19, P=0.002). *Post hoc* analysis, however, did not show a significant separation of adult numbers between months (Fig. 3.2a) or an interaction effect between date and treatment (data not shown), because the Tukey HSD test adopts a conservative approach by employing experimentwise error rates (based on the number of comparisons) for the type I error (Sokal & Rohlf 1997). The post ANOVA test showed that significantly more adults were found in the residues of a late rotting stage than in the fresh residues. Compared to residues in advanced decay, early rot remnants contained fewer, but a statistically similar amount of adults (data not shown). ANOVA showed that larval densities did not vary significantly over time ($F_{11, 96}$ = 0.647, P=0.784) nor interacted between time and treatment ($F_{33, 96}$ = 0.761, P=0.812) (Fig. 3.2b), but were significantly different between treatments ($F_{3, 96}$ = 3.93, P=0.011). *Post hoc* testing revealed significantly more larvae in toppled plants compared to the other residue classes, which were similar among themselves (data not shown). Multiple regression showed that adults in decayed residues were significantly negatively related to ambient temperature ($F_{2, 9}$ = 11.56, P<0.003, R^2=0.720, m = -0.100), while the adults in fresh residues, mean number of adults and larval numbers were not related to ambient temperature or corrected rainfall (data not shown).

Only one pupa was sampled during June in a toppled residue. The data suggested that eggs mainly hatched from spring to autumn, with larval peaks in September, November to February, May and July, eclosing mainly in November (late spring), January/February, May and September (Fig. 3.2a, 3.2b). Probable timing of eclosions was mainly based on life stages in fresh residues and assumed that adults in decayed residues during winter were not newly emerged (Fig. 3.2a, 3.2b). The adult percentage-values indicated that weevils mainly over-wintered as adults in decayed residues (mean from June to August: 62.74% adults), relatively more larvae were found in fresh residues and that relative adult and larval numbers peaked in September and December/March, respectively (Fig. 3.2a). The larval population comprised, on average, the earliest instars (smallest head capsule width) in February and August (Fig. 3.2b).

3.3.2 Ramsgate trial

3.3.2.1 Adult activity

The respective adult densities were square root (x+0.5) transformed to comply with

the assumptions of factorial ANOVA (Sokal & Rohlf 1997). Numbers of weevils trapped were significantly different over time ($F_{79, 320}$ = 7.76, P<0.001), but showed no difference between treatments ($F_{1, 320}$ = 2.20, P=0.139), nor an interaction between date and treatment ($F_{79, 320}$ = 0.60, P=0.996). *Post hoc* testing showed that the means separated in 12 groups, with 11 groups overlapping (data not shown). Considering only the first season (May 2003 to April 2004), similar patterns of significance were found, with two overlapping groups revealed in *post hoc* testing (data not shown). Multiple regression showed a significant relation between ambient temperature and adults in stationary traps ($F_{2, 77}$ = 4.47, P<0.015, R^2=0.104, m = -0.522), adults in monthly traps ($F_{2, 77}$ = 8.26, P<0.001, R^2=0.177, m = -0.785) and overall mean number of adults ($F_{2, 77}$ = 6.75, P<0.002, R^2=0.149, m = -0.653). When only the first season was considered, no significant relationship existed between the abiotic factors and adults in stationary traps, but adults in monthly traps were significantly related to ambient temperature and corrected rainfall ($F_{2, 34}$ = 6.09, P<0.006, R^2=0.264, m = -0.895 and m = 0.136, respectively), while the overall mean adult number was significantly related to ambient temperature ($F_{2, 34}$ = 4.70, P<0.016, R^2=0.217, m = -0.678). Averaging adult trapping densities per month and multiple regression with monthly adult and larval densities in the field, air temperature and/or rainfall produced no significant interaction (data not shown).

One-way ANOVA of mean adult activity between months showed a significant temporal effect ($F_{23, 117}$ = 14.43, P<0.001). The *post hoc* test revealed a significant difference between the activity in September 2003 compared to all the other months except for May 2003, June 2003 and November 2003 (Fig. 3.3). The significance of the remaining months overlapped in nine groups (Fig. 3.3).

3.3.2.2 Fecundity and sex ratio

Statistical analysis of the number of eggs per female and proportion of females with eggs was restricted to data of pheromone traps, because of insufficient data obtained from plant dissections. Data of pheromone traps were sufficient for analysis from May 2003 to September 2004. ANOVA showed that the number of eggs per female did not vary significantly over time ($F_{16, 48}$ = 1.60, P=0.125), while a significant temporal effect was found in the percentage of females with eggs ($F_{16, 48}$ = 4.59, P<0.001). Post ANOVA analysis of the proportion of females with eggs showed three overlapping groups of significance, with values generally minimised during winter (19.44 to

47.10%) and maximised during the spring and summer months (54.29 to 100.00%) (Table 3.2). Multiple regression showed a significant relationship between eggs per female ($F_{2, 14}$ = 2.80, P<0.095 (ambient temperature P=0.036), R^2=0.286, m = 0.106) and percentage females with eggs ($F_{2, 14}$ = 9.10, P<0.003, R^2=0.565, m = 6.383) with ambient temperature (range: 16.75 to 24.76 °C). The data showed that the potential oviposition (percentage females with eggs × eggs/female) peaked in spring and autumn; being minimised during winter.

The sample size of adult weevils collected in plant residues was relatively low and did not show a biased sex ratio (two-tailed binomial distribution, Bonferroni corrected), with the percentage of males varying from 33.33 to 100%. The sex ratio of beetles collected in the pheromone traps ranged from 10.00% males in September 2004 to 50.00% males in February 2005, with values significantly female biased (two-tailed binomial distribution, Bonferroni corrected) in May 2003, June 2003, August 2003, September 2003, October (mid spring) 2003 and September 2004 (data not shown).

3.3.2.3 Ontogenic field occurrence

The number of adults and larvae sampled in the field were significantly different over time ($F_{23, 192}$ = 1.62, P=0.043 and $F_{23, 192}$ = 2.19, P=0.002, respectively), between treatments ($F_{3, 192}$ = 13.47, P<0.001 and $F_{3, 192}$ = 4.76, P=0.003, respectively) and interacted between month and treatment ($F_{69, 192}$ = 1.59, P=0.007 and $F_{69, 192}$ = 1.57, P=0.009, respectively). *Post hoc* testing did not show a significant difference in adults over time (Fig. 3.4a), because the Tukey HSD test adopts a conservative approach by employing experimentwise error rates (based on the number of comparisons) for the type I error (Sokal & Rohlf 1997). The post ANOVA test revealed that significantly more adults were found in late decay residues compared to the other residue groups, which were similar among themselves (data not shown). Interactively, the values were statistically similar, except for July 2003 (late rot), which was only similar to June 2003 (late rot), September 2003 (late rot), May 2004 (early rot), July 2004 (toppled plant), September 2004 (late rot) and March 2005 (early rot) (data not shown). The post ANOVA test showed that larvae in February 2005 were significantly more numerous than larvae of 11 other months (Fig 3.4b), while statistically more larvae were collected in early rot compared to late rot residues (data not shown). The former was followed by larvae in toppled and felled plants, respectively, which was no

different to either class of decayed residues (data not shown). Interactively, most values were similar, except for February 2005 (early rot), which was different to all the values except for May 2003 (toppled plant), January 2004 (early rot) and January 2005 (felled plant). Multiple regression showed that ambient temperature was significantly negatively related to adult number in decayed residues ($F_{2, 21}$ = 2.46, P<0.109 (ambient temperature P=0.047), R^2=0.190, m = -0.186) and overall mean adult number ($F_{2, 21}$ = 4.88, P<0.018, R^2=0.317, m = -0.135), while the adults in fresh residues and larval numbers were not related to ambient temperature or corrected rainfall (data not shown).

Pupae were sampled singly in June 2003 (felled plant), December 2003 (toppled plant and early decay residue), March 2004 (early decay residue), April 2004 (toppled plant) and February 2005 (early decay residue). The data over two seasons varied, but suggested that eggs mainly hatched from spring to autumn, with larval peaks in November to December, January/February, May and July, eclosing mainly in December to February, March to May, July and September/November (Fig. 3.4a, 3.4b). Probable timing of eclosions was mainly based on life stages in fresh residues and assumed that adults in decayed residues during winter were not newly emerged (Fig. 3.2a, 3.2b). The adult percentage-values indicated that weevils (only in the first season) mainly over-wintered as adults in decayed residues (winter mean: 89.06% adults), relatively more larvae were found in fresh residues (only in the second season) and that relative adult and larval numbers peaked in August, January, February (season 1), October (season 2) and November (season 1), February (season 2), respectively (Fig. 3.4a). The larval population comprised, on average, the earliest instars (smallest head capsule width) in March/April (season 1) and May/April (season 2) (Fig. 3.4b).

3.3.3 Leisure Bay trial

3.3.3.1 Adult activity

The respective adult densities were ln (x+1) transformed to comply with the assumptions of factorial ANOVA (Sokal & Rohlf 1997). Pheromone trapping showed a significant temporal ($F_{47, 192}$ = 6.67, P<0.001) and treatment effect ($F_{1, 192}$ = 59.02, P<0.001), but no interaction between the independent variables ($F_{47, 192}$ = 1.02, P=0.442). Post ANOVA analysis revealed numerous statistical differences between sampling weeks amounting to 11 homogenous overlapping groupings (data not

shown). The stationary traps attracted significantly more beetles over the annual period (P<0.001), collecting a (back-transformed) mean of 11.12 compared to 6.10 adults per week in the traps that were moved monthly. Multiple regression showed no significant relation between weekly ambient temperature and corrected rainfall with weekly adult density (data not shown). Averaging adult trapping densities per month and multiple regression with monthly adult and larval densities in the field, air temperature and/or rainfall also produced no significant interaction (data not shown).

One-way ANOVA of mean adult activity between months was conducted to provide an appropriate resolution of the average adult activity in the field. The data again showed a significant temporal effect ($F_{11, 57}$ = 4.65, P<0.001), with *post hoc* analysis revealing statistically similar peaks in August, February, April and May (Fig. 3.5). The activity in August was significantly higher than during December (Fig. 3.5). Catches in February were statistically similar to the other months, whereas the April values also significantly exceeded numbers in December. Statistically more weevils were collected in May compared to July, September, October, November, December and January.

3.3.3.2 Fecundity and sex ratio

The mean number of eggs per female varied significantly over months ($F_{11, 47}$ = 3.76, P<0.001), but showed no significant treatment effect ($F_{2, 47}$ = 0.10, P=0.909) nor interaction between time and treatment ($F_{22, 47}$ = 1.28, P=0.236). The percentage of females containing eggs were significantly different over time ($F_{11, 47}$ = 5.80, P<0.001), between treatments ($F_{2, 47}$ = 4.49, P=0.016) and also showed an interaction between time and treatment ($F_{22, 47}$ = 1.79, P=0.048). Post ANOVA analysis showed that eggs/female was significantly higher in February (late summer) and March (early autumn) compared to June and July (early to mid winter) (Table 3.3). Females in October also contained significantly more eggs than in June (Table 3.3). The proportion of females with eggs was minimised in June (28.88%) and July (30.08%) and significantly higher in September to December and April (73.81 to 85.12%), while the values of the remaining months were no different to either group (Table 3.3). Overall, the percentage of females with eggs was significantly higher in pheromone traps (68.32%) compared to fresh residues (53.76%), while the proportion in decayed residues (60.68%) was similar to the other treatments (data not shown). Interactively, the decayed residues in June and pheromone traps in July had a

significantly lower percentage of females with eggs than the January value of the pheromone traps (Table 3.3). Multiple regression showed a significant relationship between temperature (range: 14.85 to 24.11°C), eggs per female in fresh residues ($F_{2, 9}$ = 6.32, P<0.019, R^2=0.584, m = 0.235) and overall mean eggs per female ($F_{2, 9}$ = 5.35, P<0.030, R^2=0.543, m = 0.150). The percentage of females with eggs in pheromone traps was also significantly related to ambient temperature ($F_{2, 9}$ = 4.52, P<0.044, R^2=0.501, m = 3.550). The data showed that the potential oviposition (percentage females with eggs × eggs/female) peaked in spring and autumn; being minimised during winter.

The beetles collected monthly from plant residues did not show a biased sex ratio (two-tailed binomial distribution, Bonferroni corrected) and the percentage males varied from 44.29 to 65.12%. The sex ratio of beetles collected in the pheromone traps ranged from 10.38% males in February to 29.31% males in November, with values significantly female biased (two-tailed binomial distribution, Bonferroni corrected) in all the months except during July, November and December (data not shown).

3.3.3.3 Ontogenic field occurrence

Dissection of plants showed significant differences in the number of adults and larvae sampled between months ($F_{11, 96}$ = 2.47, P=0.009 and $F_{11, 96}$ = 6.82, P<0.001, respectively), with a treatment effect only evident for larvae ($F_{3, 96}$ = 1.29, P=0.283 and $F_{3, 96}$ = 5.63, P=0.001) and no interaction between the independent variables for either dependent variable ($F_{33, 96}$ = 1.13, P=0.313 and $F_{33, 96}$ = 1.21, P=0.239, respectively). The *post hoc* test revealed that only significantly more adults were sampled in the field in April compared to December (Fig. 3.6a), while larval numbers peaked in February and March (Fig. 3.6b). February harboured significantly more larvae than the winter (June to August) and spring months (September to November), whereas the numbers for March was statistically higher than all the months except February (Fig. 3.6b). Significantly more larvae were present in the toppled plants compared to the decayed residues (early and late rotting stages), with statistically similar values in felled and toppled plants (data not shown). Multiple regression showed no relationship between adults and ambient temperature and/or corrected rainfall, but revealed a significant relationship between ambient temperature and larvae in the decayed residues ($F_{2, 9}$ = 8.49, P<0.008, R^2=0.654, m = 0.311) and the

overall (decayed and fresh residues) number of larvae ($F_{2, 9}$ = 4.57, P<0.043, R^2=0.504, m = 0.356).

Pupae were sampled irregularly in June, September, February, March and May with overall respective means (±SE) of 0.17±0.17, 0.17±0.17, 0.33±0.33, 2.67±1.67 and 0.17±0.17. The data suggested that eggs mainly hatched from spring to autumn, with larval peaks in September, December to March and May, eclosing mainly in November, February to April and August (Fig. 3.6a, 3.6b). Probable timing of eclosions was mainly based on life stages in fresh residues and assumed adults in decayed residues during winter were not newly emerged (Fig. 3.2a, 3.2b). The adult percentage-values indicated that weevils mainly over-wintered as adults in decayed residues, relatively more larvae were found in fresh residues and that relative adult and larval numbers peaked in November and December, respectively (Fig. 3.6a). The larval population comprised, on average, the earliest instars (smallest head capsule width) in May and December (Fig. 3.6b).

3.4 Discussion

The three trial locations showed constant differences in weevil densities trapped, and collected from plants in the field. The Munster site harboured the lower number, while the Leisure Bay location showed the highest infestation. It was generally found that beetles were active throughout the year, with optimum activity occurring in May (late autumn). High numbers of beetles were also collected in September (early spring) and June (early winter). Previous reports concluded that weevil activity in South Africa (Mpumalanga) peaks in either spring (Schoeman 1996) or spring and autumn (De Jager 1993), while the latter was also reported in China (Luo *et al*. 1985; Maolin 1994). Activity of the weevil in Australia showed a major peak in spring, but weevils were also very active in autumn (Treverrow *et al*. 1992). The significant decline in activity during the second season at Ramsgate suggested that pheromone trapping caused destructive sampling. A declining tendency in trapping numbers has also been reported from pseudostem trapping in Brazil (Arleu *et al*. 1984).

Adult numbers in the semiochemical traps was not related to adult or larval densities in the field, but a negative and a positive function of ambient temperature and corrected rainfall, respectively. Activity increases have been reported shortly after rain in the tropics and subtropics (Treverrow *et al*. 1992, Smith 1995, Gold *et al*.

1999b, Govender & Viljoen 2002; Pinese & Elder 2004), but the results are in contrast to Schoeman (1996), who reported that catches in rhizome traps were positively correlated with temperature (in the Kiepersol area, South Africa). Of the current factors, temperature was the superior predictor of activity. Trapping densities were, however, not related to temperature (or corrected rainfall) at the highly infested site, suggesting that other variables (e.g. density) also influenced attraction to semiochemicals. No correlation between adult catches and rainfall or sunlight has also been reported in Columbia (Cárdenas & Arango 1986), and monitoring with pseudostem traps in Brazil also showed general uniform adult movement with no climate dependence (Arleu *et al*. 1984).

Analysis of fecundity variables showed that eggs per female were similar between weevils collected in traps or from plants, while the proportion of females with eggs peaked in traps, followed by beetles in decayed and fresh residues, respectively. Eggs per female and percentage females with eggs was reduced in winter and was a positive function of ambient temperature, in accordance with the Australian findings, where eggs were mostly laid in spring, late summer and autumn (Treverrow *et al*. 1992) and generally ceased during winter (Treverrow & Bedding 1993). Under local conditions, oviposition was not related to rainfall as has been reported in the tropics (Cuillé 1950). Although it was not empirically tested, the relative number of adults compared to larvae between the trials suggested that ovipositional rates were a negative function of weevil density (Abera *et al*. 1999; Gold *et al*. 1999b). The beetles sampled from plants represented an equal sex ratio, while the pheromone traps collected a female biased sex ratio in spring and autumn/early winter. Results should, however, be interpreted with caution, because the significance of the binomial distribution was dependent on absolute weevil number, which was relatively low in the plant residues. Nevertheless, the results supported the generally accepted 1:1 sex ratio (Cuillé 1950, Viswanath 1976, Delattre 1980; Gold *et al*. 1999b) of the weevil and the hypothesis that sexes have different behaviour patterns (Delattre 1980).

Cosmopolites sordidus had overlapping generations with a peak of adults and larvae in April/May (mid to late autumn) and February/March (late summer to early autumn), respectively. Adults were mainly associated with decayed residues while larvae were mostly found in fresh plants (toppled plants). The occurrence of adults in decayed residues was negatively related to ambient temperature, but this was not found at the highly infested site, where larval density was positively related to

ambient temperature. The data suggested that at relatively lower infestations, beetles do not mainly breed in decayed residues, but the adult preference of decayed residues in winter are more pronounced. In Brazil, no correlation between adult population fluctuation and rainfall, relative humidity, or temperature was found, but larval populations were positively related to temperature and rainfall (Arleu *et al*. 1984; Batista Filho *et al*. 1991). In the South Coast of KwaZulu-Natal (South Africa), eggs mainly hatched from spring to autumn, with a faint or absent larval peak in September (early spring), a moderate peak in November to December (late spring or early summer), a pronounced peak in February (late summer) and a variable peak in May (late autumn) and/or July (winter). Adult densities showed a moderate peak in November (late spring), a variable peak in February (late summer), a pronounced peak in April/May (autumn) and a moderate peak in July (winter). The data suggested that the beetle is multivoltine in the study areas and is in general agreement with the observations of the weevil in Australia and China, where adults mainly emerge during spring and autumn and has four to six generations per year (Froggatt 1926, Luo *et al*. 1985, Treverrow 1985, Treverrow & Bedding 1993, Maolin 1994; Pinese & Elder 2004). Adults were the main over-wintering life stage, which is in contrast to weevils in China, where mainly the larvae over-winter in old banana stems (Maolin 1994). Relative to larvae, adult numbers usually peaked in spring, while relative larval numbers peaked in summer. In general, the earliest instars in the field were sampled during autumn.

The trail series provided valuable insight into the population dynamics of the banana weevil in South Africa. From a management perspective, the time intervals for different control strategy options could be identified. Semiochemical mass-trapping or semiochemical attraction to biopesticides will be optimally applied in early spring and late autumn to early winter just after rain and/or when lower ambient temperatures prevail. Systemic chemicals and/or butt sprays (contact insecticides) to control adults should be applied in autumn and late spring, while treatment in summer should be validated by dissecting and inspecting plants. Systemic insecticides for larval control are recommended in late summer and late spring/early summer, while application in autumn should be validated by dissecting and inspecting plants. Contact insecticides should be used for injection of decayed residues during winter, especially for adult control. Release of potential egg parasitoids are recommended from spring to autumn (especially during the warmest times of the year), while adults and larvae are most

accessible (in decayed residues) to predators from autumn to spring and summer to winter, respectively.

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3.6 References

ABERA, A.M.K. 1997. *Oviposition Preferences and Timing of Attack by the Banana Weevil (*Cosmopolites sordidus *Germar) in East African Highland Banana (*Musa *spp.)*. M.Sc. Thesis, Makerere University, Uganda.

ABERA, A.M.K., GOLD, C.S. & KYAMANYWA, S. 1999. Timing and distribution of attack by the banana weevil (Coleoptera: Curculionidae) in East African highland banana (*Musa* spp.). *Florida Entomologist* 82: 631-641.

ALPIZAR, D., FALLAS, M., OEHLSCHLAGER, A.C., GONZALEZ, L. & JAYARAMAN, S. 1998. Pheromone-based mass-trapping of the banana weevil, *Cosmopolites sordidus* (Germar) and the West Indian sugarcane weevil *Metamasius hemipterus* L. (Coleoptera: Curculionidae) in plantain and banana. In: *Memorias XIII Reunion ACORBAT, Guayaquil, Ecuador*. November 1998: 515-538.

ANONYMOUS. 2004. *Pheromone trapping system,* Cosmopolites sordidus *and* Metamasius hemipterus. Information pamphlet, CTI IPM products. ChemTica Internacional, S.A., Costa Rica.

ARLEU, R.J., NETO, S.S., GOMES, J.A., NOBREGA, A.C. & SARDINI, D.M. 1984. Dinamica populacional do *Cosmopolites sordidus* (Germ. 1824) (Col: Curculionidae) em bananais da cv. Prata (Grupo AAB), em Alfredo Chaves, Espirito Santo. *Turrialba* 34: 473-480.

BATISTA FILHO, A., SATO, M.E., RAGA, A., LEITE, L.G. & PRADA, A. 1991. Flutuacao populacional da broca da bananeira (*Cosmopolites sordidus* Germar) em Miracatu, SP. *Ecossistema* 16: 46-53.

BECCARI, F. 1967. Contributo alla conoscenza del *Cosmopolites sordidus* (Germ.) (Coleopt., Curcul.). *Rivista di Agricultura Subtropicale e Tropicale, Firenze* 61: 131-150.

BUDENBERG, W.J., NDIEGE, J.O. & KARAGO, F.W. 1993. Evidence for volatile male produced pheromone in banana weevil *Cosmopolites sordidus*. *Journal of Chemical Ecology* 19: 1905-1916.

CARDENAS, R. & ARANGO, L.G. 1986. Fluctuacion poblacional y dispersion del picudo negro del plátano *Cosmopolites sordidus* (Germar 1824). *Revista Colombiana de Entomologia* 12: 37-45.

CUILLÉ, J. 1950. *Recherches sur le Charancon du Bananier*. Institut des Fruits Agrumes Coloniaux; Serie Technique No 4, Paris.

DE GRAAF, J., GOVENDER, P., SCHOEMAN, A.S. & VILJOEN, A. 2005. Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa. *International Journal of Pest Management* 51: 209-218.

DE JAGER, K. 1993. Banana weevil borer. In: Robinson, J.C. (Ed.) *Handbook of Banana Growing in South Africa*. 119-120. Institute for Tropical and Subtropical Crops, Nelspruit.

DELATTRE, P. 1980. Recherche d'une methode d'estimation des populations du charancon du bananier, *Cosmopolites sordidus* Germar (Col., Curc.). *Acta Oecologia* 1: 83-92.

DOCHEZ, C. 1998. *Study on Pest Status and Control of* Cosmopolites sordidus *(Germar) in South Africa*. M.Sc. Thesis, Heriot-Watt University, Scotland.

FEAKIN, S.D. 1971. *Pest Control in Bananas*. 2nd Edition. London, PANS.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

FROGGATT, J.L. 1925. The banana weevil borer (*Cosmopolites sordidus*). *Queensland Agricultural Journal* 24: 558-593.

FROGGATT, J.L. 1926. *The Banana Weevil Borer*. Bulletin No. 4. Queensland Department of Agriculture and Stock, Brisbane, Australia.

GOLD, C.S. & MESSIAEN, S. 2000. *The Banana Weevil,* Cosmopolites sordidus. Musa Pest Fact Sheet No. 4, INIBAP.

GOLD, C.S., NEMEYE, P.S. & COE, R. 1999a. Recognition and duration of the larval instars of banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 7: 49-62.

GOLD, C.S., PEÑA, J.E. & KARAMURA, E.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews* 6: 79-155.

GOLD, C.S., RUKAZAMBUGA, N.D.T.R., KARAMURA, E.B., NEMEYE, P. & NIGHT, G. 1999b. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 33-50.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., TUSHEMEREIRWE, W.K. & KASHAIJA, I.N. 1994. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2: 309-321.

GOVENDER, P. & VILJOEN, A. 2002. The biology and management of the banana weevil, *Cosmopolites sordidus* in South Africa. *Infomusa* 11: 10.

HASYIM, A. & HARLION, D. 1998. *Dinamika Populasi Hama Penggerek Bonggol Pisang di Sitiung, Sumatera Barat*. Laporan tahunan Anggaran tahunan, APBN 1997-1998.

HORD, H.Y. & FLIPPEN, R.S. 1956. Studies of banana borer in the Honduras. *Journal of Economic Entomology* 49: 296-300.

JAYARAMAN, S., NDIEGE, I.O., OEHLSCHLAGER, A.C., GONZALEZ, L.M., ALPIZAR, D., FALLAS, M., BUDENBERG, W.J. AND AHUYA, P. 1997. Synthesis, analysis, and field activity of sordidin, a male produced aggregation pheromone of the banana weevil, *Cosmopolites sordidus*. *Journal of Chemical Ecology* 23: 1145-1161.

KOPPENHÖFER, A.M. 1993. Observation on egg laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata* 68: 187-192.

LONGORIA, A. 1968. Diferencias sexuales en la morfologia externa de *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae). *Ciencia Biologica la Habana* 1: 1-11.

LUO, L.Y., LUO, Q.C., YAO, X. & LIU, Z.L. 1985. Weevils injurious to banana in Guizhou and their biological features. *Insect Knowledge (Kunchong Zhishi)* 22: 265-267.

MAOLIN, S. 1994. Status of nematode and weevil borer problems affecting banana in China. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines, INIBAP*. 57-62.

MESQUITA, A.L.M., ALVES, E.J. & CALDAS, R.C. 1984. Resistance of banana cultivars to *Cosmopolites sordidus* (Germar 1824). *Fruits* 39: 254-257.

NDIEGE, I.O., JAYARAMAN, S., OEHLSCHLAGER, A.C., GONZALEZ, L., ALPIZAR, D. & FALLAS, M. 1996. Convenient synthesis and field activity of a male-produced aggregation pheromone of *Cosmopolites sordidus*. *Naturwissenschaften* 83: 280-282.

OSTMARK, H.E. 1974. Economic insect pests of bananas. *Annual Review of Entomology* 19: 161-176.

PARNITZKI, P. 1992. *Biologische Bekämpfung des Rüsselkäfers* Cosmopolites sordidus *(Germar) mit entomopathogenen Nematoden der Gattungen* Heterorhabditis *und* Steinernema *sowie Untersuchungen zur Biologie de Schädlings*. Ph.D. Thesis, University of Bonn, Germany.

PINESE, B. & ELDER, R. 2004. *Banana Weevil Borer*. Queensland Government, Department of Primary Industries and Fisheries, Horticulture and Fresh Produce. World Wide Web: http://www.dpi.qld.gov.au/horticulture/2507.html

ROTH, L.M. & WILLIS, E.R. 1963. The humidity behavior of *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Annals of the Entomological Society of America* 56: 41-52.

RUKAZAMBUGA, N.D.T.M., GOLD, C.S. & GOWEN, S.R. 1998. Yield loss in East African highland banana (*Musa* spp., AAA-EA group) caused by the banana weevil, *Cosmopolites sordidus* Germar. *Crop Protection* 17: 581-589.

SCHOEMAN, P.S. 1996. Control of the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). In: Robinson, J.C. (Ed.) *Banana Growers Association of South Africa* 1: 83-87.

SESHU REDDY, K.V., GOLD, C.S. & NGODE, L. 1999. Cultural control strategies for the banana weevil, *Cosmopolites sordidus* Germar. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 51-57.

SIMMONDS, N.W. 1959. *Bananas*. 1st Edition. Longmans Press, London.

SIMMONDS, N.W. 1966. *Bananas*. 2nd Edition. Longmans Press, London.

SMITH, D. 1995. Banana weevil borer control in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 35: 1165-1172.

SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. W.H. Freeman and Company, New York.

STATSOFT INCORPORATED. 2004. *Statistica*. Version 7.

STOVER, R.H. & SIMMONDS, N.W. 1987. *Bananas*. Third Edition. 469. John Wiley and Sons, New York.

TINZAARA, W., TUSHEMEREIRWE, W. & KASHAIJA, I. 1999. The potential of using pheromone traps for the control of the banana weevil *Cosmopolites sordidus* Germar in Uganda. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 23-28.

TRAORE, L., GOLD, C.S., BOIVIN, G. & PILON, J.G. 1996. Developpement postembryonnaire du charancon du bananier. *Fruits* 51: 105-113.

TRAORE, L., GOLD, C.S., PILON, J.G. & BOIVIN, G. 1993. Effects of temperature on embryonic development of banana weevil *Cosmopolites sordidus* Germar. *African Crop Science Journal* 1: 111-116.

TREVERROW, N.L. 1985. *Banana Weevil Borer.* Agfact H6.AE.1, 2nd edition. NSW Agriculture and Fisheries, Australia.

TREVERROW, N.L. & BEDDING, R.A. 1993. Development of a system for the control of the banana weevil borer, *Cosmopolites sordidus* with entomopathogenic nematodes. In: Bedding, R.A., Akhurst, R. & Kaya, H. (Eds.) *Nematodes and the Biological Control of Insect Pests, Melbourne, CSIRO*. 41-47.

TREVERROW, N. & MADDOX, C. 1993. The distribution of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) between various types of banana plant material in relation to crop hygiene. *General and Applied Entomology* 23: 15-20.

TREVERROW, N., PEASLEY, D. & IRELAND, G. 1992. *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*. Banana Industry Committee, New South Wales Agriculture.

UZAKAH, R.P. 1995. *The Reproductive Biology, Behaviour, and Pheromones of the Banana Weevil,* Cosmopolites sordidus *Germar (Coleoptera: Curculionidae).* Ph.D. Thesis, University of Ibadan, Nigeria.

VISWANATH, B.N. 1976. *Studies on the Biology, Varietal Response and Control of Banana Rhizome Weevil,* Cosmopolites sordidus *(Germar) (Coleoptera: Curculionidae).* Ph.D. Thesis, University of Bangalore, Bangalore, India.

VISWANATH, B.N. 1977. Studies on the biology, varietal response and control of banana rhizome weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Mysore Journal of Agricultural Sciences* 11: 597-598.

WATERHOUSE, D.F. & NORRIS, K.R. 1987. *Cosmopolites sordidus* (Germar). In: Waterhouse, D.F. & Norris, K.R. (Eds.) *Biological Control: Pacific Prospects*. 152-158, 454. Inkata Press, Melbourne.

Table 3.1. The mean (±SE) number of eggs per female and percentage (±SE) of females containing eggs (% Egg females) of *Cosmopolites sordidus* in pheromone traps at Munster (KZN, South Africa) from May 2003 to April 2004. For each dependent variable, letters in common indicate no significant difference (P>0.05). N/A=Not available.

Date	Dependent variable	
	Eggs/female	% Egg females
May 2003	2.4±0.3[a]	84.5±3.8
Jun 2003	1.8±0.2[a]	64.4±7.2
Jul 2003	1.9±0.6[a]	85.3±14.7
Aug 2003	1.9±0.2[a]	72.6±17.5
Sep 2003	2.4±0.2[a]	89.4±5.8
Oct 2003	2.5±0.3[a]	93.7±6.3
Nov 2003	N/A	N/A
Dec 2003	2.6±0.3[a]	95.8±4.2
Jan 2004	3.8±0.2[a]	97.0±3.0
Feb 2004	1.8±0.9[a]	58.3±30.0
Mar 2004	3.4±0.4[a]	91.4±4.8
Apr 2004	1.5±0.8[a]	51.4±26.4

Table 3.2. The mean (±SE) number of eggs per female and percentage (±SE) of females containing eggs (% Egg females) of *Cosmopolites sordidus* in pheromone traps at Ramsgate (KZN, South Africa) from May 2003 to September 2004. For each dependent variable, letters in common indicate no significant difference (P>0.05).

Date	Dependent variable	
	Eggs/female	% Egg females
May 2003	2.5±0.1	79.6±10.9^{abc}
Jun 2003	1.8±0.1	47.1±8.5^{abc}
Jul 2003	2.6±0.8	35.5±7.8^{ab}
Aug 2003	0.8±0.4	19.4±10.0^{a}
Sep 2003	2.6±0.3	80.4±6.6^{bc}
Oct 2003	2.6±0.1	54.3±8.1^{abc}
Nov 2003	2.4±0.4	100.0±0.0^{bc}
Dec 2003	2.1±1.1	61.9±31.2^{abc}
Jan 2004	2.5±0.3	100.0±0.0^{c}
Feb 2004	2.3±0.1	81.7±4.4^{bc}
Mar 2004	3.2±0.2	76.4±11.9^{abc}
Apr 2004	2.1±0.3	68.1±10.8^{abc}
May 2004	2.5±0.2	77.3±5.6^{abc}
Jun 2004	1.4±0.2	37.3±2.0^{ab}
Jul 2004	1.6±0.3	35.0±8.2^{ab}
Aug 2004	1.8±0.4	35.3±7.6^{ab}
Sep 2004	2.1±0.6	78.3±12.4^{bc}

Table 3.3. The mean (±SE) number of eggs per female and percentage (±SE) of females containing eggs (% Egg females) of *Cosmopolites sordidus* in decayed plant residues, fresh plant residues and pheromone traps at Leisure Bay (KZN, South Africa) from June 2004 to May 2005. For each dependent variable, letters in common indicate no significant difference (P>0.05).

Date	Dependent variable	Plant residues		Traps	Mean
		Decayed	Fresh	Pheromone	
Jun 2004	Eggs/female	0.8±0.75	0.0	1.5±0.13	1.0±0.32^{b}
	% Egg females	11.1±11.11^{a}	0.0^{ab}	50.3±4.83^{ab}	28.9±10.38$^{\mathbf{b}}$
Jul 2004	Eggs/female	2.0±1.00	2.0±0.00	0.8±0.44	1.5±0.36^{bc}
	% Egg females	55.0±5.00^{ab}	22.5±2.50^{ab}	18.5±9.80^{a}	30.1±7.55$^{\mathbf{b}}$
Aug 2004	Eggs/female	1.8±0.75	1.3±0.25	2.3±0.19	1.8±0.26^{abc}
	% Egg females	25.3±11.04^{ab}	61.9±4.76^{ab}	52.2±5.07^{ab}	47.3±6.74$^{\mathbf{ab}}$
Sep 2004	Eggs/female	2.9±0.53	2.8±0.75	2.7±0.20	2.8±0.22^{abc}
	% Egg females	91.7±8.33^{ab}	87.5±12.50^{ab}	79.2±5.73^{ab}	85.1±4.50$^{\mathbf{a}}$
Oct 2004	Eggs/female	2.8±0.25	3.2±0.32	2.8±0.42	2.9±0.20^{ac}
	% Egg females	83.3±16.67^{ab}	68.8±18.75^{ab}	77.8±4.54^{ab}	76.8±6.17$^{\mathbf{a}}$
Nov 2004	Eggs/female	2.0±0.67	2.6±0.05	3.4±0.12	2.8±0.28^{abc}
	% Egg females	83.3±5.56^{ab}	86.1±2.78^{ab}	79.7±5.63^{ab}	82.6±2.75$^{\mathbf{a}}$
Dec 2004	Eggs/female	2.7±0.67	1.2±1.2	3.2±0.33	2.5±0.47^{abc}
	% Egg females	83.3±16.67^{ab}	50.0±50.00^{ab}	83.3±9.62^{ab}	73.8±13.54$^{\mathbf{a}}$
Jan 2005	Eggs/female	3.5±2.00	2.3±2.3	2.6±0.08	2.8±0.70^{abc}
	% Egg females	50.0±16.67^{ab}	16.2±12.36^{ab}	81.8±4.47^{b}	63.5±13.20$^{\mathbf{ab}}$
Feb 2005	Eggs/female	1.75±0.75	5.0±2.00	3.3±0.25	3.4±0.69^{a}
	% Egg females	50±16.67^{ab}	37.5±37.5^{ab}	89.8±5.11^{ab}	54.0±12.13$^{\mathbf{ab}}$
Mar 2005	Eggs/female	3.9±0.13	3.7±0.67	2.9±0.17	3.4±0.23^{a}
	% Egg females	65.0±15.00^{ab}	36.4±6.43^{ab}	82.0±0.37^{ab}	64.1±8.49$^{\mathbf{ab}}$
Apr 2005	Eggs/female	3.2±0.33	2.7±0.29	2.5±0.15	2.8±0.16^{abc}
	% Egg females	63.3±3.33^{ab}	88.9±11.11^{ab}	76.3±3.21^{ab}	76.2±4.84$^{\mathbf{a}}$
May 2005	Eggs/female	2.3±0.67	2.1±0.10	2.0±0.08	2.1±0.16^{abc}
	% Egg females	66.7±33.33^{ab}	62.5±37.5^{ab}	49.0±4.41^{ab}	57.9±11.53$^{\mathbf{ab}}$

Figure legends

Figure 3.1. The mean weekly activity (+SE) of adult *Cosmopolites sordidus* measured by semiochemical (Cosmolure®) baited pitfall traps in stationary positions (triangles with solid lines) and independent monthly positions (squares with dotted lines) at Munster (KZN, South Africa) from May 2003 to April 2004. Significance of the mean monthly activity (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference (P>0.05).

Figure 3.2a. The mean monthly number (+SE) and percentage (±SE) (secondary y-axis) of adult *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white bars) banana residues at Munster (KZN, South Africa), measured from May 2003 to April 2004. Significance of the mean monthly densities (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference (P>0.05). The black dots indicate the percentage of adults in decayed residues, while the white filled dots present the adult percentage in the fresh residues.

Figure 3.2b. The mean monthly number (+SE) and head capsule width (mm) (±SE) (secondary y-axis) of larval *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white bars) banana residues at Munster (KZN, South Africa) from May 2003 to April 2004. The shaded area represents the mean monthly densities. The black dots indicate the mean larval head capsule width in the decayed residues, while the white filled dots present the head capsule width in the fresh residues.

Figure 3.3. The mean weekly activity (+SE) of adult *Cosmopolites sordidus* measured by semiochemical (Cosmolure®) baited pitfall traps in stationary positions (triangles with solid lines) and independent monthly positions (squares with dotted lines) at Ramsgate (KZN, South Africa) from May 2003 to April 2005, represented as annual figures. Significance of the mean monthly activity (shaded area) are indicated on the x-axis's, where letters in common indicate no significant difference (P>0.05).

Figure 3.4a. The mean monthly number (+SE) and percentage (±SE) (secondary y-axis) of adult *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white

bars) banana residues at Ramsgate (KZN, South Africa) from May 2003 to April 2005, represented as annual figures. The shaded area represents the mean monthly densities. The black dots indicate the percentage of adults in decayed residues, while the white filled dots present the adult percentage in the fresh residues.

Figure 3.4b. The mean monthly number (+SE) and head capsule width (mm) (±SE) (secondary y-axis) of larval *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white bars) banana residues at Ramsgate (KZN, South Africa) from May 2003 to April 2005, represented as annual figures. Significance of the mean monthly densities (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference (P>0.05). The black dots indicate the mean larval head capsule width in the decayed residues, while the white filled dots present the head capsule width in the fresh residues.

Figure 3.5. The mean weekly activity (+SE) of adult *Cosmopolites sordidus* measured by semiochemical (Cosmolure®) baited pitfall traps in stationary positions (triangles with solid lines) and independent monthly positions (squares with dotted lines) at Leisure Bay (KZN, South Africa) from June 2004 to May 2005. Significance of the mean monthly activity (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference (P>0.05).

Figure 3.6a. The mean monthly number (+SE) and percentage (±SE) (secondary y-axis) of adult *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white bars) banana residues at Leisure Bay (KZN, South Africa) from June 2004 to May 2005. Significance of the mean monthly densities (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference (P>0.05). The black dots indicate the percentage of adults in decayed residues, while the white filled dots present the adult percentage in the fresh residues.

Figure 3.6b. The mean monthly number (+SE) and head capsule width (mm) (±SE) (secondary y-axis) of larval *Cosmopolites sordidus* in decayed (D, black bars) and fresh (F, white bars) banana residues at Leisure Bay (KZN, South Africa) from June 2004 to May 2005. Significance of the mean monthly densities (shaded area) is indicated on the x-axis, where letters in common indicate no significant difference

(P>0.05). The black dots indicate the mean larval head capsule width in the decayed residues, while the white filled dots present the head capsule width in the fresh residues.

Figure 3.1

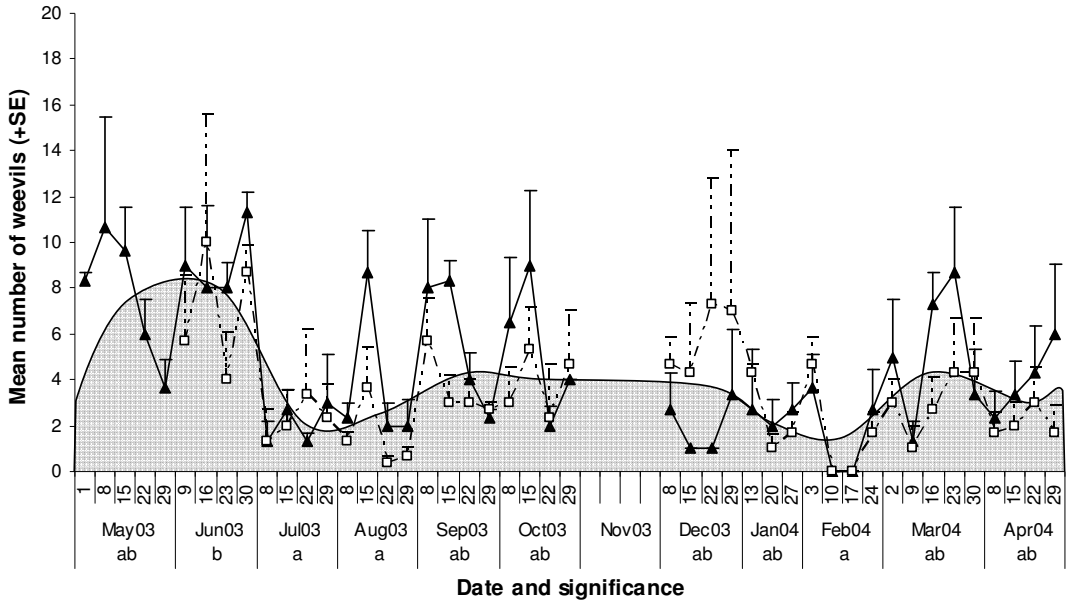

Mean number of weevils (+SE)
20
18
16
14
12
10
8
6
4
2
0
1 8 15 22 29 9 16 23 30 8 15 22 29 8 15 22 29 8 15 22 29 8 15 22 29 8 15 22 29 8 15 22 29 13 20 27 3 10 17 24 2 9 16 23 30 8 15 22 29
May03 ab
Jun03 b
Jul03 a
Aug03 a
Sep03 ab
Oct03 ab
Nov03
Dec03 ab
Jan04 ab
Feb04 a
Mar04 ab
Apr04 ab
Date and significance

Figure 3.2a

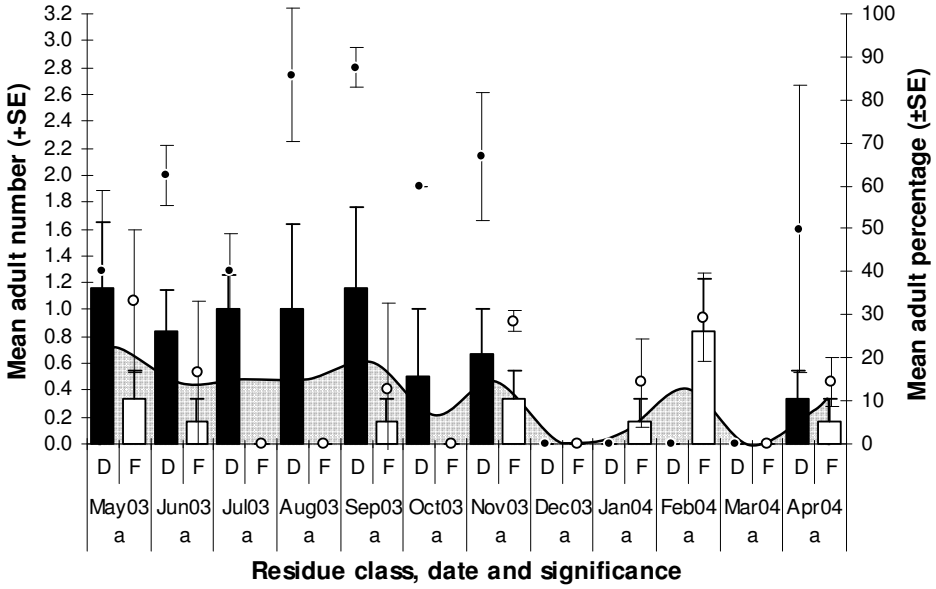

Mean adult number (+SE)
Mean adult percentage (±SE)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
100
90
80
70
60
50
40
30
20
10
0
D F D F D F D F D F D F D F D F D F D F D F D F
May03 Jun03 Jul03 Aug03 Sep03 Oct03 Nov03 Dec03 Jan04 Feb04 Mar04 Apr04
a a a a a a a a a a a a
Residue class, date and significance

Figure 3.2b

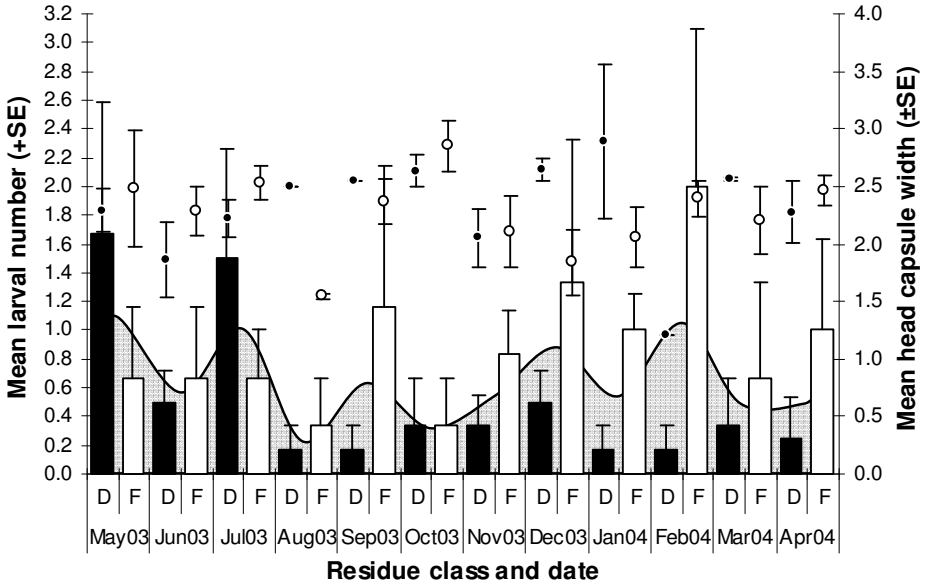

Mean larval number (+SE)
Mean head capsule width (±SE)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
D F D F D F D F D F D F D F D F D F D F D F D F
May03 Jun03 Jul03 Aug03 Sep03 Oct03 Nov03 Dec03 Jan04 Feb04 Mar04 Apr04
Residue class and date

Figure 3.3

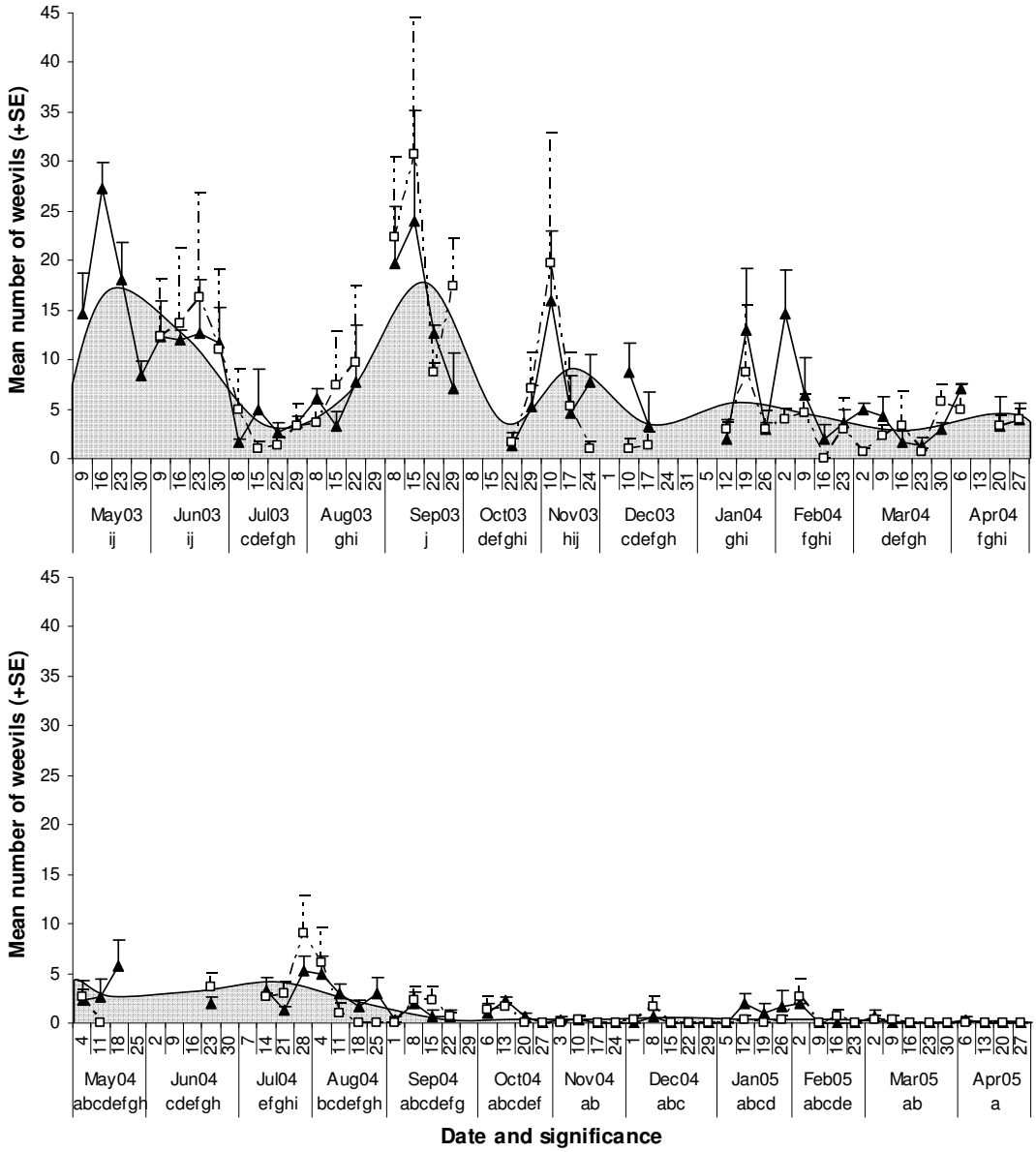

Mean number of weevils (+SE)
May03 ij
Jun03 ij
Jul03 cdefgh
Aug03 ghi
Sep03 j
Oct03 defghi
Nov03 hij
Dec03 cdefgh
Jan04 ghi
Feb04 fghi
Mar04 defgh
Apr04 fghi
Mean number of weevils (+SE)
May04 abcdefgh
Jun04 cdefgh
Jul04 efghi
Aug04 bcdefgh
Sep04 abcdefg
Oct04 abcdef
Nov04 ab
Dec04 abc
Jan05 abcd
Feb05 abcde
Mar05 ab
Apr05 a
Date and significance

Figure 3.4a

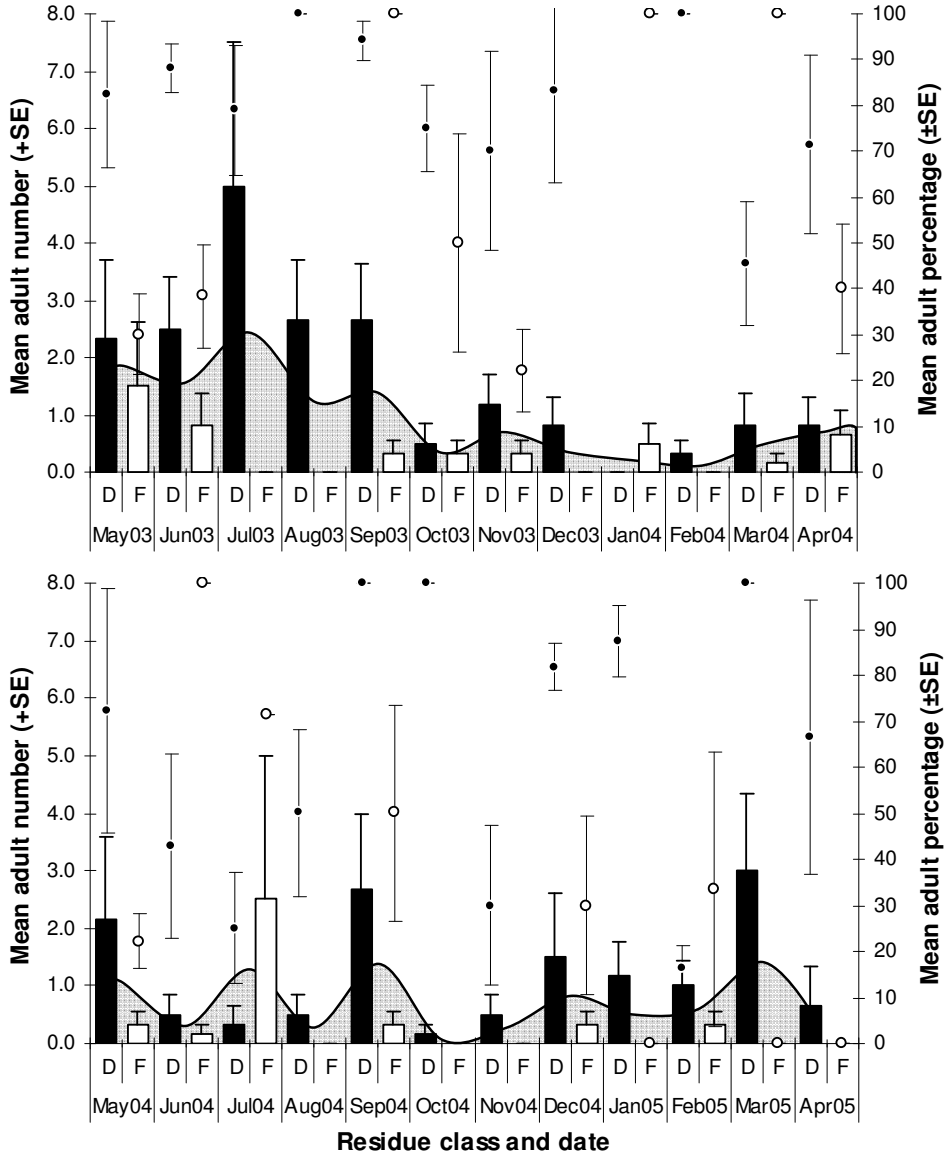
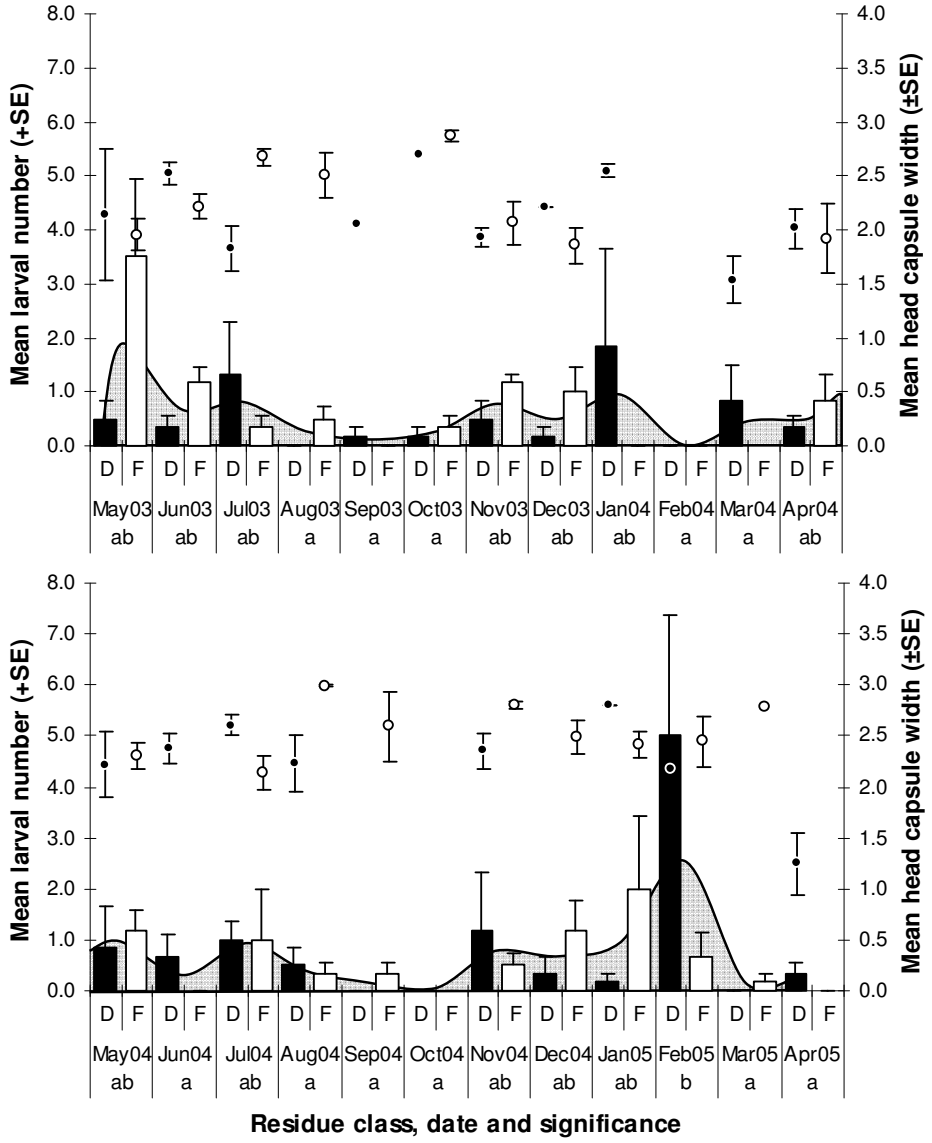

Mean adult number (+SE)
Mean adult percentage (±SE)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
10
20
30
40
50
60
70
80
90
100
D F D F D F D F D F D F D F D F D F D F D F D F
May03 Jun03 Jul03 Aug03 Sep03 Oct03 Nov03 Dec03 Jan04 Feb04 Mar04 Apr04
May04 Jun04 Jul04 Aug04 Sep04 Oct04 Nov04 Dec04 Jan05 Feb05 Mar05 Apr05
Residue class and date

Figure 3.4b


Mean larval number (+SE)
Mean head capsule width (±SE)
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7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
D F D F D F D F D F D F D F D F D F D F D F D F
May03 Jun03 Jul03 Aug03 Sep03 Oct03 Nov03 Dec03 Jan04 Feb04 Mar04 Apr04
ab ab ab a a a ab ab ab a a ab
May04 Jun04 Jul04 Aug04 Sep04 Oct04 Nov04 Dec04 Jan05 Feb05 Mar05 Apr05
ab a ab a a a ab ab ab b a a
Residue class, date and significance

Figure 3.5

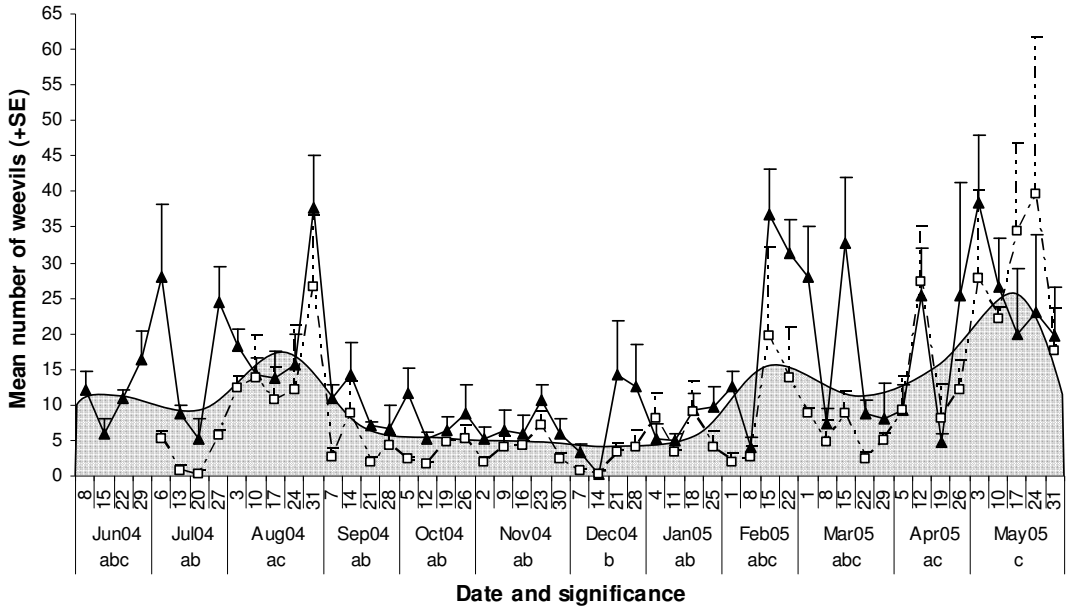

Mean number of weevils (+SE)
65
60
55
50
45
40
35
30
25
20
15
10
5
0
8 15 22 29 6 13 20 27 3 10 17 24 31 7 14 21 28 5 12 19 26 2 9 16 23 30 7 14 21 28 4 11 18 25 1 8 15 22 1 8 15 22 29 5 12 19 26 3 10 17 24 31
Jun04 Jul04 Aug04 Sep04 Oct04 Nov04 Dec04 Jan05 Feb05 Mar05 Apr05 May05
abc ab ac ab ab ab b ab abc abc ac c
Date and significance

Figure 3.6a

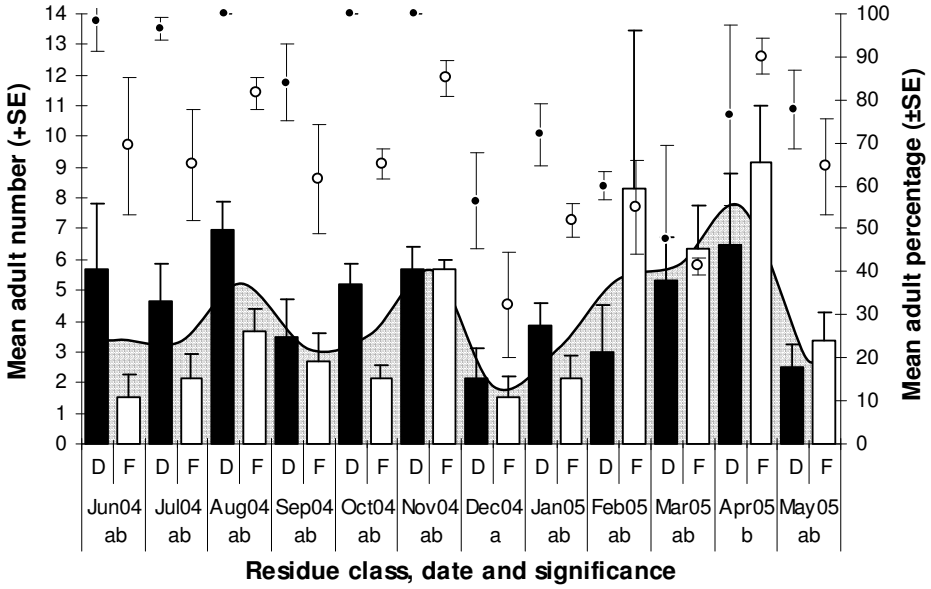
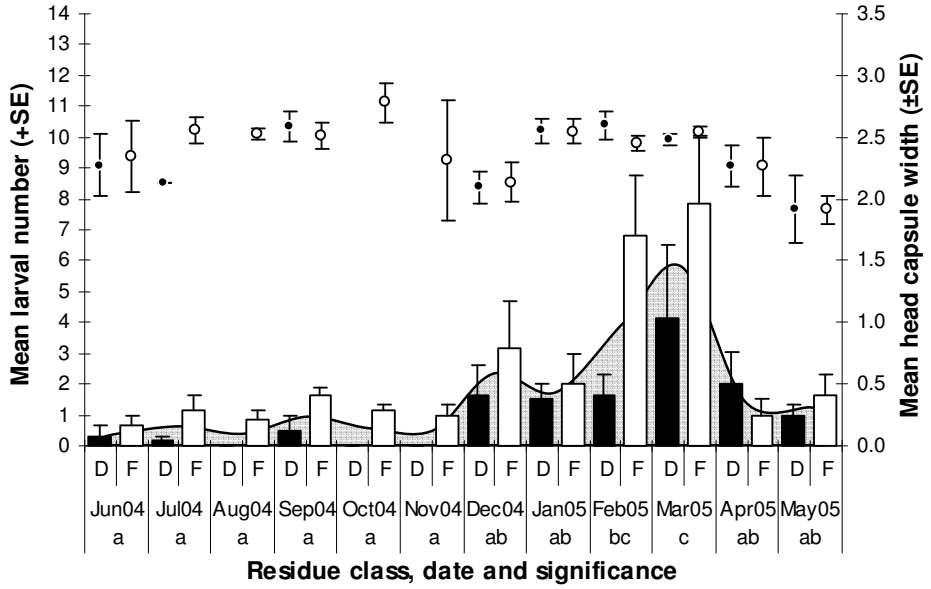

Mean adult number (+SE)
Mean adult percentage (±SE)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
10
20
30
40
50
60
70
80
90
100
D F D F D F D F D F D F D F D F D F D F D F D F
Jun04 ab
Jul04 ab
Aug04 ab
Sep04 ab
Oct04 ab
Nov04 ab
Dec04 a
Jan05 ab
Feb05 ab
Mar05 ab
Apr05 b
May05 ab
Residue class, date and significance

Figure 3.6b


Mean larval number (+SE)
Mean head capsule width (±SE)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
D F D F D F D F D F D F D F D F D F D F D F D F
Jun04 a
Jul04 a
Aug04 a
Sep04 a
Oct04 a
Nov04 a
Dec04 ab
Jan05 ab
Feb05 bc
Mar05 c
Apr05 ab
May05 ab
Residue class, date and significance

Chapter 4

Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa

Formatted according to the International Journal of Pest Management: De Graaf, J., Govender, P., Schoeman, A.S. and Viljoen, A. 2005. Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa. *International Journal of Pest Management* 51: 209-215.

Abstract

The banana weevil (*Cosmopolites sordidus*) is an important pest of bananas (Musaceae: *Musa* species) in South Africa. Adult trapping methods were compared in field trials using a randomised block design. Pseudostem traps, pitfall traps containing a pheromone (either Cosmolure® (Pheromone A) or Cosmolure+® (Pheromone B)), and unbaited pitfall traps (control), were compared over 5 weeks during all seasons along the Southeast coast of South Africa. Pseudostem traps treated with an insecticide, and rhizome traps were included as additional treatments in autumn. In summer two treatments were also added: individual suspension of both pheromones above a pitfall trap either in combination with or without a pseudostem trap. The adult beetles were sexed, and the number of internal eggs noted. Pheromone A proved to be the most effective of the different traps. Grouping of the pheromones resulted in a synergistic response, while combining the pseudostem did not enhance trap efficacy. The different plant material traps and the control were usually equally effective in catching weevils. Plant material traps caught greater numbers of fecund females, but pheromone traps captured a higher proportion of females. Treatment effects were much less pronounced in summer, and compared to a pseudostem trap, pitfall traps were the most efficacious during spring. Compared to conventional pseudostem trapping, Pheromone A pitfall traps should be optimally applied during spring in South Africa.

Keywords: Pheromone trap, pseudostem, sex, fecundity, season.

4.1 Introduction

Semiochemical trapping of the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), has been employed since the early twentieth century and has been retained in modern recommendations for monitoring and control (Knowles and Jepson 1912, cited in Froggat 1928, Cuille 1950, Arleu 1982, Bujulu *et al*. 1983, Allen 1989, Ogenga-Latigo and Bakyalire 1993, Mestre and Rhino 1997). Historically, semiochemical trapping of the banana weevil was exclusively based on chemicals emitted by the host plant (serving as kairomones) (Cuille 1950, Budenberg *et al*. 1993a). These traps are still used today and are developed from residual pseudostems and rhizomes (Gold *et al*. 2003). Several trap designs are known, (Hord and Flippen 1956, Castrillon 1989, 1991, cited in Gold *et al*. 2003, Batista Filho *et al*. 1990, Collins *et al*. 1991, Treverrow *et al*. 1992, Price 1993, Raga and De Oliveira 1996, Aranzazu *et al*. 2000, cited in Gold *et al*. 2003), but disk-on-stump traps, pseudostem-disk traps and split-pseudostem traps are the most common (Yaringano and Van der Meer 1975, Mitchell 1978, Koppenhöfer 1992, Treverrow *et al*. 1992, Gold *et al*. 1999). Traps manufactured from different plant clones show great variation in weevil capture, although reports are inconsistent (Gold *et al*. 2003). Pseudostems (Cuille 1950, Sumani 1997) and rhizomes (Hord and Flippen 1956, Yaringano and Van der Meer 1975, Cerda *et al*. 1995) have been claimed to be the most effective trapping material. Fresh (Delattre 1980, Koppenhöfer *et al*. 1994) or decayed (Budenberg *et al*. 1993b) material may attract the most weevils. Rhizome trap preparations are laborious to perform and pseudostem traps are more common and preferred by most growers. Traps prepared from the proximal end of the pseudostem may be the most attractive (Mestre and Rhino 1997). Recently, dead banana leaves and other non-host plants were reported to potentially exceed the attractiveness of pseudostem and rhizome material (Braimah 1997, Braimah and Van Emden 1999). The major attractive kairomone substances are unknown (Budenberg *et al*. 1993b, Braimah 1997), but lipophilic plant and annalose-11 volatiles (Jones 1968), mono- and sesquiterpenes (Ndiege *et al*. 1991) and 1,8 cineole (Ndiege *et al*. 1996a) have been suggested as attractants.

The aggregation behaviour of *C. sordidus* is well known (Cuille 1950), but evidence of an aggregation pheromone was only recently obtained and it was suggested that it is produced by males via the hindgut (Budenberg *et al*. 1993a).

Females may also produce a pheromone responsible for initial attraction, while the male pheromone may cause the main aggregation (De Mendonca *et al*. 1999). Beauhaire *et al*. (1995) identified six male specific compounds, with 80% comprised of a single compound ($C_{11}H_{20}O_2$) with formula (1S, 3R, 5R, 7S) 2, 8-dioxa 1-ethyl 3, 5, 7 – trimethyl bicyclo (3, 2, 1) octane. This was synthesised and named sordidin (Beauhaire *et al*. 1995), a compound related to known ketal pheromones produced by scolytids (Gold *et al*. 2003). Large-scale synthesis of the four diastereoisomers (*exo*-β-sordidin, *endo*-β-sordidin, *exo*-α-sordidin and *endo*-α-sordidin) of sordidin made field testing possible (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997). In field and laboratory trials, pheromones have been shown to attract significantly more weevils than plant material traps (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997, Tinzaara *et al*. 2003).

The efficacy of trapping to control the banana weevil is disputed (Gold *et al*. 1993, Fogain *et al*. 2002, Gold *et al*. 2003) and appears to be affected by population density (Seshu Reddy *et al*. 1999), trapping intensity (Fogain *et al*. 2002), management and/or immigration (Gold *et al*. 2002). Nevertheless, intensive split-pseudostem trapping (one trap/mat/month) has been shown to significantly reduce *C. sordidus* damage after one year (Gold *et al*. 2002). Semiochemical-enhanced mass trapping has also been reported to exert effective control (Alpizar *et al*. 1998). The control potential of pheromone mass trapping compared to plant material may depend on climate, cultivation practices, proportion of the population attracted and the monetary cost of trapping. These factors may vary between areas and may also be influenced by the possible occurrence of weevil biotypes.

In South Africa, management of the banana weevil is based mainly on pseudostem trapping, a practice that is both labour intensive and costly. No research comparing pheromones to conventional traps has been conducted in the country, and the only reports available address pheromone efficacy in tropical countries (Ndiege *et al*. 1996b, Alpizar and Fallas 1997, Jayaraman *et al*. 1997, Alpizar *et al*. 1998, Tinzaara *et al*. 1999). In the framework of integrated pest management, the aim of the study was to quantify the efficacy of pheromone trapping under local conditions. Plant and pheromone traps were compared during different seasons in terms of the number and fecundity of the beetles attracted.

4.2 Material and methods

4.2.1 Research sites

Trials were conducted on different commercial banana farms in the South Coast of KwaZulu-Natal, South Africa. Farms were situated in Munster (31°01'44''S; 30°12'30''E), Leisure Bay (31°00'56''S; 30°14'33''E), and Ramsgate (two locations) (a: 30°53'20''S; 30°18'38''E) (b: 30°52'23''S; 30°19'23''E), ranging from 56 to 137 meters above sea level. Experiments were conducted during August 2002 (late winter), October/November 2003 (late spring), February/March 2004 (late summer) and April 2003 (late autumn), respectively.

The Cavendish subgroup of banana cultivars (AAA) was grown at all the trial localities. The cultivars Grand Nain, Chinese Cavendish, Williams and Chinese Cavendish were cultivated at the Munster, Ramsgate a, Leisure Bay and Ramsgate b location, respectively. Plantations were planted in November/December 1993, but the Ramsgate b site was planted in November 2000. The site at Munster and Ramsgate a utilized micro jet irrigation, whilst the Ramsgate b and Leisure Bay sites used sprinkler irrigation. Plants were irrigated with 20 mm water/week, a practise only suspended if rainfall exceeded that value in the particular week. The Munster, Ramsgate a, Ramsgate b and Leisure Bay sites were treated with the oxime carbamate, aldicarb (15% GR), at a rate of 2.025 g.a.i./mat at planting. The Ramsgate a site was also treated with aldicarb once a year up to the third ratoon. Pre-trial plant inspection at all sites revealed rhizome tunnel damage by *C. sordidus*.

4.2.2 Treatments

Treatments comprised of two aggregation pheromone lures, individually suspended above pitfall traps, untreated pseudostem traps and pitfall traps with no lure (control). Two additional treatments were included in the autumn and summer trials. The autumn trial included pseudostem traps treated with an insecticide and a rhizome disk trap. The summer trial included the two different pheromone lures individually suspended above a pitfall trap and a treatment combining the latter with a pseudostem trap placed next to the mat of the plant.

Pitfall trap designs were used because it was shown to be more effective than ramp traps in Uganda (Tinzaara *et al*. 1999), even though the contrary was concluded in Costa Rica (Alpizar and Fallas 1997). The commercially available aggregation

pheromones, Cosmolure® (Pheromone A) and Cosmolure+® (Pheromone B), containing kairomone and four sordidin diastereoisomers, were imported from the producers, ChemTica Internacional S.A., situated in San José, Costa Rica. Pitfall traps were prepared by cutting four windows (200 × 200 mm) at the sides of rectangular prism-shaped containers (width:length:height: 250:300:350 mm) and suspending the pheromone with wire cable in the middle of the openings from the top end of the trap. Pitfall traps of the winter trial consisted of smaller cylindrical containers (radius: 70 mm; height: 200 mm) with the lid suspended by wire pillars 50 mm above the ground. Pitfall traps were filled with a mixture of ethylene glycol and water to reduce evaporation and lower the surface tension of the solution, to drown attracted beetles. The traps were placed in-line with the planting row at a constant direction to the mat. Pitfall traps were buried 150 mm in the soil (200 mm for the winter pitfall traps) at a distance of 300 mm from the pseudostem of the plant. Pseudostem trap material was randomly selected from plants harvested within 2 weeks before trap preparation at a plantation similar to but isolated (by a dirt road) from the specific trial sites. Only one trap was prepared from each plant and pseudostems with internal damage/necrosis/tunnels were discarded. Pseudostem traps were 300 mm in length (pseudostem section 300-600 mm above the collar), bisected longitudinally and each half placed (with the cut surface ventrally) directly next to the mat of the plant. Two halves were placed on opposite sides of the mat and regarded as one trap. The autumn trial included pseudostem traps treated with a pyrethroid, cyfluthrin (trade name: Baythroid®, manufacturer: Bayer) (10% WP) at 0.02 g.a.i. per half pseudostem. Rhizome disk traps (selected from the widest part of the rhizome) were also prepared from plants used for pseudostem traps during the autumn trial series. The rhizomes used for traps had a circumference of at least 600 mm and were cut to a thickness of 50 mm. One rhizome trap was prepared from each plant and rhizomes with internal damage/necrosis/tunnels were discarded. The plant material traps were covered with mulch to delay desiccation and decomposition.

Ambient temperature at each trial site was measured using a waterproof WatchDog 100-Temp 2K data logger (Spectrum Technologies Inc. 2001) suspended next to a pheromone lure and set to record hourly temperature. Rainfall was measured on site and corrected with irrigation quantities.

4.2.3 Experimental design

The layout of all the trials was a randomised block design. Treatments were separated by 24 m and considered independent, as the attractive radius of pheromone pitfall traps were determined to range from 2.5 to 7.5 m (Alpizar *et al*. 1998) and the former value falls within the range recommended and used in previous studies (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997, Alpizar *et al*. 1998, Tinzaara *et al*. 1999, Anonymous 2003). Plant material traps (pseudostems and rhizomes) were replaced once a week, when the samples per trap were collected and counted. Pheromones were replaced only during the autumn trial (on week 4). Adults were dissected, the sex determined by examining internal genitalia, and the percent of females with eggs and the number of eggs per female recorded. Oocytes were evaluated as eggs when covered by an egg shell (vitelline membrane and chorion). Unfortunately, beetles collected during the winter trial were destroyed before they could be dissected. Trials were monitored for 5 weeks. The winter, spring, summer and autumn trials had five, four, three and three replicates respectively, this being dependent on the size of the experimental block and number of treatments. To standardise for abiotic influences, replicates were orientated perpendicular to the sea/land breeze and moisture gradient in the field.

4.2.4 Statistical analysis

One-way ANOVA (Sokal and Rohlf 1997) was used to quantify differences between treatments and the dependent variables of total, female, male and percent female beetles attracted, eggs per female and percent of females containing eggs. The members of weevils caught between trials (seasons) were compared by converting these variables to fractions (indices of increase relative to the pseudostem trap). For each fraction, the interaction between season and treatment was determined by factorial ANOVA (Sokal and Rohlf 1997). The Tukey HSD test (Sokal and Rohlf 1997) was used for all post hoc analysis. Data for all the trials were not transformed, because it showed a normal distribution and homogeneity of variances in the linear scale. The ambient temperature and corrected rainfall values were averaged per week (corresponding to collection dates) and entered as covariates. The STATISTICA Version 7 (Statsoft Inc. 2004) software program was used for analysis.

4.3 Results

4.3.1 Winter trial

4.3.1.1 Weevils attracted

The winter trial ANOVA showed a significant difference between treatments and total number of beetles attracted ($F_{3, 96}$ = 15.56, P<0.001). The results of the post hoc comparisons are presented in figure 4.1.

Pheromones A and B were equally effective (P=0.990), and attracted a mean of 10.00 and 9.44 beetles per week, respectively. The pheromone-baited traps attracted significantly more beetles than the pseudostem (P<0.001) and control traps (P<0.001), whilst efficacy of pseudostems was not significantly different (P=0.666) than the control traps. During the trial the pseudostem traps attracted a mean of 2.08 weevils per week, while no weevils were collected in the control traps.

4.3.2 Spring trial

4.3.2.1 Weevils attracted

ANOVA of the spring trial indicated significant differences between treatments and total number ($F_{3, 76}$ = 18.13, P<0.001), female number ($F_{3, 76}$ = 18.13, P<0.001), male number ($F_{3, 76}$ = 6.46, P<0.001) and female percent ($F_{3, 66}$ = 5.59, P<0.002) of weevils attracted. Post ANOVA comparisons of attracted beetles, genders and female percent are illustrated in figure 4.2a.

Pheromone A was significantly more effective than any other treatment in the total number and number of female weevils attracted. Pheromone B attracted significantly more beetles and females than the control traps, but compared to pseudostem traps, only captured significantly more females. No significant difference was found between controls and pseudostem traps regarding weevil and female captures. The number of males collected was similar between all the traps, but significantly lower in the control traps. The pseudostem traps attracted 65.32% females, a value which was significantly lower than that of the two pheromone traps, which did not differ significantly. The percent of females attracted by the control pitfall trap was similar to the other treatments. The total number of beetles captured was similar between week 1 and 5, while the first week of collection captured significantly more beetles versus week 2 to 4 (data not shown). The number of females and males attracted showed a similar pattern, but collections on week 4 also

showed no significant difference to week 1.

4.3.2.2 Fecundity variables

Treatments segregated significantly regarding the percent of females with eggs ($F_{3, 65}$ = 5.70, P<0.002) and mean eggs per female ($F_{3, 65}$ = 18.74, P<0.001). Figure 4.2b summarises the mean number of eggs per female and the percent of females with eggs during spring.

The number of eggs per female peaked at a mean of 5.07 for the pseudostem traps, which was significantly higher than any other trap; the values of the pheromone and control traps did not show a significant difference. The majority of females collected in all the treatments contained eggs, with the lowest percent of females with eggs recorded for Pheromone B at 90.24%, which was significantly lower than the 100% recorded for the pseudostem traps. Females with eggs captured in the Pheromone A trap were similar to the Pheromone B trap, but were significantly lower than the pseudostem traps. Values for the control traps were not significantly different to any treatment.

4.3.3 Summer trial

4.3.3.1 Weevils attracted

Analysis of the summer trial revealed significant disparity between treatments and total ($F_{5, 84}$ = 10.25, P<0.001), female ($F_{5, 84}$ = 7.33, P<0.001), male ($F_{5, 84}$ = 11.68, P<0.001) and female percent ($F_{4, 62}$ = 2.82, P=0.032) of weevils sampled. Figure 4.3a provides a significance summary for beetles collected and percent of females attracted between traps during the summer trial.

The control traps did not collect any weevils during the course of the trial and were excluded from the post hoc comparisons concerning proportions and eggs per female. Regarding the total number of weevils attracted, the grouping of the two pheromones and that of the latter with a pseudostem trap were similar, but both these treatments were significantly more effective than the control traps and the singular constituent treatments, which were not significantly different among themselves. The number of females collected in the Pheromone A traps was similar to all the other treatments; female number collected in the Pheromone B traps were only significantly lower than the combined pheromone traps, whilst the pseudostem trap collected a significantly lower proportion of females than both the grouping traps. The two

grouping traps collected a similar number of females. The pseudostem trap collected a mean of 1.87 females per week, a value no different to the control trap. The number of males attracted was similar between the pheromone, pseudostem and control traps and also between the two grouping traps. The amount of male beetles collected from the pseudostem traps was no different to the number of males in the pheromone grouping trap. The percent of females collected in the traps ranged from 58.13% (pseudostem traps) to 87.35% (Pheromone A traps), with no statistical difference ($0.070<P<1.000$) found between the treatments by the Tukey HSD test. The total, female and male numbers were statistically similar between all the sampling dates (data not shown).

4.3.3.2 Fecundity variables

No significant difference was found between treatment and the percent of females with eggs ($F_{4, 58} = 0.27$, $P=0.900$) and eggs per female ($F_{4, 57} = 1.12$, $P=0.358$). Figure 4.3b presents differences of eggs per female and percent of females with eggs between traps during the summer trial.

The fecundity of females was similar for all the traps. The percent of females with eggs was very high for most treatments and peaked at 93.33% for pseudostem traps, but no significant differences between traps were found.

4.3.4 Autumn trial

4.3.4.1 Weevils attracted

The autumn trial revealed significant differences between treatments and total weevils ($F_{5, 84} = 5.29$, $P<0.001$), female weevils ($F_{5, 84} = 6.22$, $P<0.001$), male weevils ($F_{5, 84} = 3.88$, $P<0.004$) and female percent ($F_{5, 55} = 6.72$, $P<0.001$). Post hoc comparisons of the percent of females, the total, female and male number of *C. sordidus* attracted to the different traps are summarised in figure 4.4a.

The trial showed that Pheromone A and Pheromone B attracted a statistically similar number of weevils. Compared to the other traps, Pheromone A captured significantly more beetles, while the number captured in Pheromone B traps was not significantly different to any other treatment. The plant material and control traps did not show significant differences. A similar tendency was found for the number of females attracted. Pheromone A attracted significantly more males than the control, but showed no difference to the other treatments. The plant material traps were equally effective in attracting males and showed no difference to the Pheromone B

trap, while the pseudostem trap also attracted more males than the control trap. The Pheromone A and Pheromone B traps attracted statistically similar and the highest percent of female *C. sordidus* (80.41% and 76.87%, respectively), only different significantly from the treated pseudostem (45.81%) and rhizome traps (39.91%), which were not significantly different among themselves. Values for the untreated pseudostems and control traps were not significantly different than any other trap. For all the different dependent variables, values for the pseudostems treated with the insecticide were similar to the other plant material traps. The total, female and male weevils attracted were similar between the sampling weeks (data not shown). The pheromone traps showed a significant decrease in weevil collections (relative to week one and two), with very low (statistically similar) numbers from the third to the fifth week (data not shown). The data from the trial were regarded as comparable with other seasons because the pheromone replacement (on the fourth week) did not cause any notable or significant change in the number of weevils, females or males attracted.

4.3.4.2 Fecundity variables

Significant differences were evident between treatments and the percent of females with eggs ($F_{5, 51}$ = 4.33, P=0.002) and eggs per female ($F_{5, 51}$ = 33.49, P<0.001) during the autumn trial. Autumn differences between traps regarding fecundity and percent of females with eggs are summarised in figure 4.4b.

Females in the insecticide treated pseudostem traps contained a mean of 7.52 eggs, which were different to the rhizome, but not the untreated pseudostem traps. Eggs per female were also significantly higher in the untreated pseudostem versus the rhizome traps. The control and pheromone treatments were not significantly different, but segregated significantly from the plant material traps. The percent of females with eggs peaked in the plant material traps, where all the females contained eggs. Between all the treatments, only Pheromone B was significantly different to the untreated pseudostem traps.

4.3.5 Seasonal comparison

4.3.5.1 Weevil attraction

Localities (representing specific seasons) were compared by linearly converting the total, female and male number of beetles attracted between treatments to indices of

increase relative to the standard pseudostem trap, specific for each replicate. Linear conversion assumed no weevil density effects. Variables were therefore compared as fractions of corresponding treatments between seasons and cultivar influence was assumed negligible. Post hoc differences between the specific seasons and total fraction ($F_{2, 189}$ = 2.99, P=0.053), female fraction ($F_{2, 177}$ = 5.10, P=0.007), male fraction ($F_{2, 157}$ = 6.19, P=0.003) and female percent ($F_{2, 146}$ = 0.78, P=0.459) are indicated in figure 4.5a.

Relative to the pseudostem traps, the two individual pheromone and control traps had a strong tendency to attract almost three times the number of weevils in spring, while the values for summer and autumn were 1.22 and 1.36, respectively. The relative number of females and males attracted during spring was significantly more than in summer, while autumn values were no different to spring and summer. The percent of females of all the treatments (pseudostem, Pheromone A, Pheromone B and control) peaked in spring, but did not show significant differences.

4.3.5.2 Fecundity variables

The percent of females with eggs ($F_{2, 141}$ = 1.45, P=0.239) showed no significant seasonal effect, while eggs per female ($F_{2, 140}$ = 4.11, P=0.018) were significantly different between seasons. Seasonal differences of all the relevant traps regarding fecundity and percent of females with eggs are summarised in figure 4.5b.

The number of eggs per female was significantly higher in autumn than in summer, while the value for spring was similar to the other seasons, assuming density effects between trials were negligible. The percent of females containing eggs peaked in spring, but values between seasons were not significantly different.

4.3.6 Season and treatment

Management proposals require resolution on the efficacy of specific treatments between seasons. Table 4.1 summarises the post ANOVA interaction between season and treatment of the total fraction ($F_{6, 180}$ = 1.09, P=0.368), female fraction ($F_{6, 168}$ = 2.21, P=0.045) and male fraction ($F_{6, 148}$ = 2.34, P=0.035).

For the number of weevils, females and males, the pheromone efficacy (relative to pseudostem traps) generally peaked in spring, followed by autumn and then summer. The relative catches of the control trap peaked in autumn, followed by spring and summer. The Pheromone A trap was the most effective treatment tested

between seasons, attracting a respective mean of 5.37, 6.97 and 1.84 times more of total, female and male weevils per week (over 5 weeks) than pseudostem traps during spring. The relative number of female and male weevils collected in the Pheromone A traps during spring was significantly higher than the corresponding values in summer. Pheromone B showed a similar pattern for male weevils. The late winter trial showed weevil indices of increase (standard error) relative to the pseudostem trap of 9.34 (3.10), 8.74 (1.98) and 0.00 (0.00) for the Pheromone A, Pheromone B and control traps, respectively (data not shown). Post-ANOVA the pheromone values were statistically similar among themselves, but significantly higher than the pseudostem and control values, which were not significantly different (data not shown). The indices of increase for total weevils, females and males attracted did not change over time (data not shown).

4.3.7 Relationship between biotic and abiotic variables

The dependent variables did not show a significant relation with ambient temperature and corrected rainfall (data not shown).

4.4 Discussion

Pheromones proved to be the most effective means of trapping *C. sordidus* in South Africa. The trial conducted in winter showed that the two pheromone traps were equally successful and the most effective means of trapping the banana weevil. The different dimensions of pitfall traps, however, prevented comparisons to other trials.

In the local subtropical climate, Pheromone A was the most effective lure regarding total and female weevils attracted during spring and autumn. This is consistent with studies conducted in the tropics that also found pheromone traps to be more effective than pseudostem traps (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997, Tinzaara *et al*. 1999, 2003). During spring and autumn, the plant material traps attracted more fecund females, but higher proportions of females were captured in pheromone traps. The summer trial showed similar tendencies regarding these variables, but differences were much less pronounced and usually not significant. The sex ratio of adults attracted to pheromone and plant material traps is different to previous reports from tropical Costa Rica that concluded pseudostem traps and pseudostem traps baited with pheromone attract an equal sex ratio (Ndiege *et al*. 1996b, Jayaraman *et al*. 1997). A study in Uganda concluded Pheromone B pitfall traps to also attract an equal amount of males and females (Tinzaara *et al*. 1999), contrary to current findings. Detergent and water was added to the pitfalls in the tropical studies, standardising the influence of gender humidity preferences between trials (Roth and Willis 1963). The discrepancy of sex ratios between traps may be related to gender behavioural differences (Delattre 1980), reproduction physiology, plant variety, climate and/or weevil biotype.

Compared to pheromone traps, plant material traps collected a higher proportion of females with eggs. Rhizome traps generally desiccated at a higher rate than pseudostem traps, which may have attributed to pseudostems collecting more fecund females. If females also prefer rhizome material as an ovipositioning substrate (Cuille 1950, Masanza 2003) under local conditions, it then appears to be independent of fecundity. Previous research showed similar differences in electroantennogram response between the sexes of *C. sordidus*. Orientation is to food resources rather than oviposition sites (Budenberg *et al*. 1993b). Our results, however, suggest that (excluding density effects) chemoreception is possibly involved in host acceptance, as was reported by Cuille (1950).

The reduction in pheromone efficacy in autumn was unclear and although it did not result from ambient temperature or rainfall/irrigation, other abiotic factors, destructive sampling, pest density and/or activity may have been responsible. During the autumn trial, addition of cyfluthrin to pseudostem traps did not alter any of the tested variables. Treated pseudostems showed a weevil mortality rate of approximately 75% per week. Jayaraman *et al*. (1997) reported a comparable 80% mortality of weevils attracted to carbaryl-soaked (10 g.a.i.) sandwich traps. Equal efficacy of rhizome and pseudostem traps is in agreement with Masanza (2003). Grouping the two pheromones in summer produced a synergistic response in terms of total, female and male beetles attracted. The data of the pheromone grouping traps were no different from a similar trap combined with a pseudostem trap, in general agreement with Ndiege *et al*. (1996b).

Seasonal behavioural differences of *C. sordidus* were observed in pheromone and unbaited pitfall traps compared to pseudostem traps. Traps attracted more fecund females in autumn versus summer, while spring values were intermediate. Tendencies may be dependent on reproduction physiology and climate, but were not related to temperature and rainfall/irrigation. The conversion of variables to fractions effectively decreased sample size and values, especially when pseudostem numbers were low and treatment numbers high, showed relatively high variability. Compared to pseudostem traps, Pheromone A traps generally attracted the highest total, female and male numbers during all the seasons. The highest total values obtained during late winter and spring were, however, considerably lower than corresponding values of 18 reported for Pheromone B pitfall traps in Uganda (Tinzaara *et al*. 1999). In Costa Rica, pseudostem traps treated with Pheromone B increased attractiveness five to ten times and Pheromone B-baited pitfall traps are two and a half times more effective than baited pseudostems (Alpizar and Fallas 1997). Weevil biotype, plant variety and/or climate may be responsible for the lower relative efficacy of pheromones in South Africa.

The economic viability of pheromone traps can be calculated based on their linear equivalent to pseudostem traps, bearing in mind that pseudostems were replaced five times to produce the mean weekly indices of increase calculated in this study. In South Africa pheromone traps show potential as an economical monitoring and mass trapping technique that should entail the weekly movement of traps by 20 m during spring and autumn.

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4.6 References

Allen RN. 1989. Control of Major Pests and Diseases of Bananas. Department of Agriculture, New South Wales.

Alpizar D, Fallas M. 1997. Pheromone Trapping System. Ministry of Agriculture, Guapiles, Costa Rica.

Alpizar D, Fallas M, Oehlschlager AC, Gonzalez L, Jayaraman, S. 1998. Pheromone-based mass-trapping of the banana weevil, *Cosmopolites sordidus* (Germar) and the West Indian Sugarcane Weevil *Metamasius hemipterus* L. (Coleoptera: Curculionidae) in plantain and banana. Memorias XIII Reunion ACORBAT, Guayaquil, Ecuador, November 23-27, 1998, pp 515-538.

Anonymous. 2003. Pheromone trapping system, *Cosmopolites sordidus*, *Metamasius hemipterus*. Information pamphlet, ChemTica Internacional, S.A., Costa Rica.

Aranzazu LF, Arcila MI, Bolanos MM, Castellanos PA, Castrillon C, Perez JC, Rodriguez JL, Balencia JA. 2000. Manejo integrado del cultivo de platano. Manual tecnico (CORPOICA, Manizales, Columbia).

Arleu RJ. 1982. Dinamica populacional e controle do *Cosmopolites sordidus* (Germ. 1824) e *Metamasius hemipterus* L. 1764 (Col: Curculionidae) em bananais da cv. Prata, no Espirito Santo, Brazil. Piravicaba, ESALQ.

Batista Filho A, Leite LG, Raga A, Sato ME. 1990. Atracao de *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) por iscas do tipo “sanduiche” e “telha”. Arquivos do Instituto Biologico (Sao Paulo) 57**:**9-13.

Beauhaire J, Ducrot PH, Malosse C, Rochat D, Ndiege IO, Otieno DO. 1995. Identification and synthesis of sordidin, a male pheromone emitted by *Cosmopolites sordidus*. Tetrahedron Letters 36:1043-1046.

Braimah H. 1997. Laboratory studies on the host plant searching behaviour and chemical ecology of the banana weevil, *Cosmopolites sordidus* (Germar 1824) (Coleoptera: Curculionidae). Ph.D. thesis, University of Reading, UK.

Braimah H, Van Emden HF. 1999. Evidence for the presence of chemicals attractive to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in dead banana leaves. Bulletin of Entomological Research 89:485-491.

Budenberg WJ, Ndiege JO, Karago FW. 1993a. Evidence for volatile male produced pheromone in banana weevil *Cosmopolites sordidus*. Journal of Chemical Ecology 19:1905-1916.

Budenberg WJ, Ndiege JO, Karago FW, Hansson BS. 1993b. Behavoiral and electro-physiological responses on the banana weevil *Cosmopolites sordidus* to host plant volatiles. Journal of Chemical Ecology 19:267-277.

Bujulu J, Uronu B, Cumming CNC. 1983. The control of banana weevils and parasitic nematodes in Tanzania. East African Agricultural and Forestry Journal 49:1-13.

Castrillon C. 1989. Plagas del cultivo del platano. Curso de actualizacion sobre problemas sanitarios en platano. La Dorada, Columbia: ICA.

Castrillon C. 1991. Manejo del picudo negro (*Cosmopolites sordidus* Germar) en platano y banano de la zona cafetera de Colombia. Memorias IX ACORBAT. pp 349-362.

Cerda H, Lopez A, Fernandez G, Sanchez P, Jaffe K. 1995. Etude de la response olfactive du charancon des bananiers a des stimuli degages par differentes plantes. Fruits 50:323-331.

Collins PJ, Treverrow NL, Lambkin TM. 1991. Organophosphorus insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Australia. Crop Protection 10:215-221.

Cuille J. 1950. Recherches sur le charancon du bananier. Institut de Fruits et Agrumes Coloniaux, Serie Technique 4, Paris.

Delattre P. 1980. Recherche d'une methode d'estimation des populations du charancon du bananier, *Cosmopolites sordidus* Germar (Col., Curculionidae). Acta Oecologia 1:83-92.

De Mendonca FAC, Vilela EF, Eiras AE, Sant'Ana AEG. 1999. Response of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) to host volatiles and conspecifics in olfactometer. Revista Brasileira de Zoologia 16:123-128.

Fogain R, Messiaen S, Fouré E. 2002. Studies on the banana borer weevil in Cameroon. PROMUSA proceedings VIII-IX, Banana Weevil Working Group Inauguration, Tenerife, Canary Islands, Spain, March, 2002.

Froggat JL. 1928. The banana weevil borer in Java, with notes on other crop pests. Queensland Agricultural Journal 6:530-541.

Gold CS, Okech SH, Nokoe S. 2002. Evaluation of pseudostem trapping as a control measure against banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in Uganda. Bulletin of Entomological Research 92: 35-44.

Gold CS, Ogenga-Latigo MW, Tushemereirwe W, Kashaija I, Nankinga C. 1993. Farmer perceptions of banana pest constraints in Uganda: Results from a rapid rural appraisal. In: Gold CS, Gemmil B, editors. Biological and integrated control of highland banana and plantain pests and diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA. pp 3-24.

Gold CS, Pena JE, Karamura EB. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). Integrated Pest Management Reviews 6:79-155.

Gold CS, Ssennyonga J, Okech SH, Bagamba F, Kiggundu A, Tinzaara W, Masanza M, Nampala P. 1999. Cultural control of banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in Uganda. African Crop Science Conference Proceedings 4:555-562.

Hord HY, Flippen RS. 1956. Studies of banana borer in the Honduras. Journal of Economic Entomology 49:296-300.

Jayaraman S, Ndiege IO, Oehlschlager AC, Gonzalez LM, Alpizar D, Fallas M, Budenberg WJ, Ahuya P. 1997. Synthesis, analysis, and field activity of sordidin, a male produced aggregation pheromone of the banana weevil, *Cosmopolites sordidus*. Journal of Chemical Ecology 23:1145-1161.

Jones DE. 1968. Attraction of banana rhizome volatiles to the banana root borer, *Cosmopolites sordidus* Germar. United Fruit Company, La Lima, Honduras.

Knowles LH, Jepson FP. 1912. Department of agriculture, Fiji Bulletin.

Koppenhöfer AM. 1992. Predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Col., Curculionidae) in western Kenya. Journal of Applied Entomology 114:530-533.

Koppenhöfer AM, Seshu Reddy KV, Sikora RA. 1994. Reduction of banana weevil populations with pseudostem traps. International Journal of Pest Management 40:300-304.

Masanza, M. 2003. Effect of crop sanitation on banana weevil *Cosmopolites sordidus* (Germar) populations and associated damage. Ph.D. thesis. Wageningen University, Wageningen, The Netherlands.

Mestre J, Rhino B. 1997. Les etudes sur le charancon des bananiers, *Cosmopolites sordidus* (Germar 1824). Bilan sommaire – Neufchateau 1995-1997, CIRAD-FLHOR document JM-97-04, Neufchateau.

Mitchell G. 1978. The estimation of banana borer population and resistance levels, Technical Bulletin 2. Windward Island Banana Growers Association (WINBAN), St. Lucia.

Ndiege IO, Budenberg WJ, Lwande W, Hassanali A. 1991. Volatile components of banana pseudostem of a cultivar susceptible to the banana weevil. Phytochemistry 30:3929-3930.

Ndiege IO, Budenberg WJ, Otieno DO, Hassanali A. 1996a. 1, 8-Cineole: An attractant for the banana weevil, *Cosmopolites sordidus*. Phytochemistry 42:369-371.

Ndiege IO, Jayaraman S, Oehlschlager AC, Gonzalez L, Alpizar D, Fallas M. 1996b. Convenient synthesis and field activity of a male-produced aggregation pheromone of *Cosmopolites sordidus*. Naturwissenschaften 83:280-282.

Ogenga-Latigo MW, Bakyalire R. 1993. Use of pseudostem traps and coefficient of infestation (PCI) for assessing banana infestation and damage by *Cosmopolites sordidus* Germar. African Crop Science Journal 1:39-48.

Price NS. 1993. Preliminary weevil trapping studies in Cameroon. In: Gold CS, Gemmil B, editors. Biological and integrated control of highland banana and plantain pests and diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA. pp 57-67.

Raga A, De Oliveira JA. 1996. Insecticidal efficacy against the banana borer (*Cosmopolites sordidus*) (Coleoptera: Curculionidae) in Vale do Ribeira region, State of Sao Paulo. Arquivos do Instituto Biologico (Sao Paulo) 63:81-84.

Roth LM, Willis ER. 1963. The humidity behavior of *Cosmopolites sordidus* (Coleoptera: Curculionidae). Annals of the Entomological Society of America 56:41-52.

Seshu Reddy KV, Gold CS, Ngode L, 1999. Cultural control strategies for the banana weevil, *Cosmopolites sordidus* Germar. Proceedings of a Workshop on Banana IPM in Nelspruit, South Africa, November 1998. pp 51-57.

Sokal RR, Rohlf FJ. 1997. Biometry. New York: W.H. Freeman and Company. pp 57-678.

Spectrum Technologies Incorporated. 2001. Plainfield, IL, USA.

Statsoft Incorporated. 2004. Statistica. Version 7. Tulsa, USA.

Sumani AJ. 1997. Patterns of relationship between banana (*Musa* spp.) types and the banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae). Ph.D.

thesis, University of Zambia, Lusaka, Zambia.

Tinzaara W, Dicke M, Van Huis A, Van Loon JJA, Gold CS. 2003. Different bioassays for investigating orientation responses of the banana weevil, *Cosmopolites sordidus*, show additive effects of host plant volatiles and a synthetic male-produced aggregation pheromone. Entomologia Experimentalis et Applicata 106:169-175.

Tinzaara W, Tushemereirwe W., Kashaija I. 1999. The potential of using pheromone traps for the control of the banana weevil *Cosmopolites sordidus* Germar in Uganda. Proceedings of a Workshop on Banana IPM in Nelspruit, South Africa, November 1998. pp 23-28.

Treverrow N, Peasley D, Ireland G. 1992. Banana weevil borer, a pest management handbook for banana growers. Banana Industry Committee, New South Wales Agriculture.

Yaringano C, Van der Meer F. 1975. Control del gorgojo del platano, *Cosmopolites sordidus* Germar, mediante trampas diversas y pesticidas granulados. Revista Peruana de Entomologia 18:112-116.

Table 4.1. Mean total, female and male number of *Cosmopolites sordidus* (standardised as pseudostem trap indices of increase) collected in different traps per week over 5 weeks in southern KwaZulu-Natal. Standard errors are in parenthesis. For each dependent variable, means with letters in common indicate no significant difference (P>0.05).

Dependent variable (fractions)	Season	Treatment			
		Pheromone A	Pheromone B	Control	Pseudostem
Total	Spring	5.37 (1.46)^{b}	4.46 (1.95)^{bc}	0.20 (0.06)^{a}	1.00 (0.00)^{ac}
	Summer	2.47 (1.23)^{abc}	1.40 (0.45)^{abc}	0.00 (0.00)^{a}	1.00 (0.00)^{abc}
	Autumn	2.78 (0.80)^{abc}	1.36 (0.29)^{abc}	0.32 (0.28)^{ac}	1.00 (0.00)^{abc}
Female	Spring	6.97 (1.54)^{c}	5.08 (1.68)^{cd}	0.23 (0.08)^{b}	1.00 (0.00)^{ab}
	Summer	1.14 (0.24)^{abd}	1.17 (0.37)^{abd}	0.00 (0.00)^{ab}	1.00 (0.00)^{abd}
	Autumn	4.53 (1.34)^{acd}	2.30 (0.56)^{abd}	0.35 (0.28)^{ab}	1.00 (0.00)^{abd}
Male	Spring	1.84 (0.37)^{b}	1.53 (0.38)^{bc}	0.19 (0.07)^{a}	1.00 (0.00)^{abc}
	Summer	0.53 (0.26)^{ac}	0.22 (0.22)^{a}	0.00 (0.00)^{a}	1.00 (0.00)^{abc}
	Autumn	0.95 (0.30)^{abc}	0.54 (0.16)^{ac}	0.32 (0.31)^{a}	1.00 (0.00)^{abc}

Figure legends

Figure 4.1. The mean (+ standard error) number of *Cosmopolites sordidus* attracted per week to different traps during August 2002 (winter). Means with letters in common indicate no significant difference ($P > 0.05$).

Figure 4.2a. The mean (+ standard error) total, female, male and percent of females of *Cosmopolites sordidus* individuals attracted per week to different traps during October/November 2003 (spring). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$).

Figure 4.2b. The mean (+ standard error) number of eggs per female and percent of females containing eggs of *Cosmopolites sordidus* individuals attracted per week to different traps during October/November 2003 (spring). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$).

Figure 4.3a. The mean (+ standard error) total, female, male and percent of females of *Cosmopolites sordidus* attracted per week to different traps during February/March 2004 (summer). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$). Ph, Pheromone; PS, Pseudostem.

Figure 4.3b. The mean (+ standard error) number of eggs per female and percent of females containing eggs of *Cosmopolites sordidus* attracted per week to different traps during February/March 2004 (summer). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$). Ph, Pheromone; PS, Pseudostem.

Figure 4.4a. The mean (+ standard error) total, female, male and percent of females of *Cosmopolites sordidus* attracted per week to different traps during April 2003 (autumn). Percentage means are indicated by black dots and refer to the secondary y-

axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$). Ph, Pheromone; PS, Pseudostem.

Figure 4.4b. The mean (+ standard error) number of eggs per female and percent of females containing eggs of *Cosmopolites sordidus* attracted per week to different traps during April 2003 (autumn). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$). Ph, Pheromone; PS, Pseudostem.

Figure 4.5a. The mean (+ standard error) total fraction, female fraction, male fraction and percent of females of *Cosmopolites sordidus* attracted per week to all seasonally corresponding traps during spring (October/November 2003), summer (February/March 2004) and autumn (April 2003). Fractions represent indices of increase relative to pseudostem traps. Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$).

Figure 4.5b. The mean (+ standard error) number of eggs per female and percent of females containing eggs of *Cosmopolites sordidus* attracted per week to all seasonally corresponding traps during spring (October/November 2003), summer (February/March 2004) and autumn (April 2003). Percentage means are indicated by black dots and refer to the secondary y-axis. For each dependent variable, means with letters in common indicate no significant difference ($P > 0.05$).

Figure 4.1

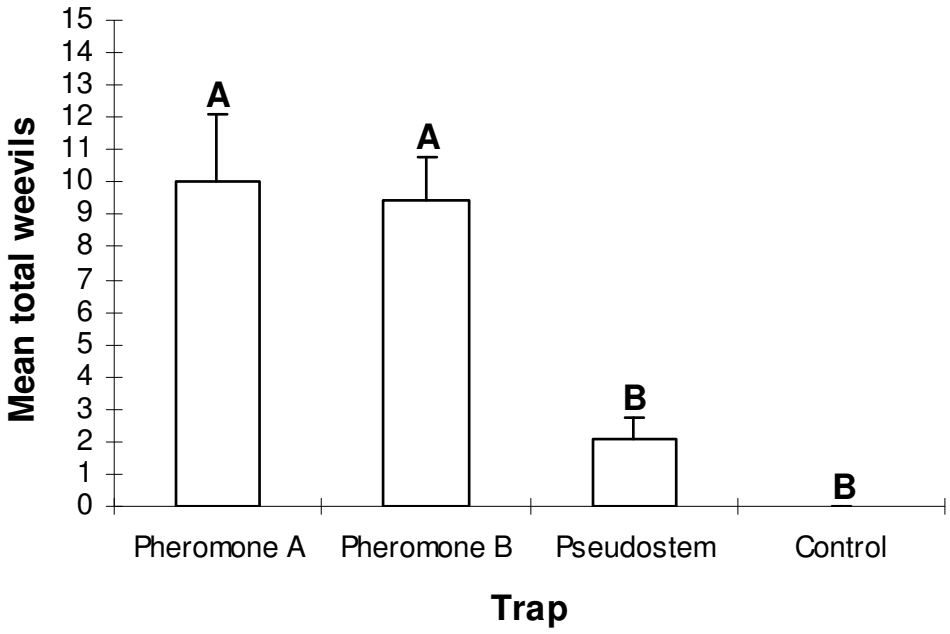

Mean total weevils
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
A
A
B
B
Pheromone A
Pheromone B
Pseudostem
Control
Trap

Figure 4.2a

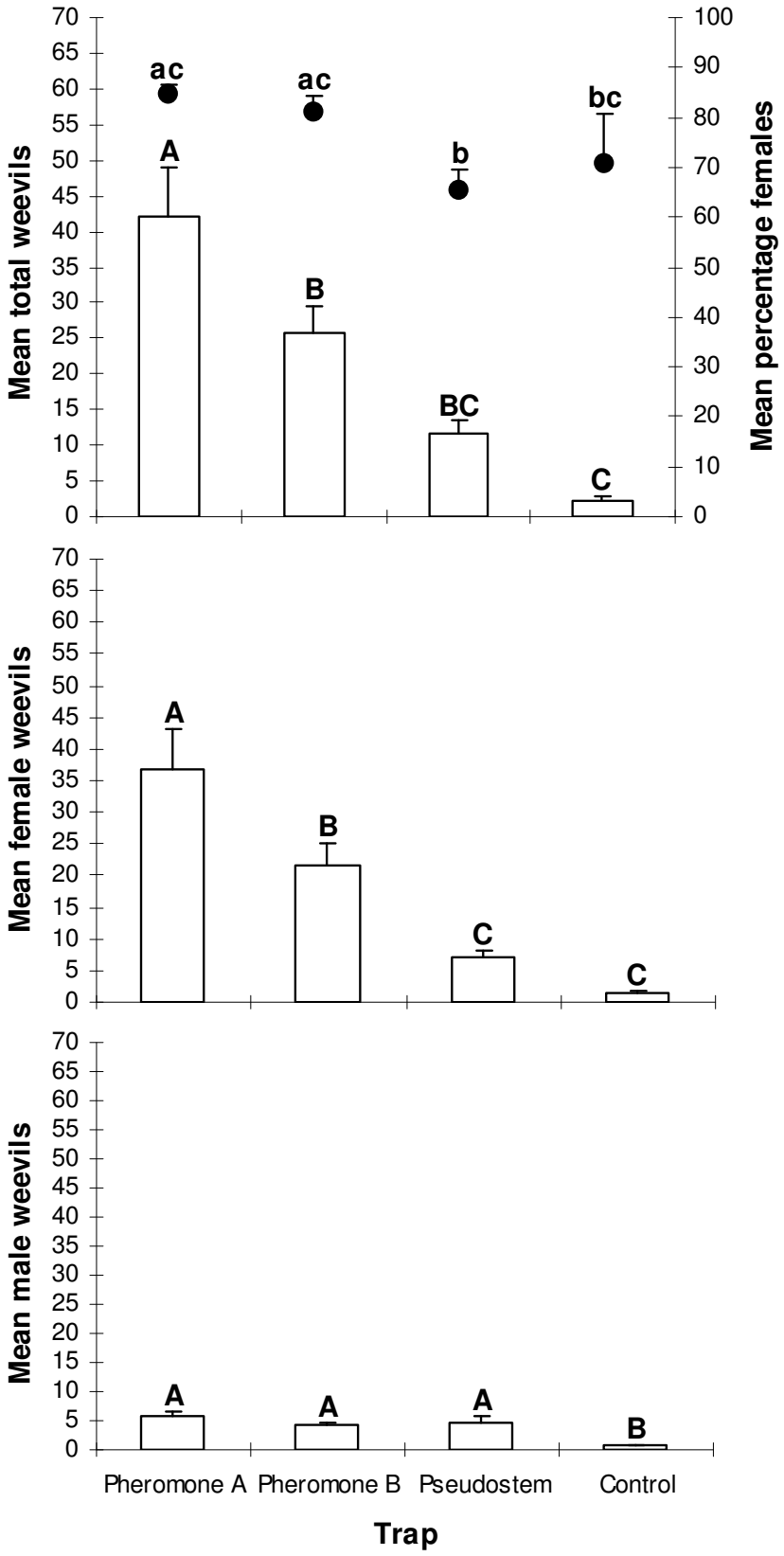

Mean total weevils
Mean percentage females
ac
ac
b
bc
A
B
BC
C
Mean female weevils
A
B
C
C
Mean male weevils
A
A
A
B
Pheromone A
Pheromone B
Pseudostem
Control
Trap

Figure 4.2b

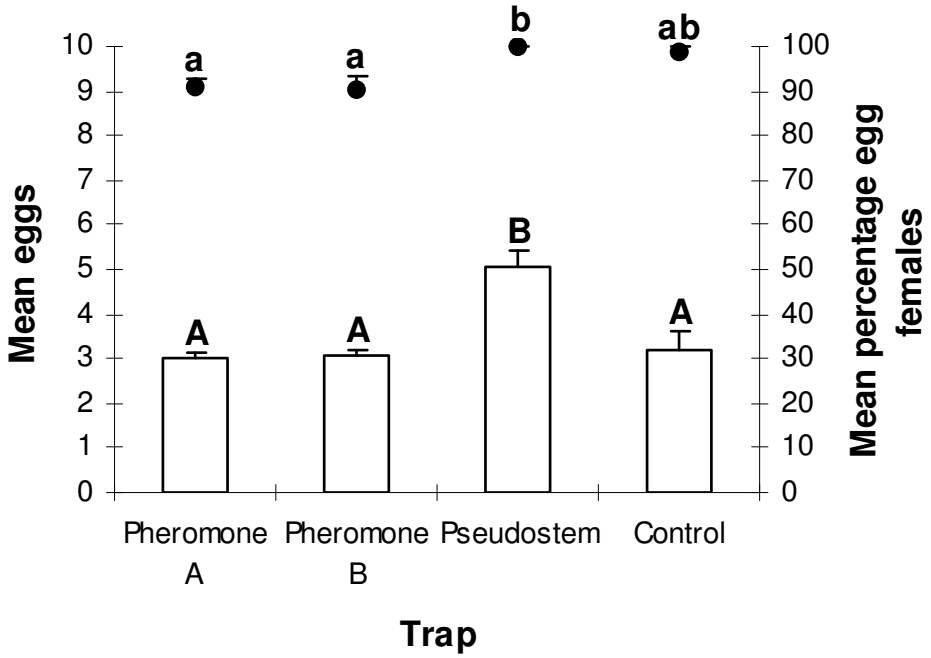

Mean eggs
Mean percentage egg females
10
9
8
7
6
5
4
3
2
1
0
100
90
80
70
60
50
40
30
20
10
0
a
a
b
ab
A
A
B
A
Pheromone A
Pheromone B
Pseudostem
Control
Trap

Figure 4.3a

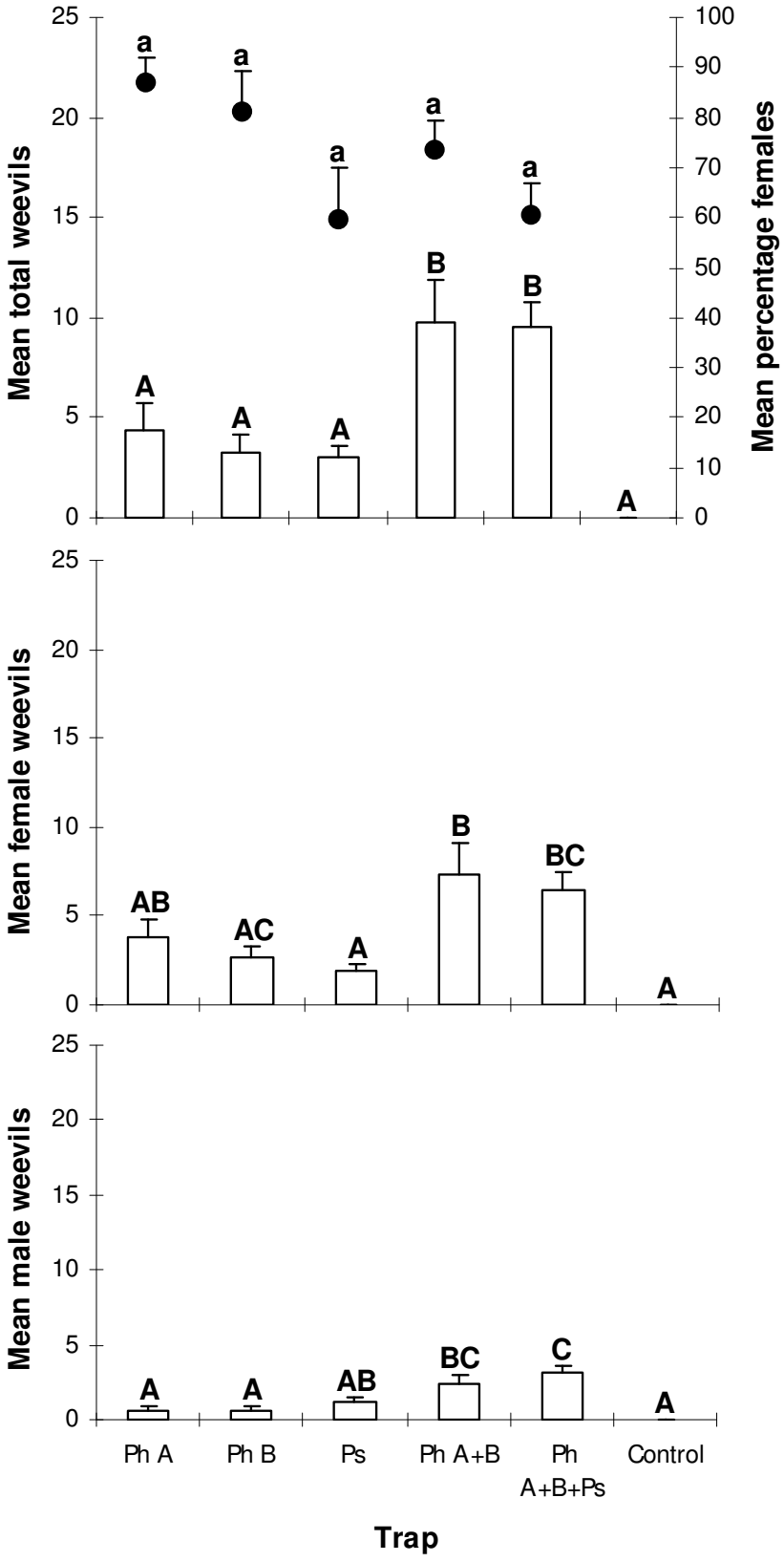
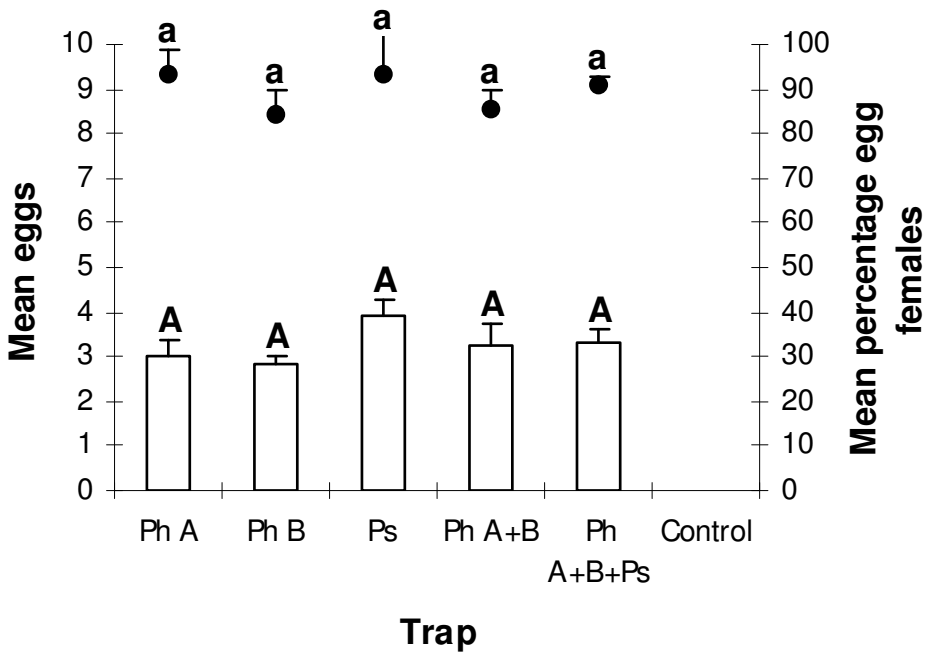

Mean total weevils
Mean percentage females
Mean female weevils
Mean male weevils
a
a
a
a
a
A
A
A
B
B
A
AB
AC
A
B
BC
A
A
A
AB
BC
C
A
Ph A
Ph B
Ps
Ph A+B
Ph A+B+Ps
Control
Trap

Figure 4.3b


Mean eggs
Mean percentage egg females
Trap
Ph A
Ph B
Ps
Ph A+B
Ph A+B+Ps
Control
a
A
0
1
2
3
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6
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9
10
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30
40
50
60
70
80
90
100

Figure 4.4a

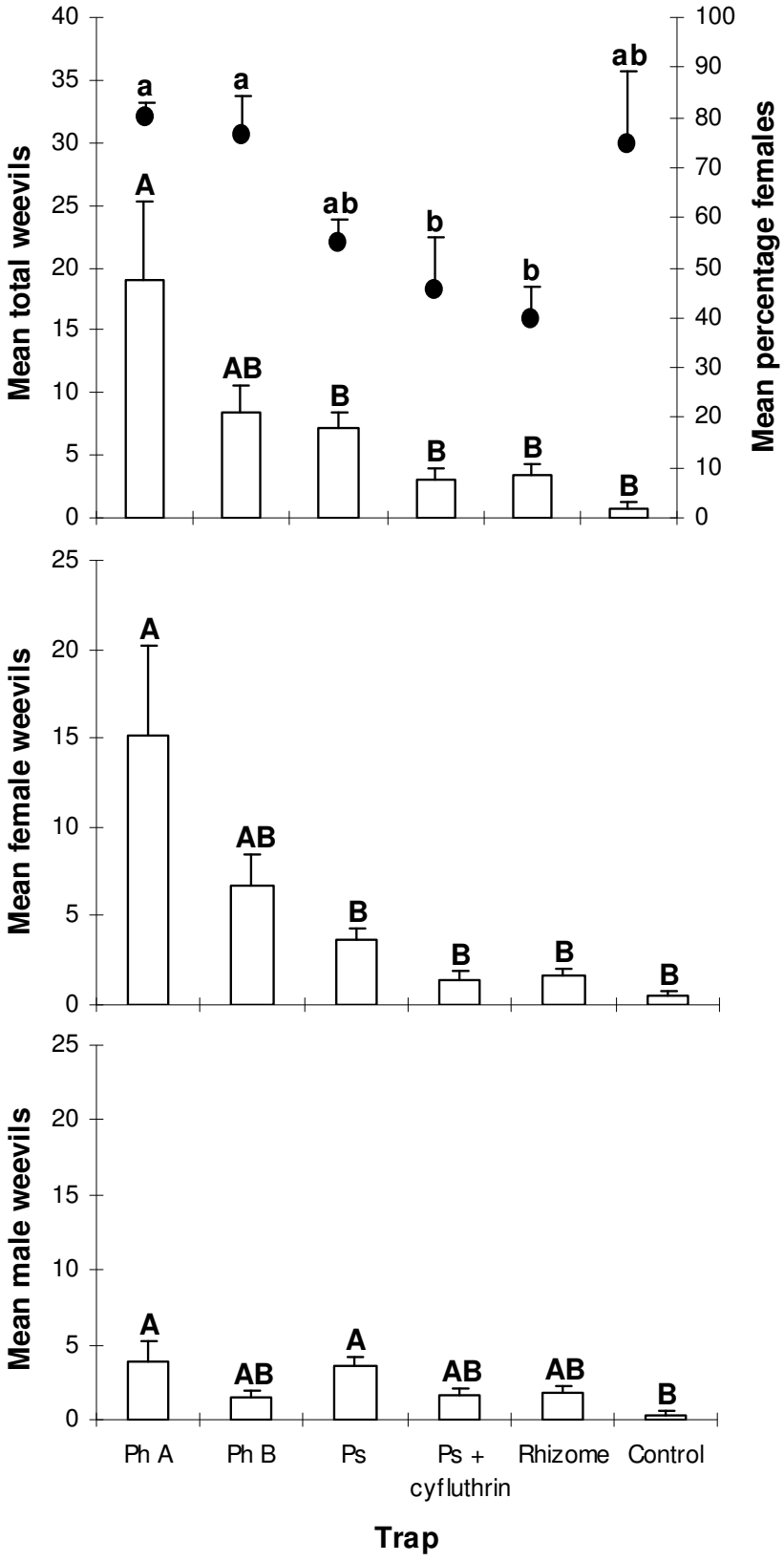

Mean total weevils
Mean percentage females
Mean female weevils
Mean male weevils
a
a
ab
b
b
ab
A
AB
B
B
B
B
A
AB
B
B
B
B
A
AB
A
AB
AB
B
Ph A
Ph B
Ps
Ps + cyfluthrin
Rhizome
Control
Trap

Figure 4.4b

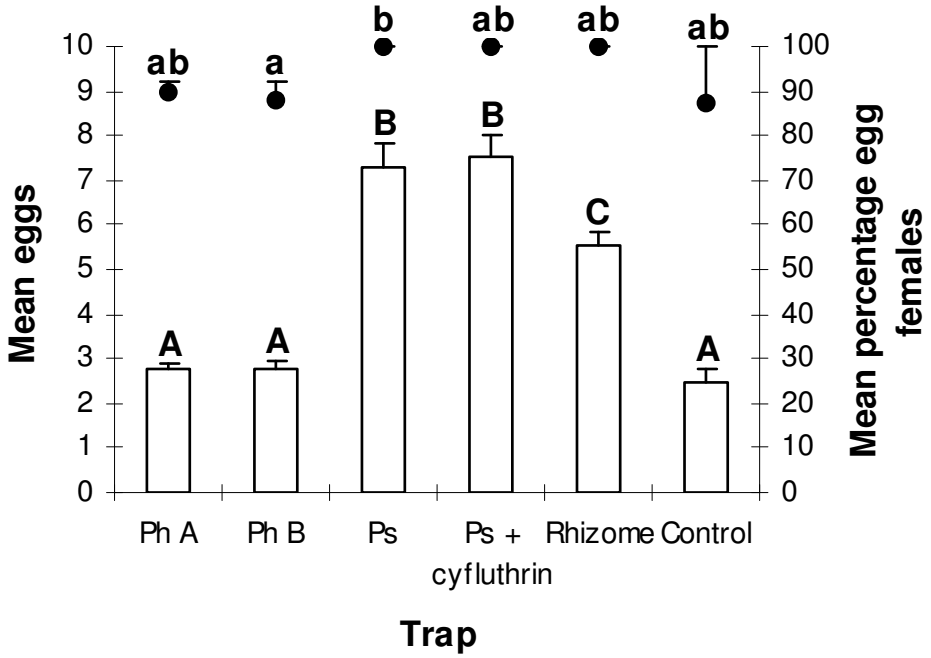

Mean eggs
Mean percentage egg females
ab
a
b
ab
ab
ab
A
A
B
B
C
A
Ph A
Ph B
Ps
Ps + cyfluthrin
Rhizome
Control
Trap

Figure 4.5a

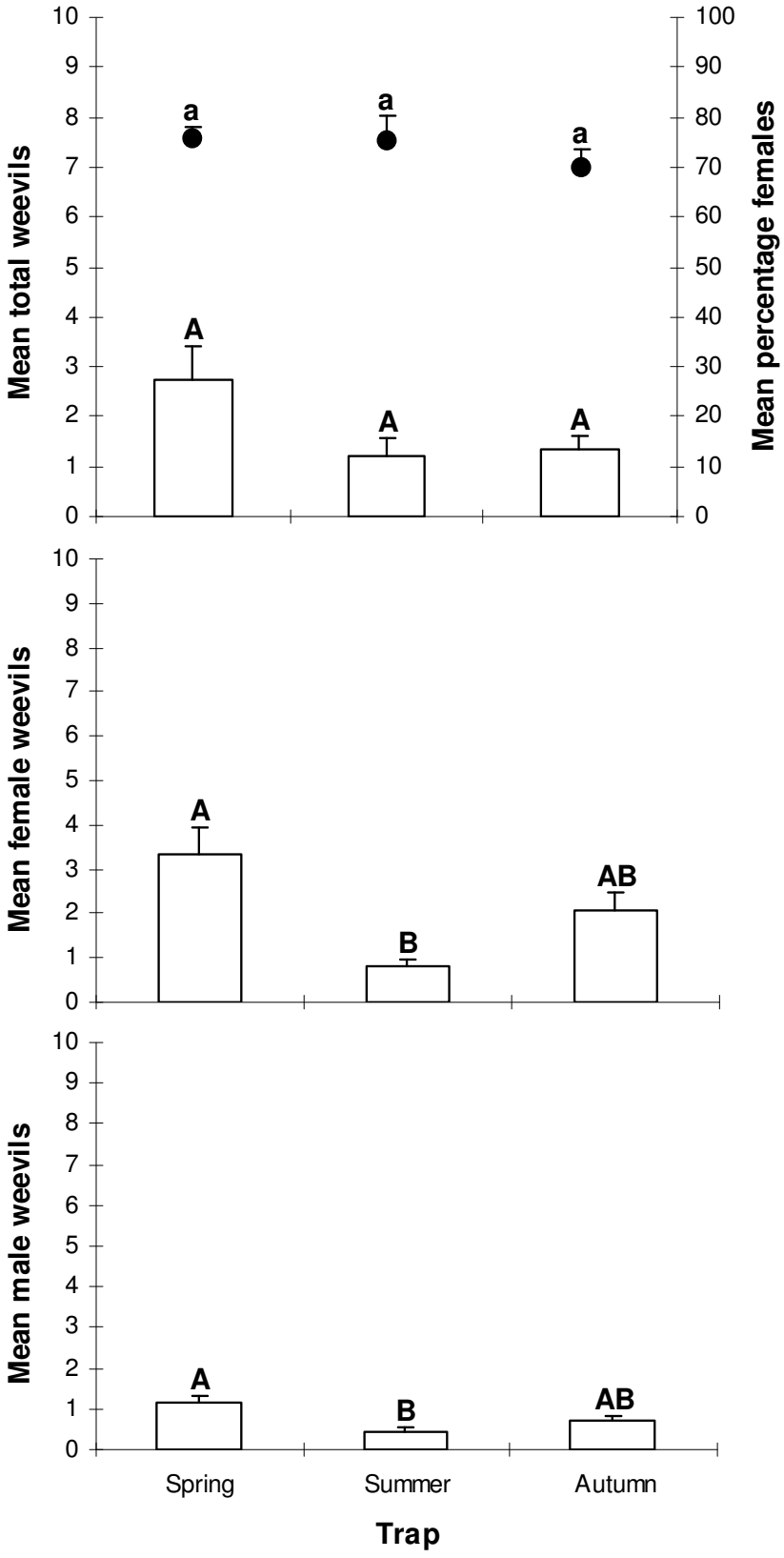
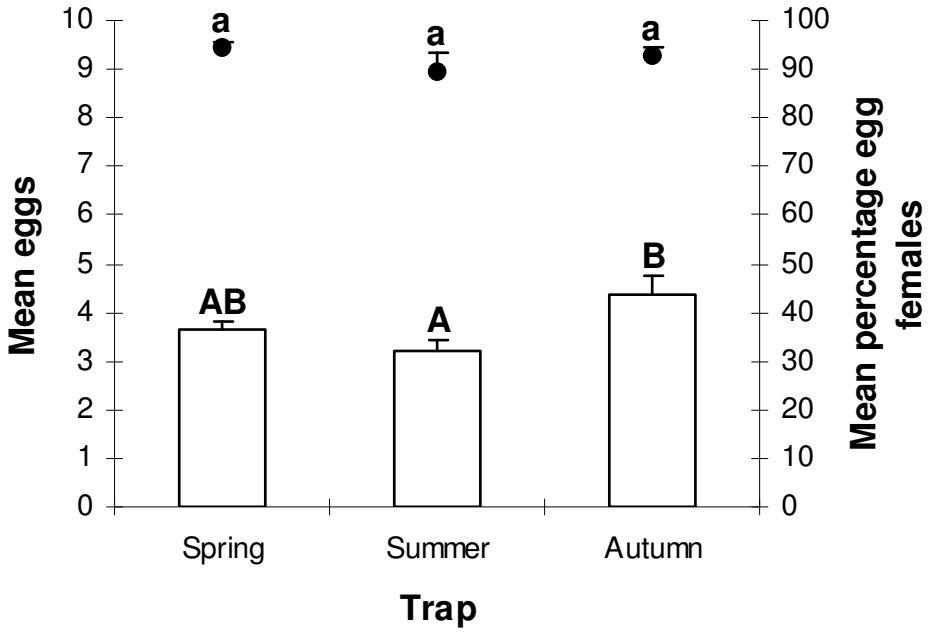

Mean total weevils
Mean percentage females
Mean female weevils
Mean male weevils
a
a
a
A
A
A
A
B
AB
A
B
AB
Spring
Summer
Autumn
Trap

Figure 4.5b


Mean eggs
Mean percentage egg females
10
9
8
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90
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a
a
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AB
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B
Spring
Summer
Autumn
Trap

Chapter 5

Cultural control of *Cosmopolites sordidus* in South Africa

Abstract

The banana weevil, *Cosmopolites sordidus*, is the most important insect pest of banana and plantain in the world. Cultural control methods were investigated over 2 years at an ongoing trial in the Southern KwaZulu Natal, South Africa. Harvesting at ground level and dissection of remnants, and covering of the mat with soil and moving debris to the inter-row, were compared to a positive control that involved treatment of plants with a registered pesticide, and a negative control that involved harvesting at approximately 150 cm with no soil or sanitation amendments. Yield, weevil damage and pseudostem girth of plants were measured from August to November annually, while adult beetle densities were assessed over 4 weeks in October/November and April. Nematode samples were analysed in October/November every year. Damage parameters included the Coefficient of Infestation, the Percentage Coefficient of Infestation (PCI) at two intervals, the summed PCI value, the percentage cross sectional damage of the central cylinder and cortex, and the mean cross sectional damage percentage. A replicated block design was used in the experiment. The parameters were similar before the onset of the trial. Fruit yield and plant girth, corrected by nematode densities, were not significantly different in any treatment, nor were the nematodes controlled. Soil cover and recession of remnants was the only effective treatment, significantly reducing the Coefficient of Infestation, but not the adult density or any other damage parameter. The former showed promise as a cultural control method because it only needs to be applied seasonally and reduced the percentage cross sectional damage of the central cylinder, the damage parameter most closely related to yield, by 14.18%.

Keywords: Cultural control, soil cover, yield, damage, banana weevil

5.1 Introduction

The banana weevil, *Cosmopolites sordidus* (Germar), is a major insect pest of banana and plantain in the world (Waterhouse & Norris 1987; Gold *et al*. 1999). Eggs are usually laid at ground level (Franzmann 1972) in the crown of the rhizome and pseudostem base (Abera *et al*. 1999). The larvae are the damaging stage and tunnel into the rhizome and occasionally the pseudostem, interfering with root initiation (Treverrow *et al*. 1992), plant nutrition (Chavarria-Carvajal & Irizarry 1997) and water transport (Collins *et al*. 1991), resulting in plant stunting, delayed maturation (Gold *et al*. 1998), reduced fruit size and bunch weight, and even plant snapping or toppling (Batchelder 1954, Franzmann 1972, Koppenhöfer 1993; Rukazambuga 1996). Interior corm damage possibly affects nutrient transport and stem growth (Taylor 1991), while peripheral damage may adversely affect root development (Gold *et al*. 1994). Morphological and physiological symptoms of infested plants include reduced vigour, leaf chlorosis (Franzmann 1972), choking of the bunch in the pseudostem (Pinese & Elder 2004), decreased vigour of followers (Rukazambuga 1996) and a different proportion of water suckers (Gold *et al*. 1999). Adult weevils feed on plant tissues or crop debris but the resultant damage is considered negligible (Franzmann 1972; Treverrow *et al*. 1992). Infestation by banana root nematodes can show similar symptoms, including a reduction in vigour, leaf chlorosis, plant toppling and yield reduction (Bujulu *et al*. 1983, Smith 1995; Willers *et al*. 2001).

Cultural control is an important strategy for managing the banana weevil in subsistence and organic farming systems (Simmonds 1959). It is based on the manipulation of the weevil habitat to adversely affect the pest and promote the banana plant. Cultural control is applied at the crop establishment (preventative control) and crop management (curative control) stages. The former includes using uninfested plants as propagating material to prevent the spread of the weevil and reduce damage, as eggs and larvae can be disseminated in infested planting material. If suckers are used, rhizomes should be trimmed and pared (Franzmann 1972; Fogain *et al*. 2002). Hot water treatment of suckers is also recommended (Gettman *et al*. 1992), but can be problematic (Gold *et al*. 1998). In South Africa, commercial growers mainly use *in vitro* planting material (Robinson 1996). Tissue culture plants are free of banana weevils and nematodes (Robinson 1996), making them ideal to 'start clean, stay clean' (Peasley & Treverrow 1986). All banana plant material

should be removed from fields to be replanted and left fallow or used for annual crops for a minimum of 1 year (Seshu Reddy *et al*. 1993), but 18 months or 2 years are preferred (Treverrow *et al*. 1992). New plantings should preferably be made in virgin soil and/or removed from infested fields. Deep planting (45-60 cm) delays weevil infestation rates and lower weevil incidence (Seshu Reddy *et al*. 1993). *Tephrosia* spp. and neem (*Azadirachta indica* A. Juss.) have a repellent effect (Walangululu *et al*. 1993), while the latter also negatively affects the physiology of the weevil (Musabyimana *et al*. 2001), thereby helping to delay infestation rates of new plantings (Musabyimana 1999; Fogain *et al*. 2002). Intercropping with coffee has also been reported to reduce weevil numbers (Kehe 1988) and susceptible banana cultivars and residues can serve as trap crops in multi-cultivar stands (Masanza 2003).

High weevil densities and inadequate fallow periods in local commercial systems lead to re-infestation of clean fields from neighbouring plantations. The growing habits (Robinson 1996) and susceptibility of *in vitro* plants to *C. sordidus* may negate their advantage (Nuno & Ribeiro 2002). Deep planting is labour intensive and under these conditions some plant varieties (e.g. plantains) will produce a new rhizome above the previous one (Seshu Reddy *et al*. 1993). High rates of powdered neem are phytotoxic (Musabyimana *et al*. 2000) and it is not effective as a curative treatment (Fogain *et al*. 2002). Moreover, intercropping can reduce banana yield (Uronu 1992) and is troublesome due to the closing of the banana canopy (Seshu Reddy *et al*. 1993). Most of the mechanisms by which diversified systems can reduce herbivore attack, including higher efficacy of natural enemies, effects on immigration/emigration rates and modification of the micro-environment, are not relevant to the banana weevil (Gold *et al*. 1999).

Locally, cultural control is more applicable at the crop management stage. Covering the base of stools with soil mounds up to 30 cm high was associated with low weevil infestations in the Ivory Coast (Kehe 1988). The additional soil assists in delaying high mat formation and provides a firm anchorage for the plant (Seshu Reddy *et al*. 1999). Felling pseudostems at ground level (Simmonds 1959; Annecke & Moran 1982) and diligent crop hygiene, the destruction or removal of accumulating crop trash and fallen plants, are also recommended to minimise additional sheltering and breeding sites of *C. sordidus* (Peasley & Treverrow 1986, Collins *et al*. 1991, Treverrow *et al*. 1992; Fogain *et al*. 2002). Desiccation rate is

enhanced by cutting debris along the longitudinal axis (Treverrow *et al* 1992). The area around plants should be free of trash and remnants should be placed in the inter-row (Stanton 1994). The efficacy of cultural control is not well understood and has not been evaluated under local conditions. The aim of the study was to quantify the efficacy of covering the base of banana stools with soil, alternate felling heights and practicing crop hygiene on weevil control in South Africa. The cultural control treatments were compared to treatment of plants with the registered chemical, aldicarb.

5.2 Material and methods

5.2.1 Research site

The banana weevil cultural control trial was conducted on a commercial farm at the South Coast of KwaZulu-Natal, South Africa. Soil in the area is a Glenrosa form, with an orthic A and lithocutanic B zone. It is a sandy loam soil with 16% clay, 30% loam and 54% sand (Dochez 1998). The trial site was in Ramsgate (30º52'33''S; 30º19'28''E), 130 meters above sea level. The experiment was conducted from August 2003 to November 2005. The location was all in a summer rainfall area (750-1000 mm per year), and during the trial the ambient temperature ranged from 12 to 25 °C.

The Cavendish cultivar, Grand Nain (AAA group), was grown at the trial, planted in November 2000 at a density of 2222 plants.ha^{-1} (300 × 150 cm). High mat was evident in the plantation, with the collar (junction between pseudostem and rhizome) commonly more than 10 cm above ground level. The plantation was sprinkler irrigated with 2 cm water/week, a practise only suspended if rainfall exceeded that value in the particular week. The site was treated at planting with the oxime carbamate, aldicarb (Temik 15% GR), at the registered dosage of 2.025 g.a.i./mat, to provide nematode and weevil control (Nel *et al*. 2002; Anonymous 2005). Regular chemical weed control with glyphosate (Roundup), leaf removal, desuckering and propping of bunch bearing plants were practised. Pre-trial plant inspections revealed rhizome tunnel damage by *C. sordidus*.

5.2.2 Experimental design

Four treatments were compared: harvesting at ground level and longitudinal

dissection of all remnants, covering the mat with soil up to 30 cm from the collar and moving all debris to the inter-row, application of aldicarb at the registered dosage and the standard practise of harvesting at 150 cm with no debris management or covering of the mat (control). The layout of the trial followed a randomised block design with three replicates. Each plot consisted of 72 plants and was separated by a two-row barrier. To standardise for abiotic influences, replicates were orientated perpendicular to the sea/land breeze and moisture gradient in the field.

The cultural treatments were maintained monthly in summer and bi-monthly in winter (soil cover was maintained seasonally) and the chemical applied to the soil, as recommended by the manufacturers, in October/November and March. Yield, damage parameters and pseudostem girth of plants felled during a 3-month period (August to November) in 2003 to 2005 were measured, while adult densities were assessed over 4 weeks in October/November (from 2003 to 2005) and April (from 2004 to 2005). To consider the effect of nematode damage on research results, nematode samples were analysed in October/November 2003 to 2005. Root samples were collected from three randomly selected mother plants per plot, and sent to the ARC - Institute for Tropical and Subtropical Crops (Nelspruit, Mpumalanga), where 30 g of roots (randomly selected per plot) were examined for nematodes. The initial data were recorded before any of the treatments were applied.

Yield was determined at the pack-house by weighing of bananas (bunches excluding the peduncle). Weevil damage and girth sampling of plants were conducted within a week of harvest. The Coefficient of Infestation (CI) was determined by paring the corm and scoring the proportion of the rhizome circumference with weevil galleries (Vilardebó 1973). Intervals of 2.5% were included up to a level of 10% damage. Damage was also rated by the Percentage Coefficient of Infestation (PCI) (Mitchell 1978, 1980), which involved scoring the presence/absence of peripheral damage for ten sections, each covering 18° of the corm surface. The latter was determined at 5 cm (Gold *et al.* 1994) and between 5 and 20 cm from the collar. These two PCI values were summed to provide a total PCI value. A cross section of the corm was made at 10 cm from the collar and the percentage damage of the cortex (XO) and central cylinder (XI) scored at 10% intervals, using a transparent circular grid divided into 36° sections (modified from Gold *et al.* 1994; Kiggundu 2000). The two cross section values were averaged to provide the mean cross sectional damage

(X mean). The circumference of harvested plants was measured at 100 cm from the collar.

Three split-pseudostem traps, placed individually next to three plants in the middle of each plot, were used to sample adult densities. Trap material was randomly selected from plants harvested within 2 weeks before trap preparation at a plantation similar to but isolated (by a dirt road) from the specific trial sites. Only one trap was prepared from each plant and pseudostems with internal damage/necrosis/tunnels were discarded. Pseudostem traps were 30 cm in length (pseudostem section 30-60 cm above the collar), bisected longitudinally and each half placed (with the cut surface ventrally) directly next to the mat of the plant. The two halves were placed on opposite sides of the mat and regarded as one trap. The split pseudostems were covered with mulch to delay desiccation and decomposition. Traps were replaced once a week, when the samples per trap were counted and destroyed.

5.2.3 Statistical analysis

Analysis of covariance (ANCOVA) (Sokal and Rohlf 1997) was used to quantify yield and girth over time, among treatments and between the interactions of time and treatment. The nematode number of all the species were combined and entered as a covariate. Nematode densities over time and between treatments were ascertained by factorial ANOVA, while the pre-treatment densities were compared by one-way ANOVA (Sokal and Rohlf 1997). The seven parameters used for damage estimation were compared over time, between treatments and among the interactions of time and treatment using repeated measures ANOVA. One-way ANOVA (Sokal and Rohlf 1997) was used to ascertain pre-trial differences in adult densities. Differences of adult densities over time, between treatments and between the interactions of the independent variables were determined by factorial ANOVA (Sokal and Rohlf 1997). The Tukey HSD test (Sokal and Rohlf 1997) was used for all *post hoc* analysis. Unless stated otherwise, the data were not transformed and showed a normal distribution and homogeneity of variances in the linear scale. The STATISTICA Version 7 (Statsoft Inc. 2004) software program was used for analysis.

5.3 Results

5.3.1 Yield, girth and nematodes

No differences were found in yield ($F_{3, 7} = 0.14$, $P = 0.934$) or plant girth ($F_{3, 7} = 0.65$, $P = 0.607$) between plots before the onset of the trial (spring 2003). The initial nematode densities between plots were also similar ($F_{3, 8} = 0.07$, $P = 0.973$). While the average bunch weight increased from 2004 (29.67 ± 0.510 (SE) kg per bunch) to 2005 (32.12 ± 0.815 (SE) kg per bunch), no significant difference in yield was found ($F_{1, 15} = 4.40$, $P = 0.053$). The bunch yield for the different treatments (range: 30.60 to 31.08 kg per bunch) was similar ($F_{3, 15} = 0.01$, $P = 0.998$) and no interaction between the independent variables was found ($F_{3, 15} = 0.29$, $P = 0.835$). Plant girth showed no significant effect of time (2004: 67.179 ± 0.7512 (SE) cm, 2005: 67.828 ± 0.8445 (SE) cm) ($F_{1, 15} = 0.06$, $P = 0.809$), treatment (range: 66.612 cm to 68.694 cm) ($F_{3, 15} = 1.61$, $P = 0.229$), or interaction between time and treatment ($F_{3, 15} = 0.57$, $P = 0.642$).

The density of the nematode-complex was similar in October/November of 2004 and 2005 ($F_{1, 16} = 0.46$, $P = 0.507$). The average number of nematodes per 30 g roots ranged from 700.00 to 1316.67 for the aldicarb and low harvest-and-remnant destruction treatments, respectively. No significant difference was, however, found between the treatments ($F_{3, 16} = 2.24$, $P = 0.123$), or the interaction between time and treatment ($F_{3, 16} = 0.15$, $P = 0.926$). The annual samples (2003 to 2005) mainly comprised of spiral nematodes (*Helicotylenchus* spp.), while relatively low numbers of root knot (*Meloidogyne* spp.) and lesion nematodes (*Pratylenchus* spp.) were present. No burrowing nematodes (*Radopholus similis* (Cobb)) were found during the study.

5.3.2 Damage parameters

The pre-trial plant damage estimations of the PCI (0-5 cm), PCI (5-20 cm), Total PCI, CI, XO, XI and X mean were similar between plots ($F_{3, 8} = 0.09$, $P = 0.963$; $F_{3, 8} = 0.18$, $P = 0.907$; $F_{3, 8} = 0.07$, $P = 0.974$; $F_{3, 8} = 0.11$, $P = 0.951$; $F_{3, 8} = 0.13$, $P = 0.942$; $F_{3, 8} = 0.39$, $P = 0.766$ and $F_{3, 8} = 0.13$, $P = 0.938$, respectively). No temporal effect was found for any of the dependent variables between 2004 and 2005 ($0.002 < F_{1, 16} < 1.66$, $0.216 < P < 0.962$). A significant treatment effect was only found for CI ($F_{3, 16} = 4.17$, $P = 0.023$). Post ANOVA analysis showed that the soil cover and movement of debris-treatment significantly reduced the damage parameter compared to the control (Fig. 5.1). The former treatment also showed the lowest values for the three PCI

damage parameters (Fig. 5.1). Relative to control plants, covering of the plant bases with soil and movement of debris to the inter-row caused the greatest reduction in the percentage damage to the cortex and X mean, while aldicarb application showed the greatest reduction in the XI (Fig. 5.2).

5.3.3 Adult densities

The pre-trial adult densities were not different between plots ($F_{3, 8}$ = 1.92, P = 0.206). Subsequent collections showed a significant difference in the number of adults collected ($F_{3, 32}$ = 6.96, P = 0.001). There were no significant treatment effects or an interaction between time and treatment ($F_{3, 32}$ = 0.79, P = 0.506; $F_{9, 32}$ = 1.52, P = 0.184, respectively). The Tukey *post hoc* test showed that the mean number of adults collected in April 2005 (11.48 ± 1.014 (SE)), was significantly less than the numbers in October/November 2005 (19.08 ± 1.801 (SE)), April 2004 (19.14 ± 1.581 (SE)) and October/November 2004 (19.17 ± 1.551 (SE)), which were all statistically similar. Covering the plant bases with soil and movement of debris to the inter-row caused a slight reduction in the adult density (Fig. 5.3).

5.4 Discussion

Neither the cultural control methods investigated in this study, nor the chemical registered for control of the banana weevil in South Africa, caused a significant increase in plant yield or plant girth after 2 years. The cultural treatments and chemical application did not significantly reduce adult beetle densities or any of the damage parameters either, except when the mat was covered with soil and remnants were moved to the inter-row, which resulted in lower damage to the periphery of plants. It was interesting that neither the weevil density, nor root infestation by nematodes, was reduced by aldicarb, a chemical known for its effect on these banana pests (Jones & Dieckmann 1982; De Jager *et al*. 1991). The beneficial mechanism of a soil cover may be related to weevil oviposition and/or an increase in plant vigour. Covering the mat with soil may provide additional support to plants, especially when high mat is present. In Uganda, plants harvested low and covered with soil had lower oviposition (400%) compared to uncovered plants during the wet season, although the dry season showed a 73% higher oviposition rate between the treatments (Masanza 2003). The application of cultural methods is usually problematic due to labour costs

(Dochez 1998). Soil cover of plant bases only needs to be applied seasonally, because plant roots grow into and attach the additional soil to the rhizome. In the short term, covering stools with soil are recommended in South Africa. The trial will be continued to determine the long-term effects of the cultural control treatments.

Movement of remnants of banana pseudostems and leaves to the inter-row is expected to reduce moisture and adult activity near the mat of plants. Recession of the mulch to more than 100 cm from the pseudostem compared to mulching to the base of the pseudostem over a 3-year period in Uganda, however, did not significantly reduce weevil density or damage to the plant (McIntyre *et al*. 2003). In Australia, dissection of pseudostems and raking mulch into the mid-row three to four times per year also did not result in a reduction of weevil adults or damage over 3 years (Smith 1995). The most effective component of the combined soil cover and residue recession treatment, therefore, appears to be the former, assuming there were no interaction effects between the treatments.

The rationale for low harvesting of plants is to accelerate desiccation of residues, a condition unfavourable for weevil development. However, Daniells and O'farrell (1987) found that harvesting at a 200 cm versus 10 cm height increased bunch mass on the follower by 12% and decreased time to the next harvest by 5%. Some nutrients may be lost to a plant from using harvested pseudostems for mulch as opposed to senesced pseudostems that may 'feed' followers through direct nutrient translocation (Wortman *et al*. 1994). In this study, we have hoped that a significant reduction in weevil damage could have compensated for the yield loss that one would have expected. The damage, however, remained relatively constant under low harvest conditions, suggesting that the effect of felling height on yield may vary between cropping systems, or that more than two seasons are required before the effect is evident. The efficacy of banana crop sanitation is questionable because residual corms, that are the most important source of pest populations, are not amendable to the practise of crop hygiene (Nanne & Klink 1975; Treverrow & Maddox 1993). Removal of the rhizome is labour intensive and will weaken followers by reducing the support of the mat. Residues can serve as traps and in some varieties it is more attractive to egg-laying females than standing plants (Waterhouse & Norris 1987, Gold *et al*. 1999; Masanza 2003). Poor sanitation can, however, increase weevil damage and the beetle population (Masanza 2003, Masanza *et al*. 2005b). Double the number of weevils complete development in toppled compared to standing plants,

because of greater ovipositional accessibility to softer corm material and an increased oviposition area (Treverrow *et al*. 1992). The developmental rate may also be positively related to residue age (Masanza 2003), although fresh residues are usually more attractive (Masanza *et al*. 2005a). In the current study, more than 2 years of assessment could, therefore, have been required before the beneficial effects of sanitation became evident, as was found in Uganda (Masanza 2003; Masanza *et al*. 2005b).

Plants were propped during the trial and plant loss, which can contribute more to yield loss than reduction in bunch weight (Rukazambuga 1996), was not considered. The damage parameter of Cavendish bananas that is most closely related to effective bunch weight (fruit weight) is the percentage damage to the central cylinder (Chapter 7). Under certain conditions, however, the mean percentage damage to the cortex and central cylinder of the corm is also important (Chapter 7). Soil cover and recession of remnants reduced the respective parameters by 14.18% and 31.52%, respectively.

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5.6 References

ABERA, A.M.K., GOLD, C.S. & KYAMANYWA, S. 1999. Timing and distribution of attack by the banana weevil (Coleoptera: Curculionidae) in East African highland banana (*Musa* spp.). *Florida Entomologist* 82: 631-641.

ANNECKE, D.P. & MORAN, V.C. 1982. *Insects and Mites of Cultivated Plants in South Africa*. 67-68. Butterworths, Durban.

ANONYMOUS. 2005. *Agricultural remedies*. National Department of Agriculture. World Wide Web: http://www.nda.agric.za/act36/AR/Insecticides.htm

BATCHELDER, C.H. 1954. Experimentos con insecticidas para combater el picudo negro, *Cosmopolites sordidus* (Germar), en plantaciones de abaca. *Turrialba* 4: 88-93.

BUJULU, J., URONU, B. & CUMMING, C.N.C. 1983. The control of banana weevils and parasitic nematodes in Tanzania. *East African Agricultural and Forestry Journal* 49: 1-13.

CHAVARRIA-CARVAJAL, J.A. & IRIZARRY, H. 1997. Rates, application intervals and rotation of four granular pesticides to control nematodes and the corm-weevil (*Cosmopolites sordidus* Germar) in plantain. *Journal of Agriculture of the University of Puerto Rico* 81: 43-52.

COLLINS, P.J., TREVERROW, N.L. & LAMBKIN, T.M. 1991. Organophosphorus insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Australia. *Crop Protection* 10: 215-221.

DANIELLS, J.W. & O'FARREL, P.J. 1987. Effect of cutting height of the parent pseudostem on yield and time of production of the following sucker in banana. *Scientia Horticulturae* 31: 89-94.

DE JAGER, K., RABIE, E.C. & ANDERSON, S.H. 1991. Chemiese beheer van die piesangwortelboorder, *Cosmopolites sordidus* en aalwurms, veral die booraalwurm, *Radopholus similis*. *Inligtingsbulletin - Navorsingsinstituut vir Sitrus en Subtropiese Vrugte* 228: 17-20.

DOCHEZ, C. 1998. *Study on Pest Status and Control of* Cosmopolites sordidus *(Germar) in South Africa*. M.Sc. Thesis, Heriot-Watt University, Scotland.

FOGAIN, R., MESSIAEN, S. & FOURÉ, E. 2002. Studies on the banana borer weevil in Cameroon. *Infomusa* 11: 8-9.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

GETTMAN, A.D., MITCHELL, W.C., LI, P. & MAU, R.F.L. 1992. A hot water treatment for control of the banana root borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in banana planting stock. *Proceedings of the Hawaiian Entomological Society* 31: 59-63.

GOLD, C.S., NIGHT, G., ABERA, A. & SPEIJER, P.R. 1998. Hot-water treatment for the control of the banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 6: 215-221.

GOLD, C.S., RUKAZAMBUGA, N.D.T.R., KARAMURA, E.B., NEMEYE, P. & NIGHT, G. 1999. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 33-50.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., TUSHEMEREIRWE, W.K. & KASHAIJA, I.N. 1994. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2: 309-321.

JONES, R.K. & DIECKMANN, F. 1982. Control of the banana root borer, *Cosmopolites sordidus* Germar. *Information Bulletin, Citrus and Subtropical Fruit Research Institute* 13-17.

KEHE, M. 1988. Le charançon du bananier (*Cosmopolites sordidus*), les aquis et les perspectives de la recherché: contribution de L'IRFA-CIRAD/Cote d'Ivoire. In: INIBAP (Ed.) *Nematodes and the Borer weevil in Bananas: Present Status of Research and Outlook. Proceedings of a Workshop in Bujumbura, Burundi*. December 1987: 47-51.

KIGGUNDU, A. 2000. *Host Plant Reactions and Resistance Mechanisms to Banana Weevil, Cosmopolites sordidus (Germar) in Ugandan Musa Germplasm*. M.Sc. Thesis, Orange Free State University, South Africa.

KOPPENHÖFER, A.M. 1993. Observation on egg laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata* 68: 187-192.

MASANZA, M. 2003. *Effect of Crop Sanitation on Banana Weevil* Cosmopolites sordidus *(Germar) Populations and Associated Damage*. Ph.D. Thesis. Wageningen University, Wageningen, The Netherlands.

MASANZA, M., GOLD, C.S., VAN HUIS, A. & RAGAMA, P.E. 2005a. Effects of covering highland banana stumps with soil on banana weevil *Cosmopolites sordidus* (Coleoptera: Curculionidae) oviposition. *International Journal of Tropical Insect Science* 25: 19-24.

MASANZA, M., GOLD, C.S., VAN HUIS, A., RAGAMA, P.E. & OKECH, S.H.O. 2005b. Effect of crop sanitation on banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) populations and crop damage in farmers' fields in Uganda. *Crop Protection* 24: 275-283.

MCINTYRE, B.D., GOLD, C.S., SSALI, H. & RIHA, S.J. 2003. Effects of mulch location on banana weevil, soil and plant nutrients, soil water and biomass in banana fields. *Biology and Fertility of Soils* 39: 74-79.

MITCHELL, G. 1978. *The Estimation of Banana Borer Population and Resistance levels*. Technical Bulletin 2, Windward Island Banana Growers Association (WINBAN), St. Lucia.

MITCHELL, G. 1980. *Banana Entomology in the Windward Islands. Final report 1974-1978*. Centre for Overseas Pest Research, London.

MUSABYIMANA, T. 1999. *Neem Seed for the management of the Banana Weevil*, Cosmopolites sordidus *Germar (Coleoptera: Curculionidae) and Banana Parasitic Nematode Complex*. Ph.D. Thesis, Kenyatta University, Kenya.

MUSABYIMANA, T., SAXENA, R.C., KAIRU, E.W., OGOL, C.K.P.O., KHAN, Z.R. 2000. Powdered neem seed and cake for management of the banana weevil, *Cosmopolites sordidus*, and parasitic nematodes. *Phytoparasitica* 28: 321-330.

MUSABYIMANA, T., SAXENA, R.C., KAIRU, E.W., OGOL, C.P.K.O. & KHAN, Z.R. 2001. Effects of neem seed derivatives on behavioural and physiological responses of the *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Journal of Economic Entomology* 94: 449-454.

NANNE, H.W. & KLINK, J.W. 1975. Reducing banana root weevil adults from an established banana plantation. *Turrialba* 25: 177-178.

NEL, A., KRAUSE, M. & KHELAWANLALL, N. 2002. *A Guide for the Control of Plant Pests*. 39th Edition. Directorate, Agricultural Production Inputs, Department of Agriculture, South Africa.

NUNO, L. & RIBEIRO, V.P. 2002. *Cosmopolites sordidus* in the autonomous region of Madeira. *Infomusa* 11: 10.

PEASLEY, D. & TREVERROW, N. 1986. *Count, Cut and Dry: Management of Banana Weevil Borer in Bananas. Agdex 231/62Z.* NSW Agriculture and Fisheries, Australia.

PINESE, B. & ELDER, R. 2004. *Banana Weevil Borer*. Queensland Government, Department of Primary Industries and Fisheries, Horticulture and Fresh Produce. World Wide Web: http://www.dpi.qld.gov.au/horticulture/2507.html

ROBINSON, J.C. 1996. *Bananas and Plantains*. CAB International, Wallingford.

RUKAZAMBUGA, N.D.T.M. 1996. *The Effects of Banana Weevil* (Cosmopolites sordidus *Germar) on the Growth and Productivity of Bananas* (Musa *AAA EA) and the Influence of Host Vigour on Weevil Attack*. Ph.D. Thesis, University of Reading, UK.

SESHU REDDY, K.V., GOLD, C.S. & NGODE, L. 1999. Cultural control strategies for the banana weevil, *Cosmopolites sordidus* Germar. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 51-57.

SESHU REDDY, K.V., KOPPENHÖFER, A.M. & URONU, B. 1993. Cultural practises for the control of the banana weevil. In Gold, C.S. & Gemmil, B. (Eds.) *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting in Cotonou, Benin: IITA*. 140-146.

SIMMONDS, N.W. 1959. *Bananas*. 1st Edition. Longmans Press, London.

SMITH, D. 1995. Banana weevil borer control in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 35: 1165-1172.

SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. W.H. Freeman and Company, New York.

STANTON, J.M. 1994. Status of nematode and weevil borer problems affecting banana in Australia. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 48-56.

STATSOFT INCORPORATED. 2004. *Statistica*. Version 7.

TAYLOR, B. 1991. Research field work on upland bananas, *Musa* spp., principally *acuminata* triploid AAA types, in the Kangera region of Tanzania with observations on growth and on the causes of decline in crop yield. *Revista di Agricultura Subtropicale e Tropicale* 85: 349-392.

TREVERROW, N. & MADDOX, C. 1993. The distribution of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) between various types of banana plant material in relation to crop hygiene. *General and Applied Entomology* 23: 15-20.

TREVERROW, N., PEASLEY, D. & IRELAND, G. 1992. *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*. Banana Industry Committee, New South Wales Agriculture.

URONU, B.E.M.A. 1992. *The Effect of Plant Resistance and Cultural Practises on the Population Densities of Banana Weevil* Cosmopolites sordidus *(Germar) and on banana yield*. Ph.D. Thesis, Kenyatta University, Kenya.

VILARDEBÓ, A. 1973. Le coefficient d'infestation, critere d' evaluation du degre d'attaques des bananeraies par *Cosmopolites sordidus* Germ. Le charancon noir du bananier. *Fruits* 28: 417-431.

WALANGULULU, M., LITUCHA, B.M. & MUSASA, M. 1993. Potential for the control of the banana weevil *Cosmopolites sordidus* Germar with plants reputed to have an insecticidal effect. *Infomusa* 2: 9.

WATERHOUSE, D.F. & NORRIS, K.R. 1987. *Cosmopolites sordidus* (Germar). In: Waterhouse, D.F. & Norris, K.R. (Eds.) *Biological Control: Pacific Prospects*. 152-158, 454. Inkata Press, Melbourne.

WILLERS, P., DANEEL, M.S. & DE JAGER, K. 2001. Banana. In: Van den Berg, M.A., De Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. 36. ARC – Institute for Tropical and Subtropical Crops. Ad Dynamics, Nelspruit.

WORTMAN, C.S., KARAMURA, E.B. & GOLD, C.S. 1994. Nutrient flows from harvested banana pseudostems. *African Crop Science Journal* 2: 179-182.

Figure legends

Figure 5.1. The mean values of the Percentage Coefficient of Infestation (PCI) and Coefficient of Infestation (secondary axis) damage parameters of untreated (control) plants and plants treated with aldicarb, and the two cultural control treatments, from October/November 2003 to October/November 2005 at Ramsgate (KZN, South Africa). For each dependent variable, means with letters in common are not significantly different (P>0.05) and upper case letters refer to the secondary axis. 05 = PCI from 0 to 5 cm from the collar, 20 = PCI from > 5 to 20 cm from the collar, To = Summed total PCI, Chem = Aldicarb, Harv = Low harvesting and destroying remnants, Cover = Soil cover and movement of debris to the inter-row.

Figure 5.2. The mean values of the cross sectional damage parameters of untreated (control) plants and plants treated with aldicarb, and the two cultural control treatments, from October/November 2003 to October/November 2005 at Ramsgate (KZN, South Africa). For each dependent variable, means with letters in common are not significantly different (P>0.05). XO = Cross section damage percentage of the cortex, XI = Cross section damage percentage of the central cylinder, X mean = Average cross sectional damage of the corm, Chem = Aldicarb, Harv = Low harvesting and destroying remnants, Cover = Soil cover and movement of debris to the inter-row.

Figure 5.3. The mean adult density values of untreated (control) plots and plots treated with aldicarb, and the two cultural control treatments, from October/November 2003 to October/November 2005 at Ramsgate (KZN, South Africa). For each dependent variable, means with letters in common are not significantly different (P>0.05). Chem = Aldicarb, Harv = Low harvesting and destroying remnants, Cover = Soil cover and movement of debris to the inter-row.

Figure 5.1

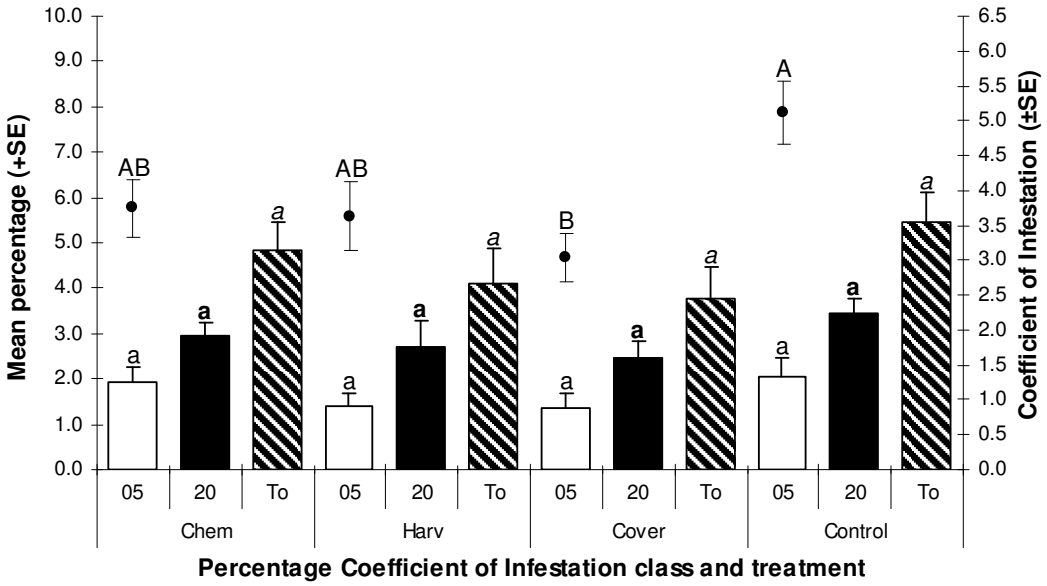

Mean percentage (+SE)
Coefficient of Infestation (±SE)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
AB
AB
B
A
a
a
a
a
a
a
a
a
a
a
a
a
05
20
To
05
20
To
05
20
To
05
20
To
Chem
Harv
Cover
Control
Percentage Coefficient of Infestation class and treatment

Figure 5.2

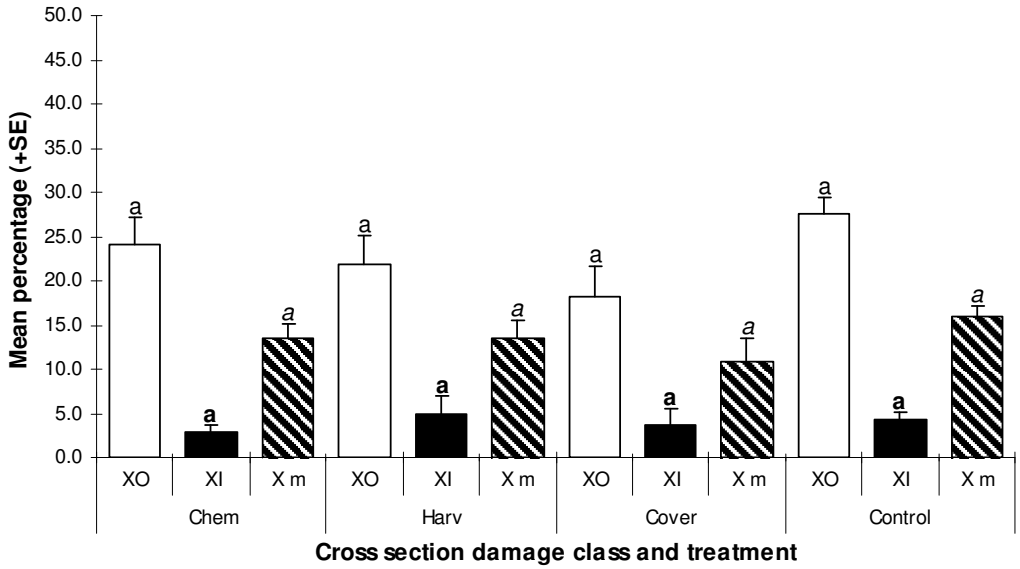
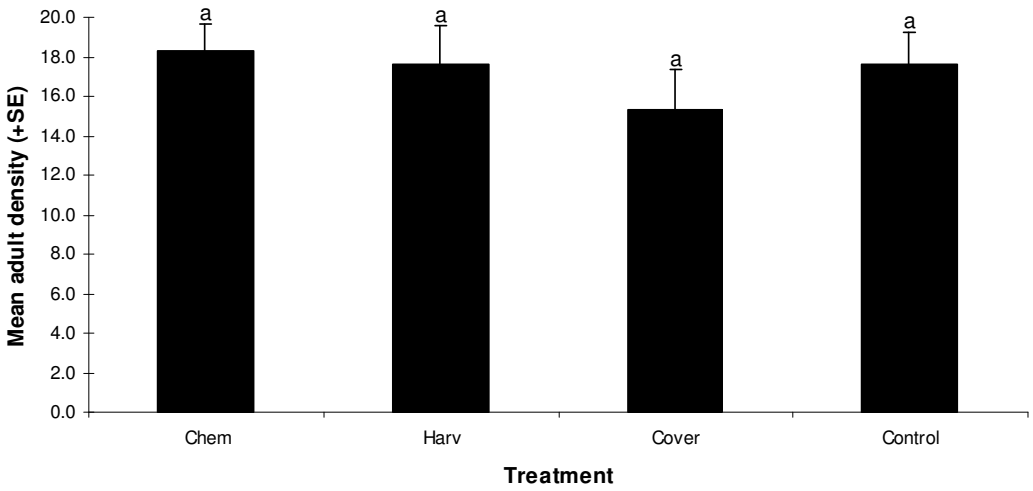

50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Mean percentage (+SE)
a
XO
XI
X m
Chem
Harv
Cover
Control
Cross section damage class and treatment

Fig. 5.3


20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Mean adult density (+SE)
a
a
a
a
Chem
Harv
Cover
Control
Treatment

Chapter 6

Chemical control of *Cosmopolites sordidus* in South Africa

Abstract

Cosmopolites sordidus (banana weevil) is a major production constraint in most areas where bananas are grown. The weevil is difficult to control, and chemical control arguably provides the best opportunity to manage the pest. The aim of this study was to determine the efficacy of injecting bifenthrin, chlorpyrifos, fipronil, imidacloprid, oxamyl and water (control) into residual banana plants. The chemicals were administered every even numbered month over 2 years at two locations in Southern KwaZulu-Natal, South Africa. Yield, weevil damage and pseudostem girth of plants felled from August to October were measured, while adult beetle densities were assessed over 4 weeks in October and April. Nematode samples were analysed in October every year. Damage parameters included the Coefficient of Infestation, the Percentage Coefficient of Infestation (PCI) at two intervals, the summed PCI value, the percentage cross sectional damage of the central cylinder and cortex, and the mean cross sectional damage percentage. Replicated block designs were used in the experiments. The parameters were similar before the onset of the trial. Fruit yield and plant girth, corrected by nematode densities, were not significantly increased after chemical applications, nor were the nematodes controlled. Fipronil and imidacloprid were highly effective against *C. sordidus*, minimising damage to the periphery, cortex and central cylinder of the rhizome and significantly reduced adult density. Fipronil caused a 95% and imidacloprid a 100% reduction in the cross sectional damage of the central cylinder, the damage parameter most closely related to yield. Injection of fipronil and imidacloprid provides an optimal chemical strategy in an integrated pest management programme for the banana weevil.

Keywords: Insecticide, injection, yield, damage, banana weevil

6.1 Introduction

The banana weevil, *Cosmopolites sordidus* (Germar), is an important pest of *Musa* and *Ensete* (Stover & Simmonds 1987, Gold & Messiaen 2000; Gold *et al*. 2003) and the dominant insect pest of bananas in South Africa. Adults feed on plant tissues or crop debris but the damage inflicted is negligible (Franzmann 1972; Treverrow *et al*. 1992). Females oviposit their eggs singularly (Froggatt 1925, Simmonds 1966; Franzmann 1972) in the crown of the rhizome and pseudostem base (Abera *et al*. 1999), favouring flowered plants (Treverrow *et al*. 1992; Abera *et al*. 1999). Upon emergence, the larvae tunnel into the rhizome, producing distinctive circular, debris-filled tunnels (Franzmann 1972). Interior corm damage affects nutrient transport and stem growth (Taylor 1991), while peripheral damage adversely affects root development (Gold *et al*. 1994). The pupa develops in a chamber at the corm periphery (Franzmann 1972) and eclosion produces a reddish, brown adult (teneral stage), which later becomes uniformly dull black (Pinese & Elder 2004). Infested plants show stunted growth, delayed maturation (Gold *et al*. 1998), reduced bunch weight, and can snap or topple (Batchelder 1954, Franzmann 1972; Koppenhöfer 1993). Infestation by banana root nematodes can show similar symptoms, including a reduction in vigour, leaf chlorosis, plant toppling and yield reduction (Bujulu *et al*. 1983, Smith 1995; Willers *et al*. 2001).

Chemical control of the beetle has been employed since the early 20th century. Pesticides consisted mainly of Paris Green, followed by the use of organochlorines like BHC and DDT (Froggatt 1925, Cuillé 1950, Simmonds 1966; Treverrow *et al*. 1992). The chemicals were usually applied with flour or other substances as baits (Froggatt 1925, Cuillé 1950, Simmonds 1966; Treverrow *et al*. 1992). The method was not very effective (Simmonds 1966) and the persistent cyclodienes, dieldrin and aldrin, showed high efficacy as a soil treatment against the banana weevil (Braithwaite 1958). Cyclodienes was used extensively around the world from the mid 1950's (Edge 1974) and was found to be effective for up to 2 years after application (Braithwaite 1967). Before 1970, however, resistance to cyclodienes was widely diagnosed (Vilardebó 1967, Anonymous 1969; Shanahan & Goodyer 1974).

Investigations into alternative chemicals (mainly organophosphates and carbamates) showed chlordecone (organochlorine), pirimiphos-ethyl, chlorpyrifos,

prothiophos and ethoprophos as viable for biannual applications, but diazinon was unsuitable because of its short residual action (Wright 1977, Collins *et al*. 1991; Smith 1995). Aldicarb, terbufos, carbofuran, carbosulfan, oxamyl, fenamiphos (Román *et al*. 1979, Cárdenas 1984, De Jager *et al*. 1991, Vittayaruk *et al*. 1994, Chavarria-Carvajal & Irizarry 1997; Fogain *et al*. 2002), isofenphos, isazofos (Bujulu *et al*. 1983), phoxim (Nuno & Ribeiro 2002) tebupirimiphos, cadusafos (Quilici 1993), fosthiazate (Chabrier *et al*. 2002), phorate, disulfoton, quinalphos (Viswanath 1977), acephate, diethyl, pada, monocrotophos, deltamethrin (pyrethroid) (Maolin 1994), fipronil (phenyl pyrazole) (Price 1995; Fogain *et al*. 2002) and bifenthrin (pyrethroid) (Smith 1995) were also found to be effective. Less than 10 years after widespread organophosphate use in Australia, resistance to pirimiphos-ethyl, prothiophos, chlorpyrifos and ethoprophos were reported in Queensland and New South Wales with evidence of cross resistance to oxamyl but not to carbofuran, isazofos or isofenphos (Collins *et al*. 1991). Subsequently soil applications of bifenthrin were found to be effective, but fipronil, carbosulfan and furathiocarb were similar to untreated controls in Southeast Queensland (Smith 1995). Resistance to carbofuran has not been found in Uganda or Australia (Collins *et al*. 1991; Gold *et al*. 1999). The high rate of resistance development was attributed to widespread, regular applications with no population monitoring (Collins *et al*. 1991).

Chemical control with non-systemic pesticides is mainly directed against adults (Simmonds 1966, Wright 1977; Collins *et al*. 1991). Dipping corms in insecticide solution were significantly more effective than hot water treatment in controlling the weevil in planting material (Cardenas Murillo *et al*. 1986). Chemical application is commonly recommended in planting holes (Franzmann 1972, Anitha *et al*. 1992; Fogain *et al*. 2002), to plant traps (bait spraying) (Treverrow *et al*. 1992) and to the bases of banana plants (butt sprays) (Braithwaite 1958, Bujulu *et al*. 1983, Collins *et al*. 1991, Smith 1995; Fogain *et al*. 2002). In Australia butt sprays are applied in spring and autumn and chemicals are injected into residual pseudostems during winter (Froggatt 1926, Treverrow 1985, Treverrow *et al*. 1992, Stanton 1994). Butt sprays are, however, detrimental to beneficial insects and only target adults in close vicinity of plants (Collins *et al*. 1991). Bait sprays are applied to fresh residues every 2nd or 4th week in spring and autumn. Poison traps save on insecticide, but are regarded as being relatively ineffective (Simmonds 1959), especially at high infestation levels (Treverrow *et al*. 1992).

Systemic chemicals (dimethoate, omethoate, aldicarb, carbofuran, carbosulfan, fenamiphos, fosthiazate, isazofos, monocrotophos, oxamyl, phorate and terbufos) can potentially control larvae following uptake by banana roots after soil application (Gold *et al*. 2003). These chemicals provide a protective treatment for plants, but have relatively shorter residual actions (Treverrow *et al*. 1992) and do not prevent attacks on plant residues after harvest (Treverrow pers. comm.). Dual action insecticide-nematicides with systemic action will be of value to treat moderate weevil infestations when nematode densities also require treatment (Treverrow *et al*. 1992).

In South Africa, late summer and early spring butt application of pirimiphos-ethyl and aldicarb has been recommended (Jones & Dieckmann 1982). Pirimiphos-ethyl was used until the mid 1990's (Schoeman 1996) and imidacloprid and prothiofos were used in 1999 (Schoeman *et al*. 1999). Locally the pesticides aldicarb, terbufos and oxamyl were also reported to be effective in controlling the banana weevil and the pratylenchid nematode, *Radopholus similis* (Cobb) (De Jager *et al*. 1991). Schoeman (1998) reported that fenamiphos and cadusafos showed promise to control the weevil in a field trial, yet Dochez (1998) showed that terbufos, fosthiazate, aldicarb and cadusafos did not reduce weevil damage locally. Only aldicarb is registered for control of the banana weevil and nematodes in South Africa (Nel *et al*. 2002; Anonymous 2005). The soil around the plants is treated and application is recommended at planting, during November (late spring) and March (late summer/early autumn). According to Quilici (1993) and Schoeman (1998), aldicarb does not provide sufficient control of the weevil and growers have also reported treatment failures. Some desperate growers have even resorted to illegal and unregistered chemical usage (Dochez 1998). The aim of this study was to determine the efficacy of injecting contact and systemic chemicals into residual banana material in South Africa throughout the year.

6.2 Material and methods

6.2.1 Research sites

Trials to evaluate the efficacy of chemicals against the banana weevil were conducted on two commercial farms at the South Coast of KwaZulu-Natal, South Africa. The trial sites were in Munster (30º59'29''S; 30º14'49''E) and Ramsgate (30º52'31''S; 30º19'29''E), 72 and 130 meters above sea level, respectively. Soil in the area is a

Glenrosa form, with an orthic A and lithocutanic B zone. It is a sandy loam soil with 16% clay, 30% loam and 54% sand (Dochez 1998). The experiments were conducted from August 2003 to October 2005. The locations were in a summer rainfall area (750-1000 mm per year), and during the trials the ambient temperature ranged from 12 to 25 °C.

The Cavendish cultivars Williams and Chinese Cavendish (AAA group) were grown at the Munster and Ramsgate trials, respectively. The former was planted in November 1995 and the latter in November 2000, both at a density of 2222 plants.ha^{-1} (300 × 150 cm). High mat was evident in the plantations, with the collar (junction between pseudostem and rhizome) commonly more than 10 cm above ground level. The Munster plantation was drip and the Ramsgate site sprinkler irrigated with 2 cm water/week, a practise only suspended if rainfall exceeded that value in the particular week. The sites were treated at planting with the oxime carbamate, aldicarb (Temik 15% GR), at the registered dosage of 2.025 g.a.i./mat, to provide nematode and weevil control. Regular chemical weed control with glyphosate (Roundup), leaf removal, desuckering and propping of bunch bearing plants were practised. Pre-trial plant inspections at all sites revealed rhizome tunnel damage by *C. sordidus*. No plantation hygiene was practised and at both sites accumulated residues were destroyed in January 2005. The sites were relatively similar, but compared to the Ramsgate location, the older Munster plantation had a lower plant density (less canopy cover) as a result of plant toppling, a higher rate of residue desiccation, more remnants present in the field and not all residues (approximately 65 to 70%) were attached to the mother plant.

6.2.2 Experimental design

Five different chemicals were evaluated, but imidacloprid was only included in the Ramsgate trial (Table 6.1). Control plants were injected with water. Treatments were applied by injecting 10 ml of chemical solution (or water) into residual banana pseudostems using a calibrated knapsack (Calibra stem applicator, Interlock CC, Pretoria, South Africa). The lance of the backpack was end-capped with a spear-shaped “dagger”, with three injector slits on opposite sides at the distal end (Interlock CC, Pretoria, South Africa). Moist tissue of softened, decayed pseudostems (or rhizomes), with at least a distal portion easily compressible by hand, were injected at a 100 cm height or less, depending on the level of decay. Chemicals were

administered at a 45° angle (downward) to the erect portion of the decayed plant, allowing introduction of the chemical dose with no leaching from the injection hole. Only the most recently harvested residual allowing injection, where possible still attached to the mother plant, was treated at each mat. The layout of the trials followed a randomised block design with three replicates. Plots had approximately 50 plants and were separated by a two-row barrier. To standardise for abiotic influences, replicates were orientated perpendicular to the sea/land breeze and moisture gradient in the field.

Application of pesticides (and water) was conducted every 2nd month from late October 2003 to late August 2005. Yield, damage parameters and pseudostem girth of plants felled during a 3-month period (August to October) in 2003 to 2005 were measured. Yield was determined at the pack-house by weighing of bananas (bunches excluding the peduncle). The plants were subjected to weevil damage and girth sampling within a week of harvest. The Coefficient of Infestation (CI) was determined by paring the corm and scoring the proportion of the rhizome circumference with weevil galleries (Vilardebó 1973). Intervals of 2.5% were included up to a level of 10% damage. Damage was also rated by the Percentage Coefficient of Infestation (PCI) (Mitchell 1978, 1980), which involved scoring the presence/absence of peripheral damage for ten sections, each covering 18° of the corm surface. The latter was determined at 5 cm (Gold *et al*. 1994) and between 5 and 20 cm from the collar. The two PCI values were summed to provide a total PCI value. A cross section of the corm was made at 10 cm from the collar and the percentage damage of the central cylinder and cortex scored in 10% intervals, using a transparent circular grid divided into 36° sections (modified from Gold *et al*. 1994, Kiggundu 2000). The two cross section values were averaged to provide the mean cross sectional damage (X mean). The circumference of harvested plants was measured at 100 cm from the collar.

Adult densities were assessed over 4 weeks in October (from 2003 to 2005) and April (from 2004 to 2005). Three split-pseudostem traps, placed individually next to three plants in the middle of each plot, were used to sample adult densities. Trap material was randomly selected from plants harvested within 2 weeks before trap preparation at a plantation similar to, but separated by a dirt road, from the specific trial sites. Only one trap was prepared from each plant and pseudostems with internal damage/necrosis/tunnels were discarded. Pseudostem traps were 30 cm in length

(pseudostem section 30-60 cm above the collar), bisected longitudinally and each half placed (with the cut surface ventrally) directly next to the mat of the plant. Two halves were placed on opposite sides of the mat and regarded as one trap. The split pseudostems were covered with mulch to delay desiccation and decomposition. Traps were replaced once a week, when the samples per trap were counted and destroyed.

Nematode samples were collected and analysed in October (from 2003 to 2005). Root samples were collected from three randomly selected mother plants per plot. Samples were sent to the ARC - Institute for Tropical and Subtropical Crops (Nelspruit, Mpumalanga), where 30 g of roots (randomly selected per plot) were examined for nematodes. The initial data were recorded before any of the treatments were applied.

6.2.3 Statistical analysis

Analysis of covariance (ANCOVA) (Sokal and Rohlf 1997) was used to quantify yield and girth over time, among treatments and between the interactions of time and treatment. The nematode number of all the species were combined and entered as a covariate. Nematode densities over time and between treatments were ascertained by factorial ANOVA, while the pre-treatment densities were compared by one-way ANOVA. The seven parameters used for damage estimation were compared over time, between treatments and among the interactions of time and treatment using repeated measures ANOVA. One-way ANOVA (Sokal and Rohlf 1997) was used to ascertain pre-trial differences in adult densities. Differences of adult densities over time, between treatments and between the interactions of the independent variables were determined by factorial ANOVA (Sokal and Rohlf 1997). The Tukey HSD test (Sokal and Rohlf 1997) was used for all *post hoc* analysis. Unless stated otherwise, the data were not transformed and showed a normal distribution and homogeneity of variances in the linear scale. The STATISTICA Version 7 (Statsoft Inc. 2004) software program was used for analysis.

6.3 Results

6.3.1 Munster trial

6.3.1.1 Yield, girth and nematodes

No differences were found in yield ($F_{4, 9} = 0.29$, $P = 0.876$) and plant girth ($F_{4, 9} =$

1.21, P = 0.372) between plots at the onset (spring 2003) of the trial. The initial nematode densities between plots were also similar ($F_{4, 10}$ = 0.52, P = 0.724).

Bunch yield was statistically similar in the spring of 2004 (24.80 ± 0.486 (SE) kg) and 2005 (26.59 ± 0.780 (SE) kg) ($F_{1, 19}$ = 0.57, P = 0.460), was no different between treatments (range: 24.9 to 26.81 kg) ($F_{4, 19}$ = 0.38, P = 0.822) and did not show a significant interaction between time and treatment ($F_{4, 19}$ = 0.57, P = 0.687). Similarly, plant girth also showed neither a significant temporal (2004: 66.257 ± 0.7912 (SE) cm, 2005: 65.889 ± 0.8694 (SE) cm) ($F_{1, 19}$ = 0.06, P = 0.813) or treatment effect (range: 64.725 to 66.728 cm) ($F_{4, 19}$ = 0.34, P = 0.845), nor an interaction between the independent variables ($F_{4, 19}$ = 1.43, P = 0.261).

The nematode-complex showed a significant difference between dates ($F_{1, 20}$ = 5.97, P = 0.024), while numbers between treatments and between interactions of time and treatment were similar ($F_{4, 20}$ = 0.12, P = 0.975 and $F_{4, 20}$ = 0.45, P = 0.771, respectively). Post ANOVA analysis showed that the average number of nematodes was significantly higher in 2005 (1770 nematodes per 30 g roots) compared to 2004 (1000 nematodes per 30 g roots). Analysis of samples in 2003 and 2004 showed that the spiral (*Helicotylenchus* spp.) and lesion nematodes (*Pratylenchus* spp.) were approximately of equal proportions. Root samples in 2005 were mainly infested with spiral nematodes, but lesion and root knot nematodes (*Meloidogyne* spp.) were also present. The burrowing nematode, *R. similis* was not found throughout the trial.

6.3.1.2 Damage parameters

The pre-trial plant damage estimations of the PCI (0-5 cm), PCI (5-20 cm), Total PCI, CI, XO, XI and X mean were similar between plots ($F_{4, 10}$ = 0.81, P = 0.548; $F_{4, 10}$ = 0.18, P = 0.943; $F_{4, 10}$ = 0.39, P = 0.810; $F_{4, 10}$ = 0.75, P = 0.580; $F_{4, 10}$ = 0.77, P = 0.567; $F_{4, 10}$ = 0.46, P = 0.764 and $F_{4, 10}$ = 0.43, P = 0.787, respectively).

The repeated measures ANOVA showed no significant difference between date (2004 and 2005) and any of the dependent variables (0.06 < $F_{1, 20}$ < 4.05, 0.06 < P < 0.805). Significant treatment effects were only found for PCI (5-20 cm) ($F_{4, 20}$ = 5.48, P = 0.004), Total PCI ($F_{4, 20}$ = 5.56, P = 0.004) and CI ($F_{4, 20}$ = 4.57, P = 0.009), but were minimised in the fipronil treatment for PCI (0-5 cm) (range: 0.63 to 1.94), XO (range: 19.42 to 34.03%), XI (range: 2.31 to 15.44%) and X mean (range: 10.86 to 23.89%). The analysis showed an interaction between date and treatment for X mean ($F_{4, 20}$ = 3.46, P = 0.027). Post ANOVA analysis found that the PCI (5-20)

parameter was significantly lower in chlorpyrifos and fipronil treated plants compared to control plants. Values for the remaining chemicals were statistically similar to all the other treatments (Fig. 6.1). Total PCI showed similar differences between means as the PCI (5-20) damage parameter. Compared to the control, the coefficient of variation (CI) was only significantly lower in fipronil treated plants (Fig. 6.1). The CI values for bifenthrin, chlorpyrifos and oxamyl treated plants were statistically similar to the fipronil treatment (Fig 6.1). The mean cross sectional damage was significantly lower in plants treated with fipronil in 2005 (7.94%) compared to control plants in 2004 (32.78%) (data not shown).

6.3.1.3 Adult densities

The one-way ANOVA showed that the pre-trial adult densities were similar between plots ($F_{4, 10} = 0.61$, $P = 0.666$). The number of adults varied significantly over time ($F_{3, 40} = 3.33$, $P = 0.029$) and between treatments ($F_{4, 40} = 5.36$, $P = 0.001$), but did not interact significantly between time and treatment ($F_{12, 40} = 0.83$, $P = 0.621$). Post ANOVA analysis showed that the mean of 1.45 adults collected (in three traps per week) in October 2004 was significantly less than 3.72 adults collected in April 2005. Values of the other months were statistically similar to October 2004 and April 2005 (data not shown). Fipronil treated plots had a significantly lower number of adults compared to the control (Fig. 6.2). The bifenthrin, chlorpyrifos and oxamyl treatment were similar to the control and fipronil treated plots (Fig. 6.2).

6.3.2 Ramsgate trial

6.3.2.1 Yield, girth and nematodes

No differences were found in yield or plant girth ($F_{5, 11} = 0.42$, $P = 0.825$ and $F_{5, 11} = 1.34$, $P = 0.316$, respectively) between plots at the onset of the trial. The initial nematode densities between plots were also similar ($F_{5, 12} = 2.06$, $P = 0.141$).

The yield in spring 2004 increased from a mean of 33.14 ± 0.801 (SE) to 35.23 ± 1.276 (SE) kg per bunch in spring 2005, but the difference was not significant ($F_{1, 23} = 1.06$, $P = 0.314$). There were no significant differences ($F_{5, 23} = 0.55$, $P = 0.740$) in yield between treatments, although the average yield per bunch increased by 11.29% in the fipronil (35.71 ± 1.497 (SE) kg) and 10.18% in the imidacloprid (35.27 ± 2.037 (SE) kg) treatments compared to the control treatment (31.68 ± 0.712 (SE) kg). The interaction between time and treatment also showed no significant

differences ($F_{5, 23}$ = 0.45, P = 0.808). Plant girth was similar between dates (2004: 72.037 ± 1.0576 (SE) cm, 2005: 69.487 ± 1.4916 (SE) cm) ($F_{1, 23}$ = 1.71, P = 0.204). Plant girth between treatments ranged from 65.875 cm in the control to 73.576 cm in the fipronil treatment (10.47% increase), but was not significantly different ($F_{5, 23}$ = 1.16, P = 0.359). There was no interaction between time and treatment ($F_{5, 23}$ = 0.43, P = 0.820).

The density of nematodes was significantly different between dates ($F_{1, 24}$ = 5.78, P = 0.024), but neither a significant treatment effect ($F_{5, 24}$ = 1.05, P = 0.414), nor an interaction between time and treatment was found ($F_{5, 24}$ = 1.52, P = 0.221). The Tukey HSD test showed that the nematode number was significantly higher in 2005 (1927.78 nematodes per 30 g roots) compared to 2004 (766.67 nematodes per 30 g roots). Spiral nematodes mainly comprised the nematode complex, but root knot and lesion nematodes were also present at relatively low densities in 2003 to 2005. Burrowing nematodes were present in two plots (averaging 975 individuals per 30 g roots) during 2005.

6.3.2.2 Damage parameters

The pre-trial plant damage estimations of PCI (0-5) ($F_{5, 12}$ = 2.59, P = 0.082), PCI (5-20) ($F_{5, 12}$ = 2.27, P = 0.113), CI ($F_{5, 12}$ = 0.93, P = 0.494), XO ($F_{5, 12}$ = 1.94, P = 0.161), XI ($F_{5, 12}$ = 1.46, P = 0.274) and X mean ($F_{5, 12}$ = 2.17, P = 0.126) showed no significant difference between plots. The Total PCI ranged from 9.44 (oxamyl treatment) to 13.67 (fipronil treatment) and was different in the ANOVA analysis ($F_{5, 12}$ = 3.66, P = 0.030), but not significantly differentiated in the *post hoc* analysis. The Tukey HSD test adopts a conservative approach by employing experimentwise error rates (based on the number of comparisons) for the type I error (Sokal & Rohlf 1997).

The ANOVA showed no significant difference between date (2004 and 2005) and any of the dependent variables ($0.01 < F_{1, 24} < 0.43$, $0.517 < P < 0.939$). Significant treatment effects were found for all the damage estimations; PCI (0-5) ($F_{5, 24}$ = 8.27, $P < 0.001$), PCI (5-20 cm) ($F_{5, 24}$ = 10.85, $P < 0.001$), Total PCI ($F_{5, 24}$ = 13.98, $P < 0.001$), CI ($F_{5, 24}$ = 12.61, $P < 0.001$), XO ($F_{5, 24}$ = 9.38, $P < 0.001$), XI ($F_{5, 24}$ = 3.81, P = 0.011) and X mean ($F_{5, 24}$ = 9.40, $P < 0.001$). The analysis showed an interaction between date and treatment for PCI (0-5) ($F_{5, 24}$ = 2.95, P = 0.032). The Tukey HSD test showed the PCI (0-5) parameter was only significantly lower in fipronil and imidacloprid treated plants compared to control plants. The oxamyl

treatment was similar to the fipronil and imidacloprid treatments, while bifenthrin was similar to fipronil treated plants (Fig. 6.3). PCI (5-20) showed that only the fipronil and imidacloprid treatments had significantly lower damage than the control plants, while the oxamyl treatment was similar to fipronil and imidacloprid. Relative to the control plants, the Total PCI was only significantly lower in oxamyl, fipronil and imidacloprid treated plants, while bifenthrin was similar to the oxamyl treatment. All the chemical treatments, except for chlorpyrifos, statistically reduced the CI parameter compared to untreated plants; imidacloprid showed the lowest value which was statistically similar to fipronil and oxamyl (Fig. 6.3). The XO was only statistically lower in the fipronil and imidacloprid treatments compared to the control; oxamyl was similar to fipronil and imidacloprid treated plants (Fig. 6.4). The imidacloprid treated plants reduced the XI damage by 100% and was the only treatment significantly lower than the control (Fig. 6.4). Fipronil caused a 95% reduction in XI. Imidacloprid, fipronil and oxamyl significantly reduced the X mean relative to untreated plants by 90.43, 81.91 and 63.48%, respectively. The bifenthrin treatment showed similar X mean values to oxamyl and fipronil (Fig. 6.4). The PCI (0-5) parameter was significantly lower in plants treated with imidacloprid in 2005 (0.00) compared to control plants in 2004 (1.83) and 2005 (2.00) (data not shown).

6.3.2.3 Adult densities

The distribution of adults between plots was similar before the trial started ($F_{5, 12}$ = 0.47, P = 0.794). Adult densities between subsequent collections ranged from 6.65 in April 2005 to 9.89 in October 2004 and were significantly different ($F_{3, 48}$ = 2.99, P = 0.040). Treatment effects were also significant ($F_{5, 48}$ = 19.96, P < 0.001), but no interaction between time and treatment was found ($F_{15, 48}$ = 1.08, P = 0.395). The Tukey HSD test did not show a difference between collection dates, because it adopts a conservative approach by employing experimentwise error rates (based on the number of comparisons) for the type I error (Sokal & Rohlf 1997). Fipronil, imidacloprid and chlorpyrifos treatment resulted in a significant decrease in adult density compared to the control (Fig. 6.5). Bifenthrin and oxamyl showed statistically similar values to the control, while the chlorpyrifos treatment was similar to the bifenthrin applications (Fig. 6.5).

6.4 Discussion

Fipronil and imidacloprid were highly effective chemicals against *C. sordidus*, minimising damage to the periphery, cortex and central cylinder of the rhizome and significantly reduced adult density. The damage parameter of Cavendish bananas most closely related to effective bunch weight is the percentage damage to the central cylinder (Chapter 7). Fipronil and imidacloprid virtually eliminated damage to this portion of the rhizome after six applications. Under certain conditions, the mean percentage damage to the cortex and central cylinder of the corm can be the best indicator of fruit yield (Chapter 7). This damage was also greatly reduced after six applications of fipronil and imidacloprid. The percentage reduction in these important damage parameters after chemical application should be considered as conservative measures. The measurement scale of the cross sectional damage estimates was crude, with an increment (and minimum) of 10% damage. The result was that slight damage (probably less than one percent) to some chemically treated plants, especially fipronil and imidacloprid, was scored as 10% damage, while extensive larval tunnels comprising a 10% area of the rhizome in control plants received a similar score. In future studies the estimate of percentage internal corm damage should therefore be refined, preferably to a one percent scale. Of the other chemical treatments, chlorpyrifos and oxamyl showed a reduction in peripheral damage, but results were inconsistent. Injection of bifenthrin was generally ineffective. In a previous study, a single injection of chlorpyrifos during winter did not reduce tunnels in the rhizome of mother plants after 10 weeks (Dochez 1998).

Banana fruit yield and plant girth, corrected by nematode densities, were not significantly increased after any of the chemical applications. Similar results have been reported after organophosphate and carbamate treatment (Román *et al.* 1983; Chavarria-Carvajal & Irizarry 1997). Nevertheless, the data showed (with nematode infestation constant) an increase of up to 11.29% in effective bunch weight and a 10.47% increase in plant girth in the fipronil and imidacloprid treatments. This increase probably would have been significant if the plot size was increased, thereby decreasing the variability. Moreover, plants were propped during the trail and plant loss, which can contribute more to yield loss than reduction in bunch weight (Rukazambuga 1996), was not considered. The Munster trial suggested that (assuming other variables were constant between the trials) if a portion of residues injected with

fipronil over an annual period is not attached to the mother plant, then an overall reduction in peripheral plant damage and adult densities can be expected, but a reduction in the more important internal damage estimates may only be evident after 2 years. The results suggested that fipronil and imidacloprid, both considered to be systemic chemicals (Potter 1998; Nel *et al.* 2002), provided a protective treatment when the injected residue is physically attached to the mother plant.

The application protocol used in this study is unique in that systemic pesticides are injected throughout the year. In Australia plants are also injected with chemicals, but it is limited to contact pesticides applied during winter (Treverrow pers. comm.). The high efficacy achieved after injection of fipronil and imidacloprid into plant residues provides an optimal chemical strategy in an integrated pest management programme for the banana weevil. Fipronil has been shown not to affect the viability of *Beauveria bassiana* Balsamo (Batista Filho *et al.* 1996). The pesticides belong to unique chemical groups and can be spatially and temporally altered to minimise resistance development. More importantly, the application is specific to the pest, targeting the residual plant, which can contain all the weevil life stages throughout the year, but where adults predominate (Chapter 3). These chemicals probably also provide control in the mother plant, which can contain all the life stages, but where weevil larvae predominate (Chapter 3).

The density of the nematode-complex increased during the trial and was not controlled by any of the chemical treatments. This is in general agreement with Pattison *et al.* (2002), who reported that oxamyl injection into harvested pseudostems was not effective in controlling burrowing nematodes. Injection of chlorpyrifos into post harvest residues during winter also provided no nematode control (Dochez 1998). In addition, no evidence of poisoning non-target species was observed during both field trials, although this aspect was not empirically evaluated.

In future, the action mechanism and residual activity of the pesticides under the application protocol should be specifically researched. Timing of applications can be optimised accordingly, and applied when larvae (November to December, February) and adults predominate (November, April/May and July) (Chapter 3).

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6.6 References

ABERA, A.M.K., GOLD, C.S. & KYAMANYWA, S. 1999. Timing and distribution of attack by the banana weevil (Coleoptera: Curculionidae) in East African highland banana (*Musa* spp.). *Florida Entomologist* 82: 631-641.

ANITHA, N., CHARLES, J.S.K. & RAJAMONY, L. 1992. Effect of sucker treatment with insecticides on incidence on banana rhizome weevil (*Cosmopolites sordidus*). *Indian Journal of Agricultural Sciences* 62: 572-573.

ANONYMOUS. 1969. Beetle borer studies. *Banana Bulletin* 33: 4.

ANONYMOUS. 2005. *Agricultural remedies*. National Department of Agriculture. World Wide Web: http://www.nda.agric.za/act36/AR/Insecticides.htm

BATCHELDER, C.H. 1954. Experimentos con insecticidas para combater el picudo negro, *Cosmopolites sordidus* (Germar), en plantaciones de abaca. *Turrialba* 4: 88-93.

BATISTA FILHO, A., LEITE, L.G., ALVES, E.B. & AGUIAR, J.C. 1996. Control of *Cosmopolites sordidus* by fipronil and its effect on *Beauveria bassiana*. *Arquivos do Instituto Biologico (Sao Paulo)* 63: 47-51.

BRAITHWAITE, B.M. 1958. Ground sprayed treatments for control of the banana beetle borer (*Cosmopolites sordidus*) (Germar). *Journal of the Australian Institute for Agricultural Science* 24: 27-34.

BRAITHWAITE, B.M. 1967. Banana beetle borer control investigations on the north coast of New South Wales. *The Agricultural Gazette of New South Wales* 78: 359-365.

BUJULU, J., URONU, B. & CUMMING, C.N.C. 1983. The control of banana weevils and parasitic nematodes in Tanzania. *East African Agricultural and Forestry Journal* 49: 1-13.

CÁRDENAS R. 1984. El picudo negro del plátano *Cosmopolites sordidus* (Germar). *Cenicafé* 120: 12.

CARDENAS MURILLO, R., ARROYAVE, R.F.P. & ARANGO BERNAL, L.G. 1986. Treatment of plantain (*Musa* AAB Simmonds) against the banana borer weevil (*Cosmopolites sordidus* Germar). *Cenicafé* 37: 61-71 (Abstract cited).

CHABRIER, C., HUBERVIC, J. & QUENEHERVE, P. 2002. Evaluation of fosthiazate (Nemathorin® 10G) for the control of nematodes in banana fields in Martinique. *Nematropica* 32: 137-147.

CHAVARRIA-CARVAJAL, J.A. & IRIZARRY, H. 1997. Rates, application intervals and rotation of four granular pesticides to control nematodes and the corm-weevil (*Cosmopolites sordidus* Germar) in plantain. *Journal of Agriculture of the University of Puerto Rico* 81: 43-52.

COLLINS, P.J., TREVERROW, N.L. & LAMBKIN, T.M. 1991. Organophosphorus insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Australia. *Crop Protection* 10: 215-221.

CUILLÉ, J. 1950. *Recherches sur le Charancon du Bananier*. Institut des Fruits Agrumes Coloniaux; Serie Technique No 4, Paris.

DE JAGER, K., RABIE, E.C. & ANDERSON, S.H. 1991. Chemiese beheer van die piesangwortelboorder, *Cosmopolites sordidus* en aalwurms, veral die booraalwurm, *Radopholus similis*. *Inligtingsbulletin - Navorsingsinstituut vir Sitrus en Subtropiese Vrugte* 228: 17-20.

DOCHEZ, C. 1998. *Study on Pest Status and Control of* Cosmopolites sordidus *(Germar) in South Africa*. M.Sc. Thesis, Heriot-Watt University, Scotland.

EDGE, V.E. 1974. Cyclodiene-BHC resistance in *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae) in New South Wales, Australia. *Bulletin of Entomological Research* 64: 1-7.

FOGAIN, R., MESSIAEN, S. & FOURÉ, E. 2002. Studies on the banana borer weevil in Cameroon. *Infomusa* 11: 8-9.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

FROGGATT, J.L. 1925. The banana weevil borer (*Cosmopolites sordidus*). *Queensland Agricultural Journal* 24: 558-593.

FROGGATT, J.L. 1926. *The Banana Weevil Borer*. Bulletin No. 4. Queensland Department of Agriculture and Stock, Brisbane, Australia.

GOLD, C.S., BAGABE, M.I. & SSENDEGE, R. 1999. Banana weevil (*Cosmopolites sordidus*) (Germar) (Coleoptera: Curculionidae) tests for suspected resistance to carbofuran and dieldrin in Masaka district, Uganda. *African Entomology* 7: 189-196.

GOLD, C.S. & MESSIAEN, S. 2000. *The Banana Weevil,* Cosmopolites sordidus. Musa Pest Fact Sheet No. 4, INIBAP.

GOLD, C.S., NIGHT, G., ABERA, A. & SPEIJER, P.R. 1998. Hot-water treatment for the control of the banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 6: 215-221.

GOLD, C.S., PEÑA, J.E. & KARAMURA, E.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews* 6: 79-155.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., TUSHEMEREIRWE, W.K. & KASHAIJA, I.N. 1994. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2: 309-321.

JONES, R.K. & DIECKMANN, F. 1982. Control of the banana root borer, *Cosmopolites sordidus* Germar. *Information Bulletin, Citrus and Subtropical Fruit Research Institute* 13-17.

KIGGUNDU, A. 2000. *Host Plant Reactions and Resistance Mechanisms to Banana Weevil, Cosmopolites sordidus (Germar) in Ugandan Musa Germplasm*. M.Sc. Thesis, Orange Free State University, South Africa.

KOPPENHÖFER, A.M. 1993. Observation on egg laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata* 68: 187-192.

MAOLIN, S. 1994. Status of nematode and weevil borer problems affecting banana in China. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines, INIBAP*. 57-62.

MITCHELL, G. 1978. *The Estimation of Banana Borer Population and Resistance levels*. Technical Bulletin 2, Windward Island Banana Growers Association (WINBAN), St. Lucia.

MITCHELL, G. 1980. *Banana Entomology in the Windward Islands. Final report 1974-1978*. Centre for Overseas Pest Research, London.

NEL, A., KRAUSE, M. & KHELAWANLALL, N. 2002. *A Guide for the Control of Plant Pests*. 39th Edition. Directorate, Agricultural Production Inputs, Department of Agriculture, South Africa.

NUNO, L. & RIBEIRO, V.P. 2002. *Cosmopolites sordidus* in the autonomous region of Madeira. *Infomusa* 11: 10.

PATTISON, A.B., VERSTEEG, C.A., MCQUINN, D.J., MATTHEWS, N.J., FARNSWORTH, W. & PIPER, R. 2002. Management of burrowing nematodes in bananas using pseudostem injection of Vydate L. DuPont, Australasia.

PINESE, B. & ELDER, R. 2004. *Banana Weevil Borer*. Queensland Government, Department of Primary Industries and Fisheries, Horticulture and Fresh Produce. World Wide Web: http://www.dpi.qld.gov.au/horticulture/2507.html

POTTER, D.A. 1998. *Destructive turfgrass pests*. Ann Arbor Press, Michigan.

PRICE, N.S. 1995. The use of a modified pseudostem trapping technique for assessing the efficacy of insecticides against the banana borer weevil. *Fruits* 50: 23-26.

QUILICI, S. 1993. Insect pests of banana. *Fruits* 48: 29-31.

ROMÁN, J., ORAMAS, D. & GREEN, J. 1979. Effect of rate and frequency of application of nematicides in plantain production. *Nematrópica* 9: 107-117.

ROMÁN, J., ORAMAS, D., GREEN, J. & TORRES, A. 1983. Control of nematodes and black weevils in plantains. *Journal of the Agricultural University of Puerto Rico* 67: 270-277.

RUKAZAMBUGA, N.D.T.M. 1996. *The Effects of Banana Weevil* (Cosmopolites sordidus *Germar) on the Growth and Productivity of Bananas* (Musa *AAA EA) and the Influence of Host Vigour on Weevil Attack*. Ph.D. Thesis, University of Reading, UK.

SCHOEMAN, P.S. 1996. Control of the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). In: Robinson, J.C. (Ed.) *Banana Growers Association of South Africa* 1: 83-87.

SCHOEMAN, P.S. 1998. Chemical control of the banana root borer. *Neltropika* July: 28-30.

SCHOEMAN, P.S., SCHOEMAN, M.H. & DOCHEZ, C. 1999. Novel techniques for the control of the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in South Africa. *Yearbook of the Banana Growers Association of South Africa* 3: 78-82.

SHANAHAN, G.J. & GOODYER, G.J. 1974. Dieldrin resistance in *Cosmopolites sordidus* in New South Wales, Australia. *Journal of Economic Entomology* 67: 446.

SIMMONDS, N.W. 1959. *Bananas*. 1st Edition. Longmans Press, London.

SIMMONDS, N.W. 1966. *Bananas*. 2nd Edition. Longmans Press, London.

SMITH, D. 1995. Banana weevil borer control in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 35: 1165-1172.

SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. W.H. Freeman and Company, New York.

STANTON, J.M. 1994. Status of nematode and weevil borer problems affecting banana in Australia. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 48-56.

STATSOFT INCORPORATED. 2004. *Statistica*. Version 7.

STOVER, R.H. & SIMMONDS, N.W. 1987. *Bananas*. Third Edition. 469. John Wiley and Sons, New York.

TAYLOR, B. 1991. Research field work on upland bananas, *Musa* spp., principally *acuminata* triploid AAA types, in the Kangera region of Tanzania with observations on growth and on the causes of decline in crop yield. *Revista di Agricultura Subtropicale e Tropicale* 85: 349-392.

TREVERROW, N.L. 1985. *Banana Weevil Borer.* Agfact H6.AE.1, 2nd edition. NSW Agriculture and Fisheries, Australia.

TREVERROW, N., PEASLEY, D. & IRELAND, G. 1992. *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*. Banana Industry Committee, New South Wales Agriculture.

VILARDEBÓ, A. 1967. Resistance of the banana tree weevil *Cosmopolites sordidus* (Germar) to chlorinated hydrocarbon insecticides. *International Congress of Plant Protection* 586.

VILARDEBÓ, A. 1973. Le coefficient d'infestation, critere d' evaluation du degre d'attaques des bananeraies par *Cosmopolites sordidus* Germ. Le charancon noir du bananier. *Fruits* 28: 417-431.

VISWANATH, B.N. 1977. Studies on the biology, varietal response and control of banana rhizome weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Mysore Journal of Agricultural Sciences* 11: 597-598.

VITTAYARUK, W., WATTANACHAIYINGCHAROEN, W., CHUAYCHAROEN, T. & WATTANACHAIYINGCHAROEN, D. 1994. Status of weevil borer problems affecting banana in Thailand. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in, Los Banos, Philippines: INIBAP*. 106-114.

WILLERS, P., DANEEL, M.S. & DE JAGER, K. 2001. Banana. In: Van den Berg, M.A., De Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. 36. ARC – Institute for Tropical and Subtropical Crops. Ad Dynamics, Nelspruit.

WRIGHT, W.E. 1977. Insecticides for the control of dieldrin resistant banana weevil borer *Cosmopolites sordidus* Germar. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17: 499-504.

Table 6.1. Chemical groups, trade names, formulations, active ingredients and gram active ingredient of chemicals evaluated against *Cosmopolites sordidus* at Ramsgate and Munster (KZN, South Africa) from October 2003 to October 2005. * Excluded from the Munster trial.

Chemical group	**Trade name (formulation)**	**Active ingredient (a.i.)**	**Gram active ingredient (g.a.i.)/plant**
Pyrethroid	Talstar (EC)	Bifenthrin ($100\ g.l^{-1}$)	0.015
Organophosphate	Dursban (WG)	Chlorpyrifos ($750\ g.kg^{-1}$)	0.125
Phenyl pyrazole	Regent (SC)	Fipronil ($200\ g.l^{-1}$)	0.01
Chloro-nicotinyl	Confidor (SC)	* Imidacloprid ($350\ g.l^{-1}$)	0.245
Oxime carbamate	Vydate (SL)	Oxamyl ($310\ g.l^{-1}$)	0.5

Figure legends

Figure 6.1. The mean values of the Percentage Coefficient of Infestation (PCI) and Coefficient of Infestation (secondary axis) damage parameters of untreated (control) plants and plants treated bimonthly with four chemicals at Munster (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05) and upper case letters refer to the secondary axis. 20 = PCI from > 5 to 20 cm from the collar, To = Summed total PCI, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil and Oxa = Oxamyl.

Figure 6.2. The mean adult banana weevil density values of untreated (control) plots and plots treated bimonthly with four chemicals at Munster (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil and Oxa = Oxamyl.

Figure 6.3. The mean values of the Percentage Coefficient of Infestation (PCI) and Coefficient of Infestation (secondary axis) damage parameters of untreated (control) plants and plants treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05) and upper case letters refer to the secondary axis. 05 = PCI from 0 to 5 cm from the collar, 20 = PCI from > 5 to 20 cm from the collar, To = Summed total PCI, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 6.4. The mean values of the cross sectional damage parameters of untreated (control) plants and plants treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). XO = Cross section damage percentage of the cortex, XI = Cross section damage percentage of the central cylinder, X mean = Average cross sectional damage of the corm, Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 6.5. The mean adult banana weevil density values of untreated (control) plots and plots treated bimonthly with five chemicals at Ramsgate (KZN, South Africa) from October 2003 to August 2005. For each dependent variable, means with letters in common are not significantly different (P>0.05). Bifen = Bifenthrin, Chlor = Chlorpyrifos, Fip = Fipronil, Imi = Imidacloprid and Oxa = Oxamyl.

Figure 6.1

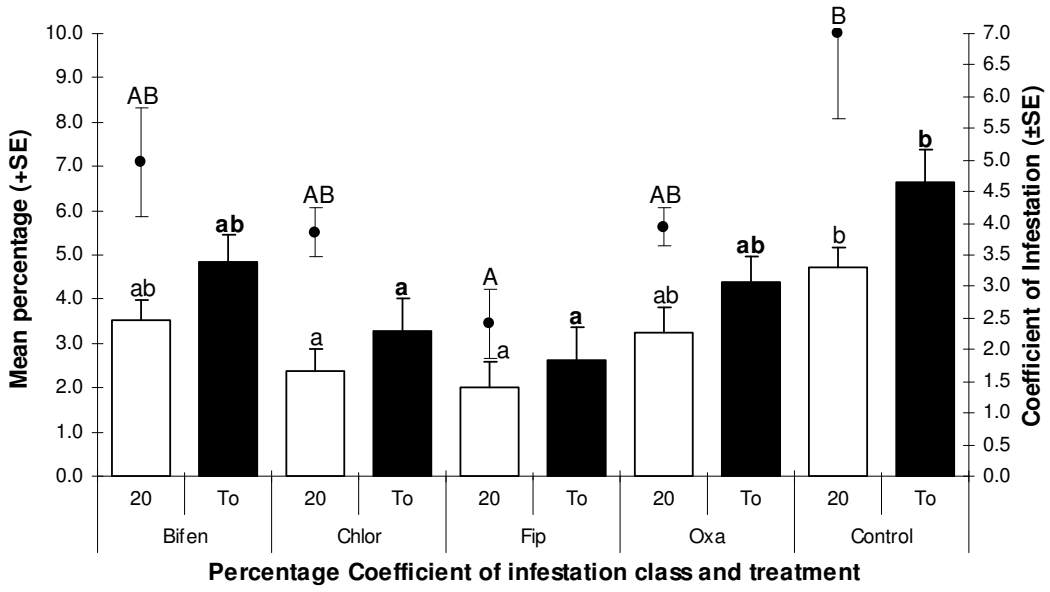

Mean percentage (+SE)
Coefficient of Infestation (±SE)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
AB
ab
ab
AB
a
a
A
a
a
AB
ab
ab
B
b
b
20
To
20
To
20
To
20
To
20
To
Bifen
Chlor
Fip
Oxa
Control
Percentage Coefficient of infestation class and treatment

Figure 6.2

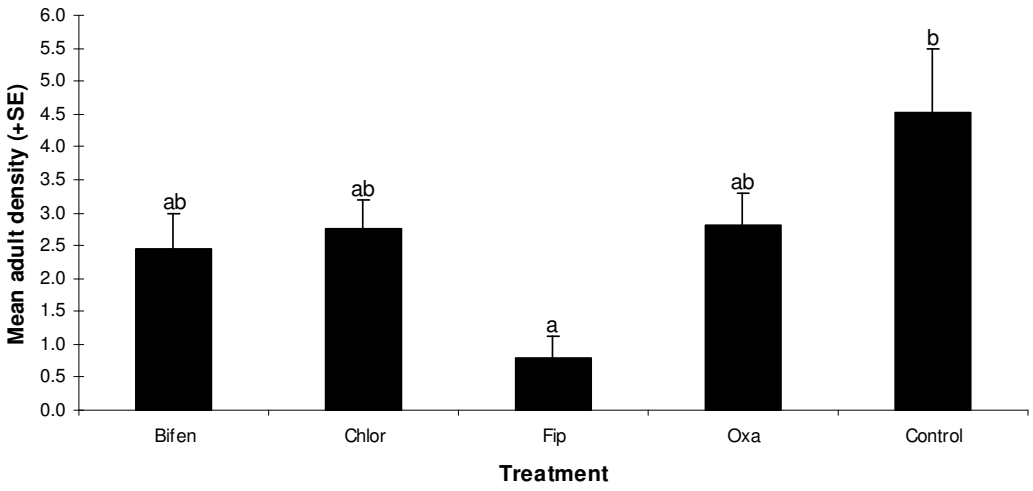

Mean adult density (+SE)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ab
ab
a
ab
b
Bifen
Chlor
Fip
Oxa
Control
Treatment

Figure 6.3

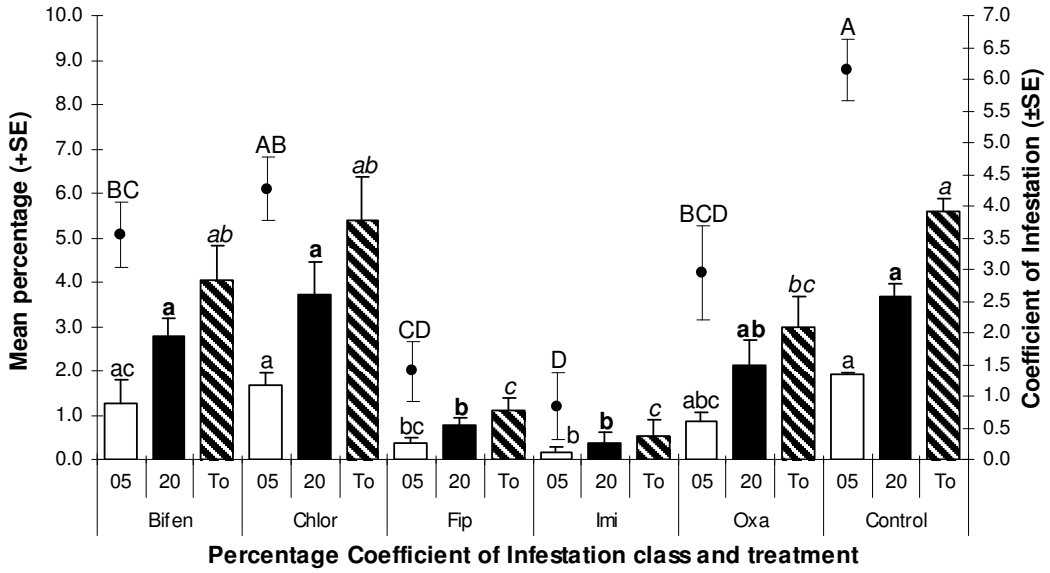

Mean percentage (+SE)
Coefficient of Infestation (±SE)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
BC
ac
a
ab
AB
a
a
ab
CD
bc
b
c
D
b
b
c
BCD
abc
ab
bc
A
a
a
a
05
20
To
Bifen
Chlor
Fip
Imi
Oxa
Control
Percentage Coefficient of Infestation class and treatment

Figure 6.4

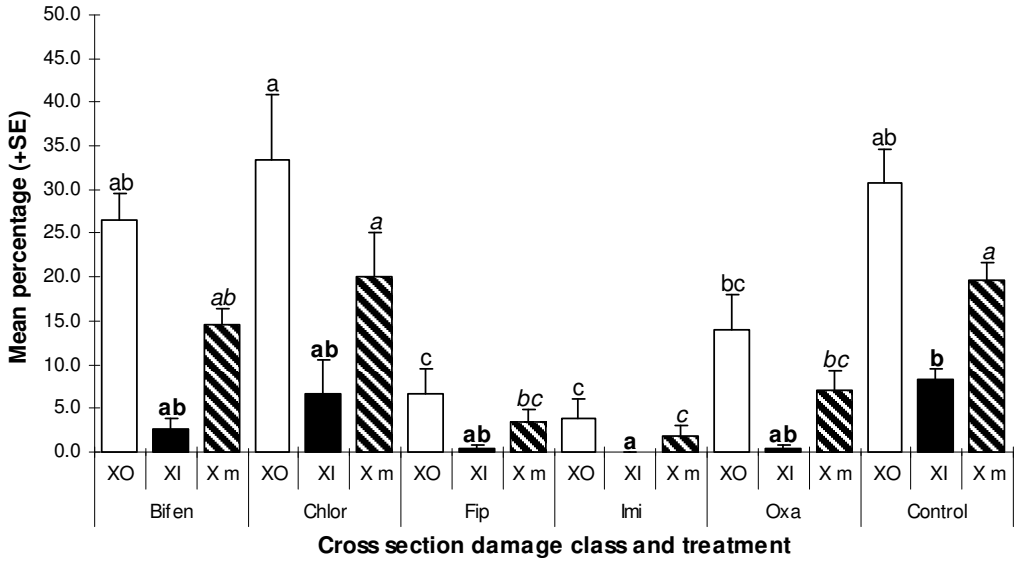
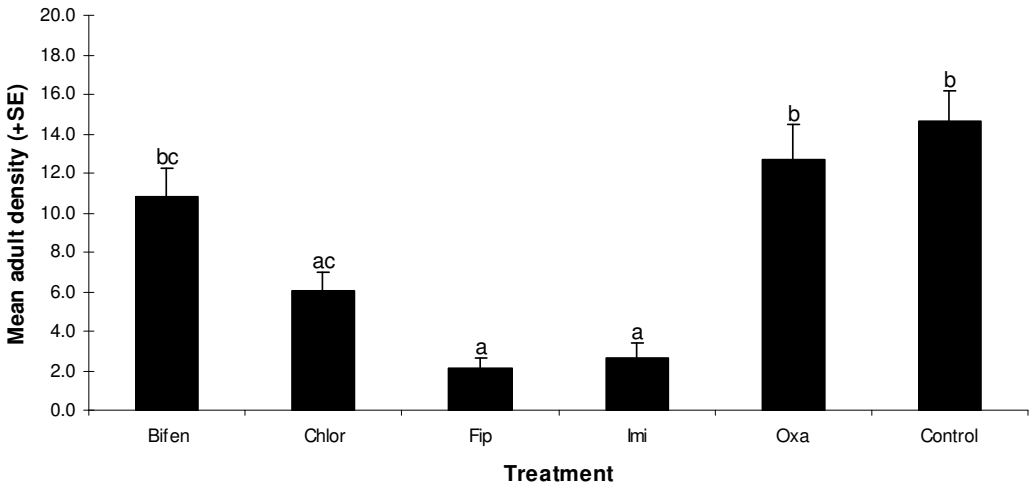

Mean percentage (+SE)
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
ab
ab
ab
a
ab
a
c
ab
bc
c
a
c
bc
ab
bc
ab
b
a
XO
XI
X m
Bifen
Chlor
Fip
Imi
Oxa
Control
Cross section damage class and treatment

Figure 6.5


20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Mean adult density (+SE)
bc
ac
a
a
b
b
Bifen
Chlor
Fip
Imi
Oxa
Control
Treatment

Chapter 7

Bio-economics and the integrated pest management of *Cosmopolites sordidus* in South Africa

Abstract

The banana weevil, *Cosmopolites sordidus*, is a serious pest of bananas (Musaceae: *Musa* species) in South Africa. In developing an integrated pest management programme, the economic thresholds of the insect were investigated on Cavendish bananas at four locations in the South Coast of KwaZulu-Natal. Yield (bunch weights) and larval damage to felled plants were measured from August to October in 2003, while adult densities were assessed over 4 weeks in October 2003. Nematode samples were collected and analysed in October 2003. Damage parameters included the Coefficient of Infestation, the Percentage Coefficient of Infestation (PCI) at 5 cm and between 5 and 20 cm from the collar, the summed PCI value, the percentage cross sectional damage (at 10 cm from the collar) of the central cylinder (XI) and cortex, and the mean cross sectional damage percentage (X mean). Replicated block designs were used in the experiments. The economic-injury level (EIL) for chemical and cultural control was calculated. Nematode densities did not influence the yield of plants. The XI was the best predictor of yield, but under certain conditions X mean was the most important. Chemical control showed the lowest EIL, with more than 1 and 7% damage to the central cylinder when applying fipronil and imidacloprid, respectively. The EIL for cultural control was more than 11% damage to the central cylinder. A recommendation algorithm is provided for IPM of the banana weevil in the South Africa. The potential use of microbial and invertebrate (especially parasitoids) biological control and semiochemical mass trapping of the weevil requires further research. Long-term research should focus on host resistance, and weevil damage to the central cylinder can serve as indicator of susceptibility of Cavendish bananas.

Keywords: Yield loss, economic injury level, Cavendish bananas, banana weevil

7.1 Introduction

An integrated pest management (IPM) philosophy acknowledges that total pest eradication is impractical and rather strives to manage the pest population below economic injury levels (Dent 1991). The bio-economic terms of economic damage (ED), economic-injury level (EIL) and economic threshold (ET), were originally proposed to encourage a more rational use of insecticides (Stern *et al.* 1959). The threshold for ED was defined as the amount of damage that justifies the cost of artificial control, EIL as the lowest population density that will cause economic damage and ET as the level at which control measures should be implemented to prevent an increasing pest population from reaching the EIL (Dent 1991). IPM is accomplished by utilising various permutations of available control methods to increase cost-effectiveness and sustainability, whilst minimizing harmful side effects to non-target organisms, the environment and consumers of the produce (Anonymous 1973, Dent 1991; Gullan & Cranston 1994). To develop an IPM system, a thorough knowledge of the host plant and biology and ecology of a pest insect is required to allow the rational use of cultivation and control techniques under different circumstances. Successful IPM is based on an understanding of biotic and abiotic factors affecting the population dynamics of the pest (Gullan & Cranston 1994) and subsequent timely application of control measures.

Bananas are a major commodity in the world trade, but are susceptible to a variety of serious and debilitating diseases and pests (Simmonds 1959, Royer *et al.* 1990, Gowen 1995, Robinson 1996; Viljoen & Robinson 2002). The most important insect pest, the banana weevil, *Cosmopolites sordidus* (Germar), is a significant production constraint and causes economic damage to the crop (Stover & Simmonds 1987; Gold *et al.* 1999, 2003, 2004). Larvae, the damaging life stage of the beetle, are responsible for feeding-tunnels in the banana plant rhizome (and pseudostem), which interfere with root initiation (Treverrow *et al.* 1992), plant nutrition (Chavarria-Carvajal & Irizarry 1997) and water transport (Collins *et al.* 1991), resulting in plant stunting, delayed maturation (Gold *et al.* 1998), reduced fruit size and bunch weight, and even plant snapping or toppling (Batchelder 1954, Franzmann 1972, Koppenhöfer 1993; Rukazambuga 1996). The weevil is found almost everywhere in the tropics and subtropics where bananas are grown, including South Africa (Cuillé 1950).

Banana weevil research can generally be divided in two categories, correlating with the food production systems of *Musa*: Studies conducted in areas with a tropical climate on locally consumed bananas and plantains, and studies in the tropics (and subtropics) on Cavendish bananas produced for sale or export. In the former, producers are commonly subsistence farmers with minimal resources to investment in crop management. In these systems, researchers investigate control strategies that are mainly preventative and concentrate on low cost, long-term approaches such as host resistance, cultural and biological control. In contrast, Cavendish production is usually associated with commercial growers that invest heavily in crop management. Weevil control in these systems is mainly of a curative or therapeutic nature, concentrating on short-term approaches, especially chemical control.

Certain biological and behavioural aspects of the weevil appear to be clear, but findings concerning different biotic and abiotic factors affecting the population processes of the banana weevil are, however, variable (Gold *et al.* 2003). The inconsistency in research results between studies may reflect on banana clones, management and production systems, ecological conditions, weevil biotypes and research methodologies (Gold *et al.* 2003). South Africa is one of only a few countries where Cavendish bananas are considered very susceptible to *C. sordidus* (Govender & Viljoen 2002). Research under local conditions, which represents a subtropical climate, specific management and production systems and possibly unique weevil biotypes, was, therefore, required to develop an integrated pest management system.

Cosmopolites sordidus is an economic pest of bananas along the KwaZulu-Natal coast of South Africa (Schoeman *et al.* 1999), an area where insect populations from the northern and southern parts were genetically relatively similar (Chapter 2). Under local conditions, weevil activity and fecundity was inversely and directly related to ambient temperature, respectively. The beetle had overlapping generations with adult density peaking in autumn and larval density peaking in late summer. Adults were mainly associated with decayed residues while larvae were mostly found in freshly toppled plants. The weevil primarily over-winter in the adult stage (Chapter 3). Compared to conventional split-pseudostem traps, semiochemical trapping (Cosmolure®, ChemTica Internacional S.A., Costa Rica) was most effective in spring and also showed potential as a mass trapping technique (De Graaf *et al.*

2005). Cultural control in terms of crop management showed that covering the base of plants with soil (up to 30 cm) and moving debris to the inter row can reduce weevil damage (Chapter 5). Application of the registered pesticide (aldicarb) was not proving effective (Chapter 5) and bimonthly injections of fipronil and imidacloprid into decayed, residual pseudostems showed high efficacy and reduced damage and adult densities in the field (Chapter 6).

Despite the economic and environmental advantages of IPM, implementation of IPM programmes, in general, has been slow due to the lack of sufficient data on the ecology of pests, knowledge of economic injury levels for each crop pest and the interdisciplinary approach required to elucidate the former and latter (Gullan & Cranston 1994). Current threshold values of the weevil are disputed and comparisons are troublesome, since specific calculations are not revealed, pest status is variable and/or nematode damage is not partitioned. A clear relationship between adult density, rhizome damage and yield is required worldwide (Ostmark 1974, Treverrow 1993, Stanton 1994, Gowen 1995; Gold *et al.* 1998). The aim of the study was to determine the economic injury levels of *C. sordidus*, and combine this with the acquired ecological and management data of the pest into an IPM recommendation algorithm, to manage the insect on Cavendish bananas in South Africa.

7.2 Material and methods

7.2.1 Research sites

Trials were conducted on commercial farms in the South Coast of KwaZulu-Natal, South Africa. Soil in the area is a Glenrosa form, with an orthic A and lithocutanic B zone. It is a sandy loam soil with 16% clay, 30% loam and 54% sand (Dochez 1998). The trial sites were in Ramsgate (two banana fields, (a) 30º52’33’’S; 30º19’28’’E; (b) 30º52’31’’S; 30º19’29’’E) and Munster (two locations, (a) 30º59’29’’S; 30º14’49’’E; (b) 30º58’13.6’’S; 30º15’33.0’’E) ranging from 72 to 130 meters above sea level. The experiments were conducted from August to October 2003. The locations were all in a summer rainfall area (750-1000 mm per year), and during the trials the ambient temperature ranged from 12 to 25 °C.

The Cavendish cultivars (AAA group) Grand Nain and Chinese Cavendish were grown at the Ramsgate (a) and Ramsgate (b) sites, respectively, while the Williams cultivar was cultivated at the two Munster localities. The Ramsgate

plantations were planted during November 2000; the Munster (a) location in November 1995 and Munster (b) in November 1992, all at a density of 2222 plants.ha^{-1} (300 × 150 cm). High mat was evident in the plantations, with the collar (junction between pseudostem and rhizome) commonly more than 10 cm above ground level. The Ramsgate plantations was sprinkler and the Munster sites drip irrigated with 2 cm water/week, a practise only suspended if rainfall exceeded that value in the particular week. The sites were treated at planting with the oxime carbamate, aldicarb (Temik 15% GR), at the registered dosage of 2.025 g.a.i./mat, to provide nematode and weevil control (Nel *et al.* 2002; Anonymous 2005a). Horticultural practises were representative of farms in the greater KZN area. These practices include harvesting of plants at 150 cm, regular chemical weed control with glyphosate (Roundup), leaf removal, desuckering and propping of bunch bearing plants, but no plantation hygiene (destruction of residues). Pre-trial plant inspections at all sites revealed rhizome tunnel damage by *C. sordidus*. The four sites were relatively similar, but the Munster (a) plantation had the lowest plant density (less canopy cover) as a result of plant toppling, a higher rate of residue desiccation, more remnants (cut residues in the fields) present in the field and less residues attached to the mother plant.

7.2.2 Experimental design

Weevil damage was compared to fruit yield, because the effect of damage can be greater on bunch weight than on plant growth or rate of plant development (Rukazambuga *et al.* 1998). To determine the relation between weevil damage and crop yield, the bunch weights and damage parameters of felled (harvested) plants were measured between August and October 2003, while adult densities were assessed over 4 weeks in October 2003. Data were collected from the Ramsgate (a), Ramsgate (b), Munster (a) and Munster (b) sites, with 12, 18, 15 and 12 replicates, respectively, arranged in a plot design. Each plot included approximately 50 plants, separated by a two-row barrier. To standardise for abiotic influences, plots were orientated perpendicular to the sea/land breeze and moisture gradient in the field. Yield was determined at the pack-house by weighing of bananas (bunches excluding the peduncle), while plants were subjected to weevil damage sampling within a week of harvest.

The Coefficient of Infestation (CI) was determined by paring the corm and scoring the proportion of the rhizome circumference with weevil galleries (Vilardebó

1973). Intervals of 2.5% were included up to a level of 10% damage. Damage was also rated by the Percentage Coefficient of Infestation (PCI) (Mitchell 1978, 1980), which involves scoring the presence/absence of peripheral damage for ten sections, each covering 18° of the corm surface. The latter was determined at 5 cm (Gold *et al*. 1994) and between 5 and 20 cm from the collar (the separation line between the corm and pseudostem). The two PCI values were summed to provide a total PCI value. A cross section of the corm was made at 10 cm from the collar and the percentage damage of the central cylinder and cortex scored in 10% intervals, using a transparent circular grid divided into 36° sections (modified from Gold *et al*. 1994, Kiggundu 2000). The two cross section values were averaged to provide the mean cross sectional damage (X mean).

Three split-pseudostem traps, placed individually next to three plants in the middle of each plot, were used to sample adult densities. Trap material was randomly selected from plants harvested within 2 weeks before trap preparation at a plantation similar to but isolated (by a dirt road) from the specific trial sites. Only one trap was prepared from each plant and pseudostems with internal damage/necrosis/tunnels were discarded. Pseudostem traps were 30 cm in length (pseudostem section 30-60 cm above the collar), bisected longitudinally and each half placed (with the cut surface ventrally) directly next to the mat of the plant. Two halves were placed on opposite sides of the mat and regarded as one trap. The split pseudostems were covered with mulch to delay desiccation and decomposition. Traps were replaced once a week, when the samples per trap were counted and destroyed. Adult data were not available at the Munster (b) locality.

Infestation by banana root nematodes can show symptoms similar to the banana weevil (including yield reduction) (Bujulu *et al*. 1983, Smith 1995; Willers *et al*. 2001). Hence, root samples were collected from three randomly selected mother plants per plot in October 2003. Samples were sent to the ARC - Institute for Tropical and Subtropical Crops (Nelspruit, Mpumalanga), where 30 g of roots (randomly selected per plot) were examined for nematodes.

7.2.3 Bio-economics

The economic thresholds of chemical and cultural management at the sites were calculated based on current costs of chemical applications, labour costs and the average value of the commodity.

The economic-injury level (EIL) was calculated according to the formula, EIL = $C.(V.b.K)^{-1}$, where C = cost of management per area ($R.ha^{-1}$), V = market value per unit of produce ($R.kg^{-1}$), b = yield loss per insect or damage unit ($kg.unit^{-1}$) and K = proportionate reduction in potential injury or damage (Pedigo 1996). A fixed economic threshold (ET) (= action threshold) was used because the growth rate of the insect under local field conditions is unknown (Pedigo 1996). The management method (in absence of the pest) was assumed not to influence the fruit yield.

7.2.4 Statistical analysis

A model II approach of multiple regression (forward step-wise) was followed to establish the relationship between weevil damage parameters and adult density with fruit yield. To determine the relationship between nematode density and fruit yield, a linear regression (model II) (Sokal and Rohlf 1997) was used. Plot level data were used. The data were not transformed and showed a normal distribution and homogeneity of variances in the linear scale (Sokal and Rohlf 1997). The STATISTICA Version 7 (Statsoft Inc. 2004) software program was used for analysis.

7.3 Results

7.3.1 Ramsgate (a)

7.3.1.1 Pest density and damage vs. yield

Multiple regression with adult weevil density and weevil damage parameters showed a model that explained 57.0% of the variation in yield (Table 7.1). Damage to the central cylinder was significantly negatively related to fruit yield (range: 23.1-32.7 kg), and with a standardised regression coefficient (*Beta*) of -0.592, contributed almost two times more to the prediction of the dependent variable than adult weevil density, which was not significantly related to yield (Table 7.1). The average cross section damage percentage of the central cylinder (XI) at the site (Grand Nain, planted November 2000) ranged from 0-23.3% and a one percent increase in the XI resulted in a 0.211 kg reduction (regression coefficient, *B*) in the weight of a fruit bunch (Table 7.1). The nematode complex only comprised spiral (*Helicotylenchus* spp.) and root knot (*Meloidogyne* spp.) species, and densities were relatively low (averaging <250 individuals per 30 g of roots) and showed no significant relation to yield ($F_{1, 10}$ = 0.39, P = 0.545, R^2 = 0.038, B = -0.002).

7.3.1.2 Bio-economics

Threshold calculations for each location were mainly based on chemical control practises, which are the most efficient management option of the weevil in South Africa (Chapter 5, 6). The costs relating to the respective chemical applications are usually site and time specific, but a conservative approach was adopted for the current analysis. Pesticide prices (minimum packaging quantities) were based on a quote from the local supplier (Coastal Farmers, Port Shepstone, KZN in Sep 2005) and the effective cost (per ha) of a knapsack applicator and nozzle was estimated at R15 and R5, respectively (Table 7.2). Personal experience showed that scouting for XI during August to October took about 3 hours per ha and 1 ha or 2222 plants can be injected in approximately 8 hours; relating to R10.98 and R29.28 per ha, respectively, with minimum labour wages (R3.66 per hour) applying (Table 7.2). The value of the commodity was based on the average national market price of packed bananas between August and October (2002 to 2004) (Table 7.2). The price per ton of bananas was increasing on an annual basis (between August and October) from 2002 to 2004 (Anonymous 2005b) and the increase was assumed to negate the fact that some

bananas on a bunch were marketed at lower prices. The proportionate reduction in XI after six applications of fipronil and imidacloprid was 95 and 100%, respectively (Chapter 6), and applied for all the trials. The EIL equation provided a threshold of accumulated damage units (percentages) per ha and was related to damage percentage per plant (Table 7.2). The data indicated that for fipronil and imidacloprid, an average XI of 1.47 and 8.69% per plant will cause economic damage at the trial site, respectively. The action threshold for the respective chemicals was set at 75% of the EIL (Table 7.2).

No management data (relating to damage) were available for biological control. The practise of covering the base of banana stools and moving debris to the inter row was the most effective cultural control measure and caused a reduction of 14.18% in XI compared to the control (Chapter 5), and applied to all the trials. Labour costs will vary spatially and temporally, but at all the research sites minimum labour wages (R3.66 per hour) applied, and an average of 45 hours per ha (per labourer) were required to maintain the treatment monthly, equating to 543 hours per ha annually when scouting costs are included (data not shown). The EIL for the cultural control practise was 13.27% XI and the action threshold (set at 75% of the EIL) 9.95% XI (data not shown).

7.3.2 Ramsgate (b)

7.3.2.1 Pest density and damage vs. yield

Multiple regression with adult *C. sordidus* density and weevil damage parameters showed a model that explained 41.8% of the variation in yield (Table 7.1). The mean cross sectional damage percentage of the cortex and central cylinder (X mean) was significantly negatively related to fruit yield (range: 27.1-40.2 kg) and ranged from 13.3-38.3% at the site (Chinese Cavendish, planted November 2000). The data showed an X mean regression coefficient of -0.346 (Table 7.1). The nematode complex only comprised of spiral and root knot species and densities were relatively low (averaging < 300 individuals per 30 g of roots) and showed no significant relation to yield ($F_{1, 16} = 0.66$, $P = 0.429$, $R^2 = 0.040$, $B = 0.002$).

7.3.2.2 Bio-economics

Personal experience showed that scouting for X mean during August to October took about 3 hours per ha (Table 7.2). The proportionate reduction in X mean after six

applications of fipronil and imidacloprid was 0.82 and 0.90, respectively (Chapter 6). The data indicated that for fipronil and imidacloprid, an average X mean of 1.04 and 5.87% per plant will cause economic damage at the trial site, respectively. The action threshold for the respective chemicals was set at 75% of the EIL (Table 7.2).

Covering the base of banana stools and moving debris to the inter row caused a reduction of 31.52% in X mean compared to the control (Chapter 5). The EIL for the cultural control practise was 3.65% X mean and the action threshold (set at 75% of the EIL) 2.73% X mean (data not shown).

7.3.3 Munster (a)

7.3.3.1 Pest density and damage vs. yield

Multiple regression of adult weevil density and weevil damage parameters with yield (range: 20.4-29 kg) showed no significant relation at the atypical site. The adult density and all the damage parameters was minimised at the location and very low (data not shown). The nematode complex comprised only of spiral and root knot species and densities were relatively low (averaging < 450 individuals per 30 g of roots) and showed no significant relation to yield ($F_{1, 13}$ = 0.934, P = 0.352, R^2 = 0.067, B = 0.002).

7.3.3.2 Bio-economics

The economic thresholds at the site were not calculated because no relationship was found between weevil infestation and damage with yield.

7.3.4 Munster (b)

7.3.4.1 Pest density and damage vs. yield

Multiple regression with adult banana weevil number and weevil damage parameters showed a model that explained 49.4% of the variation in the dependent variable (Table 7.1). The XI was significantly negatively related to fruit yield (range: 18-26.9 kg) and ranged form 0-46.7% at the site (Williams, planted November 1992). The total percentage coefficient of infestation (Total PCI) showed a significant positive relationship with yield and ranged from 6.3-13.7, suggesting that plants with higher peripheral damage at a similar infested site will have higher yield (and lower XI). Compared to Total PCI, the XI variable was the better predictor of yield (*Beta* = -0.800) (Table 7.1). The data showed an XI and Total PCI regression coefficient of -

0.152 and 1.003, respectively (Table 7.1). The nematode complex only comprised of spiral and root knot species and densities were relatively low (averaging < 400 individuals per 30 g of roots) and showed no significant relation to yield ($F_{1, 10} = 0.33$, $P = 0.581$, $R^2 = 0.032$, $B = 0.001$).

7.3.4.2 Bio-economics

Only the XI variable was used in the calculation of economic thresholds at the site, because the positive relation of Total PCI with yield could not be considered reliable and XI was the best predictor of the two variables (Table 7.1). The data showed that an average XI of 2.05 and 12.11% per plant would cause economic damage at the trial site when applying fipronil and imidacloprid, respectively. The action threshold for the respective chemicals was set at 1.54 and 9.08% (Table 7.2). The EIL for the soil cover of plant bases and moving debris to the inter row was 18.48% XI and the action threshold (set at 75% of the EIL) 13.86% XI (data not shown).

7.3.5 All locations

7.3.5.1 Pest density and damage vs. yield

Multiple regression with adult weevil number and weevil damage parameters showed a significant model with a R^2 of 0.280 (Table 7.1). The XI was significantly negatively related to yield (range: 18-40.2 kg) and ranged form 0-46.7% at all the sites. The total percentage coefficient of infestation (Total PCI) showed a significant positive relation to yield and ranged from 2.3-15.0. The XI variable was the best predictor of yield (*Beta* = -0.496) (Table 7.1); the regression coefficient of XI and Total PCI was -0.251 and 0.680, respectively (Table 7.1). The nematode complex comprised of spiral and root knot species (burrowing (*Radopholus similis* (Cobb)) and lesion nematodes (*Pratylenchus* spp.) were absent) and densities were relatively low (averaging < 350 individuals per 30 g of roots) and were not significantly related to yield ($F_{1, 55} = 1.12$, $P = 0.295$, $R^2 = 0.020$, $B = -0.002$).

7.3.5.2 Bio-economics

The XI variable was used in the calculation of economic thresholds, because the positive relationship of Total PCI with yield could not be considered reliable and XI was the more accurate predictor of the two variables (Table 7.1). An average XI of 1.24 and 7.33% per plant will cause economic damage at all the trial sites when

fipronil and imidacloprid is applied, respectively. The action threshold for the respective chemicals was set at 0.93 and 5.50% (Table 7.2). The EIL for the soil cover of plant bases and movement of debris to the inter row was 11.18% XI and the action threshold (set at 75% of the EIL) 8.39% XI (data not shown).

7.4 Discussion

The relationship between the banana weevil, *Cosmopolites sordidus*, and yield loss on Cavendish bananas in South Africa was successfully elucidated in this study. Our results demonstrated that cross sectional larval damage, particularly damage to the central cylinder of the banana rhizome, was negatively related to bunch weight. Nematode densities at the sites were at insignificant levels and did not influence the yield of plants. Damage to the central cylinder and in some cases a combination of damage to the central cylinder and cortex also showed the closest relation to yield loss in East African highland banana (AAA-EA) in tropical Uganda (Rukazambuga 1996; Gold *et al.* 2005). However, inner corm damage has been suggested to have the greatest effect on fruit production, affecting nutrient transport and stem growth (Taylor 1991), while peripheral damage may adversely affect root development of the plant (Gold *et al.* 1994). The confirmation that tunnelling on the corm surface is not a good indicator of weevil damage (Taylor 1991, Rukazambuga 1996; Gold *et al.* 2005) was demonstrated in this study, where, in certain cases, a positive relation existed between yield and peripheral damage. Cross sectional damage assessments are considered more appropriate due to relative ease, low susceptibility to bias and less damage caused to the banana mat (Gold *et al.* 1994). The principle of scoring specific areas on the corm periphery is dependent on tunnel distribution and can saturate quickly, underestimate clumped damage (Ogenga-Latigo & Bakyalire 1993) and/or score damage not derived from weevils (Gold *et al.* 1994). In agreement with Gold *et al.* (1994), the PCI grid at different depths did not provide an increase in accuracy.

The damage to the central cylinder of the corm was higher in the relatively late, compared to the early ratoon crop, probably because the severity of *C. sordidus* damage increases with crop cycle (Rukazambuga *et al.* 1998). The effect of damage to the central cylinder on fruit yield appeared to be more pronounced in the early compared to the late ratoon plantation. It should, however, be interpreted with caution, as the trial sites were separated and different banana varieties were cultivated

at each site. It is uncertain why no relationship between the banana weevil and yield was found at one location, but the relative low adult density and larval damage levels, combined with the variable and unfavourable plantation conditions, could have biased the analysis.

Economic thresholds of the weevil are variable and usually reported in terms of peripheral damage (Vilardebó 1960, 1973, Mesquita 1985, Treverrow *et al.* 1992, 1995, Smith 1995; Fogain *et al.* 2002) or adult density. The action threshold (for chemical application) has been set between one and five weevils per pseudostem-disk trap (Bullock & Evers 1962, Collins *et al.* 1991, Treverrow *et al.* 1992, Pinese & Piper 1994; Smith 1995), while in the Windward Islands it is two, and in Honduras 15-20 weevils per split-pseudostem trap that indicate the action threshold (Vilardebó & Ostmark 1977; Mitchell 1978). Most studies did not relate trap catch to yield losses and these thresholds are questionable (Gold *et al.* 2003). In this study, adult density (sampled with pseudostem traps) was not related to fruit yield, which was also found in North Queensland, Australia (Stanton 1994).

Economic injury levels for chemical control varied between trial sites and pesticides, mainly reflecting the location specific relationship of damage to yield and the monetary cost of chemicals, respectively. In general, when fipronil will be applied, more than 1% damage to the central cylinder caused economic damage, while the corresponding value for imidacloprid was more than 7%. To offset labour costs relative to the efficacy of cultural control, the average damage to the central cylinder should exceed 11%.

From results obtained in the current study, and considering findings in previous studies on the control of the banana weevil in South Africa (Chapter 2, 3, 4, 5, 6), a recommendation algorithm is provided for IPM of the banana weevil in the country (Fig. 7.1). This algorithm is assumed to be representative for all banana weevil populations in South Africa, despite the genetic disparity between populations from KwaZulu-Natal and the Northern Province (Chapter 2). The forked branches in the algorithm indicate decision-making stages. Economic thresholds were based on sampling annually from August to October. The first steps in the algorithm deal with identifying the pest symptoms and determining the extent of infestation. Weevil larvae produce distinctive circular, debris-filled tunnels in the rhizome, while sampling damage of a transverse rhizome section is relatively simple and inexpensive. More regular sampling may be advantageous, but the pest is regarded to have a low

reproductive activity (Cuillé 1950), with high field mortality of eggs and larvae (Treverrow & Bedding 1993; Abera 1997, cited in Gold *et al*. 1999).

As a rule of thumb, plantations should be stratified in plots of approximately 100 plants, and about 10 randomly selected recently harvested plants per plot should be sampled to accommodate the distribution patterns of the weevil. The thresholds per plot should be calculated and can be extrapolated to hectares if the infestations are relatively homogenous. The action threshold will depend on the control method applied, the cultivar and age of the plantation (Table 7.2). If the plantation is not similar to any of the current analysed sites, then the value for all the locations can be adopted (Table 7.2). Because the action threshold in this investigation was fixed and is, therefore, subjective, preventative control is recommended at damage levels below this threshold (Fig. 7.1). Toppled plants harbour the majority of larvae (Chapter 3) and should be destroyed and cut longitudinally (to enhance desiccation) on a monthly basis in summer and bimonthly in winter. Sound horticultural management (i.e. weed control, fertilising, desuckering) is especially important in plantations where weevils are present and flowering plants should be propped. Remnants in the field should be minimised by not severing the pseudostem at harvest, but cutting a transverse "V" in the pseudostem to reach the bunch. All the banana material should be destroyed when weevil infested fields are removed, preferably during summer or autumn. Fields should be left fallow for 2 years, with a minimum of 1 year. Where possible, new plantings should be removed as far as possible from infested areas and the use of virgin soil and tissue culture plants are recommended.

Damage ratings that are equal or more than the action threshold will merit additional control measures. The efficacy and thresholds of biological control measures are unknown, but commercial application of *Beauveria bassiana* (Bbweevil®, BCP, Pinetown, South Africa) may be considered and natural enemies will be promoted by refraining from broad applications of wide spectrum pesticides. Release of potential egg parasitoids are recommended from spring to autumn (especially during the warmest times of the year), while adults and larvae are most accessible (in decayed residues) to predators from autumn to spring and summer to winter, respectively.

When the action threshold for cultural control measures is reached or exceeded, then plant bases should be covered with soil (up to 30 cm) and debris moved to the inter row. The thresholds and efficacy of pheromone and pseudostem

trapping are unknown, but Cosmolure® will be optimally applied in early spring and late autumn, while pseudostem trapping will be most effective in summer (Fig. 7.1).

When damage ratings equals or exceeds the EIL of chemical management, fipronil or imidacloprid should be injected into residual plants (attached to the mat of the plant) every even numbered month (i.e. October, December etc.). Fipronil or imidacloprid should only be injected during the optimal application times (late spring, late summer, autumn and winter (Chapter 3)) when damage levels exceed the action threshold but are below the EIL. Fipronil and imidacloprid have to be temporally and spatially alternated, to combat resistance development. Sampling in late winter to mid spring after implementation of the management programme will determine the strategy for the following season (Fig. 7.1).

The efficacy of semiochemical mass-trapping and microbial control should be related to damage of the rhizome central cylinder. Research into microbial control needs to address the ecological impact, host specificity, delivery systems and field efficacy of inoculative and inundative application of entomopathogens. Biological control attempts should focus on parasitoids, which have proven successful in several biological control programmes and tend to have narrower host ranges than predators (Greathead 1986, Herren & Neuenschwander 1991; Hasyim & Gold 1999). The efficacy of formicids as natural enemies around the world and endophytes as control agents are in need of research (Gold *et al*. 2003). Neem application in the crop establishment phase merits further research (Gold *et al*. 2003). In the future, for all banana systems, host resistance will aid in providing economical and sustainable management of the weevil. A better understanding of the mechanisms of host resistance are needed to lead to accurate selection criteria, which can be applied before the harvest stage to speed up breeding experiments (Gold & Messiaen 2000). Genetic transformation of bananas using foreign genes or resistance genes from *Musa* may facilitate the development of resistant clones that retain locally desirable fruit characteristics (Gold *et al*. 2003). Conventional and non-conventional breeding programmes should standardise the susceptibility measures of plants, to allow for direct comparisons (Fogain & Price 1994). Our study showed that weevil damage to the central cylinder of the rhizome is an important susceptibility measure of Cavendish bananas in South Africa.

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7.6 References

ABERA, A.M.K. 1997. *Oviposition Preferences and Timing of Attack by the Banana Weevil (*Cosmopolites sordidus *Germar) in East African Highland Banana (*Musa *spp.)*. M.Sc. Thesis, Makerere University, Uganda.

ANONYMOUS. 1973. *Report of the Fourth Session of the FAO Panel of Experts on Integrated Pest Control. December 1972*. FAO, Rome.

ANONYMOUS. 2005a. *Agricultural remedies*. National Department of Agriculture. World Wide Web: http://www.nda.agric.za/act36/AR/Insecticides.htm

ANONYMOUS. 2005b. *Market prices January 1999 to June 2005*. Banana Growers Association of South Africa (BGASA), Nelspruit, South Africa.

BATCHELDER, C.H. 1954. Experimentos con insecticidas para combater el picudo negro, *Cosmopolites sordidus* (Germar), en plantaciones de abaca. *Turrialba* 4: 88-93.

BUJULU, J., URONU, B. & CUMMING, C.N.C. 1983. The control of banana weevils and parasitic nematodes in Tanzania. *East African Agricultural and Forestry Journal* 49: 1-13.

BULLOCK, R.C. & EVERS, C. 1962. Control of the banana root borer (*Cosmopolites sordidus* Germar) with granular insecticides. *Tropical Agriculture (Trinidad)* 39: 109.

CHAVARRIA-CARVAJAL, J.A. & IRIZARRY, H. 1997. Rates, application intervals and rotation of four granular pesticides to control nematodes and the corm-weevil (*Cosmopolites sordidus* Germar) in plantain. *Journal of Agriculture of the University of Puerto Rico* 81: 43-52.

COLLINS, P.J., TREVERROW, N.L. & LAMBKIN, T.M. 1991. Organophosphorus insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae), in Australia. *Crop Protection* 10: 215-221.

CUILLÉ, J. 1950. *Recherches sur le Charancon du Bananier*. Institut des Fruits Agrumes Coloniaux; Serie Technique No 4, Paris.

DE GRAAF, J., GOVENDER, P., SCHOEMAN, A.S. & VILJOEN, A. 2005. Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa. *International Journal of Pest Management* 51: 209-218.

DENT, D. 1991. *Insect Pest Management*. CAB International, Wallingford.

DOCHEZ, C. 1998. *Study on Pest Status and Control of* Cosmopolites sordidus *(Germar) in South Africa*. M.Sc. Thesis, Heriot-Watt University, Scotland.

FOGAIN, R., MESSIAEN, S. & FOURÉ, E. 2002. Studies on the banana borer weevil in Cameroon. *Infomusa* 11: 8-9.

FOGAIN, R. & PRICE, N.S. 1994. Varietal screening of some *Musa* cultivars for susceptibility to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Fruits* 49: 247-251.

FRANZMANN, B.A. 1972. Banana weevil borer in North Queensland. *Queensland Agricultural Journal* 98: 319-321.

GOLD, C.S., KAGEZI, G.H., NIGHT, G. & RAGAMA, P.E. 2004. The effects of banana weevil, *Cosmopolites sordidus*, damage on highland banana growth, yield and stand duration in Uganda. *Annals of Applied Biology* 145: 263-269.

GOLD, C.S. & MESSIAEN, S. 2000. *The Banana Weevil,* Cosmopolites sordidus. Musa Pest Fact Sheet No. 4, INIBAP.

GOLD, C.S., NIGHT, G., ABERA, A. & SPEIJER, P.R. 1998. Hot-water treatment for the control of the banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), in Uganda. *African Entomology* 6: 215-221.

GOLD, C.S., PEÑA, J.E. & KARAMURA, E.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews* 6: 79-155.

GOLD, C.S., RAGAMA, P.E., COE, R. & RUKAZAMBUGA, N.D.T.M. 2005. Selection of assessment methods for evaluating banana weevil *Cosmopolites sordidus* (Coleoptera: Curculionidae) damage on highland cooking banana (*Musa* spp., genome group AAA-EA). *Bulletin of Entomological Research* 95: 115-123.

GOLD, C.S., RUKAZAMBUGA, N.D.T.R., KARAMURA, E.B., NEMEYE, P. & NIGHT, G. 1999. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 33-50.

GOLD, C.S., SPEIJER, P.R., KARAMURA, E.B., TUSHEMEREIRWE, W.K. & KASHAIJA, I.N. 1994. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Science Journal* 2: 309-321.

GOVENDER, P. & VILJOEN, A. 2002. The biology and management of the banana weevil, *Cosmopolites sordidus* in South Africa. *Infomusa* 11: 10.

GOWEN, S.R. 1995. Pests. In: Gowen, S.R. (Ed.) *Bananas and Plantains*. 382-402. Chapman & Hall, London.

GREATHEAD, D.J. 1986. Parasitoids in classical biological control. In: Waage, J.D. & Greathead, D.J. (Eds.) *Insect Parasitoids*. 289-318. Academic Press, London.

GULLAN, P.J. & CRANSTON, P.S. 1994. Sensory systems and behaviour. In: Gullan, P.J. & Cranston, P.S. (Eds.) *The Insects: An Outline of Entomology*. 96-121. Chapman & Hall, London.

HASYIM, A. & GOLD, C.S. 1999. Potential of classical biological control for banana weevil, *Cosmopolites sordidus* Germar, with natural enemies from Asia (with emphasis on Indonesia). In: *Proceedings of a Workshop on Banana IPM, Nelspruit, South Africa*. November 1998: 59-71.

HERREN, H.R. & NEUENSCHWANDER, P. 1991. Biological control of cassava pests in Africa. *Annual Review of Entomology* 36: 257-283.

KIGGUNDU, A. 2000. *Host Plant Reactions and Resistance Mechanisms to Banana Weevil, Cosmopolites sordidus (Germar) in Ugandan Musa Germplasm*. M.Sc. Thesis, Orange Free State University, South Africa.

KOPPENHÖFER, A.M. 1993. Observation on egg laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata* 68: 187-192.

MESQUITA, A.L.M. 1985. *Avaliacao do Ataque do* Cosmopolites sordidus *(Germar, 1824) (Col.: Curculionidae) em Rizoma de Bananeira*. Pesquisa em Andamento. CNPMF, EMBRAPA (NO. 21).

MITCHELL, G. 1978. *The Estimation of Banana Borer Population and Resistance levels*. Technical Bulletin 2, Windward Island Banana Growers Association (WINBAN), St. Lucia.

MITCHELL, G. 1980. *Banana Entomology in the Windward Islands. Final report 1974-1978*. Centre for Overseas Pest Research, London.

NEL, A., KRAUSE, M. & KHELAWANLALL, N. 2002. *A Guide for the Control of Plant Pests*. 39th Edition. Directorate, Agricultural Production Inputs, Department of Agriculture, South Africa.

OGENGA-LATIGO, M.W. & BAKYALIRE, R. 1993. Use of pseudostem traps and coefficient of infestation (PCI) for assessing banana infestation and damage by *Cosmopolites sordidus* Germar. *African Crop Science Journal* 1: 39-48.

OSTMARK, H.E. 1974. Economic insect pests of bananas. *Annual Review of*

Entomology 19: 161-176.

PEDIGO, L.P. 1996. *Entomology and Pest Management*. 2nd Edition. Prentice-Hall Inc., New Jersey.

PINESE, B. & PIPER, R. 1994. *Bananas - Insect and Mite Management*. Queensland Department of Primary Industries: Brisbane.

ROBINSON, J.C. 1996. *Bananas and Plantains*. CAB International, Wallingford.

ROYER, M.H., DOWLER, W.M. & HUBER, D.M. 1990. *Major Diseases of the Tropics and Sub-tropics of Bananas, Cacao, Cassava*. United States Department of Agriculture Agricultural Research Service.

RUKAZAMBUGA, N.D.T.M. 1996. *The Effects of Banana Weevil* (Cosmopolites sordidus *Germar) on the Growth and Productivity of Bananas* (Musa *AAA EA) and the Influence of Host Vigour on Weevil Attack*. Ph.D. Thesis, University of Reading, UK.

RUKAZAMBUGA, N.D.T.M., GOLD, C.S. & GOWEN, S.R. 1998. Yield loss in East African highland banana (*Musa* spp., AAA-EA group) caused by the banana weevil, *Cosmopolites sordidus* Germar. *Crop Protection* 17: 581-589.

SCHOEMAN, P.S., SCHOEMAN, M.H. & DOCHEZ, C. 1999. Novel techniques for the control of the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in South Africa. *Yearbook of the Banana Growers Association of South Africa* 3: 78-82.

SIMMONDS, N.W. 1959. *Bananas*. 1st Edition. Longmans Press, London.

SMITH, D. 1995. Banana weevil borer control in south-eastern Queensland. *Australian Journal of Experimental Agriculture* 35: 1165-1172.

SOKAL, R.R. & ROHLF, F.J. 1997. *Biometry*. W.H. Freeman and Company, New York.

STANTON, J.M. 1994. Status of nematode and weevil borer problems affecting banana in Australia. In: Valmayor, R.V., Davide, R.G, Stanton, J.M., Treverrow, N.L., & Roa, V.N. (Eds.) *Proceedings of Banana Nematode/Borer Weevil Conference in Los Banos, Philippines: INIBAP*. 48-56.

STATSOFT INCORPORATED. 2004. *Statistica*. Version 7.

STERN, V.M., SMITH, R.F., VAN DEN BOSCH, R. & HAGEN, K.S. 1959. The integrated control concept. *Hilgardia* 29: 81-101.

STOVER, R.H. & SIMMONDS, N.W. 1987. *Bananas*. Third Edition. 469. John Wiley and Sons, New York.

TAYLOR, B. 1991. Research field work on upland bananas, *Musa* spp., principally *acuminata* triploid AAA types, in the Kangera region of Tanzania with observations on growth and on the causes of decline in crop yield. *Revista di Agricultura Subtropicale e Tropicale* 85: 349-392.

TREVERROW, N.L. 1993. *An Integrated Management Programme for Banana Weevil Borer*. Horticultural Research and Development Corporation. Final report, FR/0012/RO.

TREVERROW, N., AKEHURST, A., IRELAND, G. & NEWLY, P. 1995. *Reducing Insecticide Use in Bananas: Monitoring Banana Weevil Borer Populations*. Agnote – New South Wales Agriculture.

TREVERROW, N.L. & BEDDING, R.A. 1993. Development of a system for the control of the banana weevil borer, *Cosmopolites sordidus* with entomopathogenic nematodes. In: Bedding, R.A., Akhurst, R. & Kaya, H. (Eds.) *Nematodes and the Biological Control of Insect Pests, Melbourne, CSIRO*. 41-47.

TREVERROW, N., PEASLEY, D. & IRELAND, G. 1992. *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*. Banana Industry Committee, New South Wales Agriculture.

VILARDEBO, A. 1960. *Los Insectos y Nematodos de las Bananeras del Ecuador*. Instituto Franco-Euaotiano de Investigaciones Agromicas, Paris.

VILARDEBÓ, A. 1973. Le coefficient d'infestation, critere d' evaluation du degre d'attaques des bananeraies par *Cosmopolites sordidus* Germ. Le charancon noir du bananier. *Fruits* 28: 417-431.

VILARDEBÓ, A. & OSTMARK, H.E. 1977. *Crop Loss Assessments*. Supplement 2, FAO, Rome.

VILJOEN, A. & ROBINSON, J.C. 2002. *Leaf Diseases and Disorders of Banana in South Africa. Identification and Management Guide*. Forestry and Agricultural Biotechnology Institute (FABI), University of Pretoria, Pretoria.

WILLERS, P., DANEEL, M.S. & DE JAGER, K. 2001. Banana. In: Van den Berg, M.A., De Villiers, E.A. & Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. 36. ARC – Institute for Tropical and Subtropical Crops. Ad Dynamics, Nelspruit.

Table 7.1. Multiple regression (model II, forward step-wise) of yield with *Cosmopolites sordidus* adult density and damage parameters on Cavendish bananas at four localities in the South Coast of KwaZulu-Natal, South Africa in 2003. Significant *P*-values of the predictor variables are in bold.

	Model statistics			Predictor variable	Predictor statistics		
Location	R^2	***F***	***P***		***Beta***	***B***	***P***
Ramsgate a	0.570	5.95 [2]	<0.023	XI [6]	-0.592	-0.211	**0.032**
				Adult density	-0.307	-0.139	0.220
Ramsgate b	0.418	11.50 [3]	<0.004	X mean [7]	-0.647	-0.346	**0.004**
Munster a	0.232	1.82 [4]	<0.204	PCI [8] 0-5 cm	0.726	1.526	0.087
				PCI [8] 5-20 cm	-0.447	-0.601	0.273
[1]Munster b	0.494	4.40 [2]	<0.046	XI [6]	-0.800	-0.152	**0.022**
				Total PCI [8]	0.704	1.003	**0.037**
[1]All sites	0.280	10.47 [5]	<0.001	XI [6]	-0.496	-0.251	**<0.001**
				Total PCI [8]	0.436	0.680	**0.001**

[1] Adult density not included as a predictor variable

[2] $F_{2, 9}$

[3] $F_{1, 16}$

[4] $F_{2, 12}$

[5] $F_{2, 54}$

[6] Cross section damage percentage of the central cylinder

[7] The mean cross sectional damage percentage of the cortex and central cylinder

[8] Percentage Coefficient of Infestation

Table 7.2. The economic-injury level (EIL) and action threshold (AT) of *Cosmopolites sordidus* on Cavendish bananas calculated according to two predictor variables, the mean percentage cross section damage of the central cylinder and the cortex (X mean) and the percentage cross sectional damage to the central cylinder (XI), at three localities in the South Coast of KwaZulu-Natal, South Africa in 2003. EIL = $C.(V.b.K)^{-1}$, where C = cost of management per area ($R.ha^{-1}$), V = market value per unit of produce ($R.kg^{-1}$), b = yield loss per insect or damage unit ($kg.unit^{-1}$) and K = proportionate reduction in potential injury or damage.

Location	Predictor variable		EIL variable					
	X mean	XI	C	V [3]	b	K [4]	EIL [5]	AT
Ramsgate a	No	Yes	R1477.07 x [1] R9179.32 y [2]	R2.25	0.211	0.95 x 1.00 y	1.47 x 8.69 y	1.10 x 6.52 y
Ramsgate b	Yes	No	R1477.07 x R9179.32 y	R2.25	0.346	0.82 x 0.90 y	1.04 x 5.87 y	0.78 x 4.40 y
Munster b	No	Yes	R1477.07 x R9179.32 y	R2.25	0.152	0.95 x 1.00 y	2.05 x 12.11 y	1.54 x 9.08 y
All sites	No	Yes	R1477.07 x R9179.32 y	R2.25	0.251	0.95 x 1.00 y	1.24 x 7.33 y	0.93 x 5.50 y

[1] Management x = six applications of fipronil (Regent) at 0.01 g.a.i. per plant (22.22 g.a.i. per ha) (Chapter 6) (R1416.81, Coastal Farmers), equipment (knapsack R15 per ha, nozzle R5 per ha) and labour cost (scouting R10.98 per ha, chemical injection R29.28 per ha).

[2] Management y = six applications of imidacloprid (Confidor) at 0.245 g.a.i. per plant (544.39 g.a.i. per ha) (Chapter 6) (R9119.06, Coastal Farmers), equipment and labour costs (R60.62 per ha).

[3] Average national market price between August and October 2002 to 2004 (Anonymous 2005b).

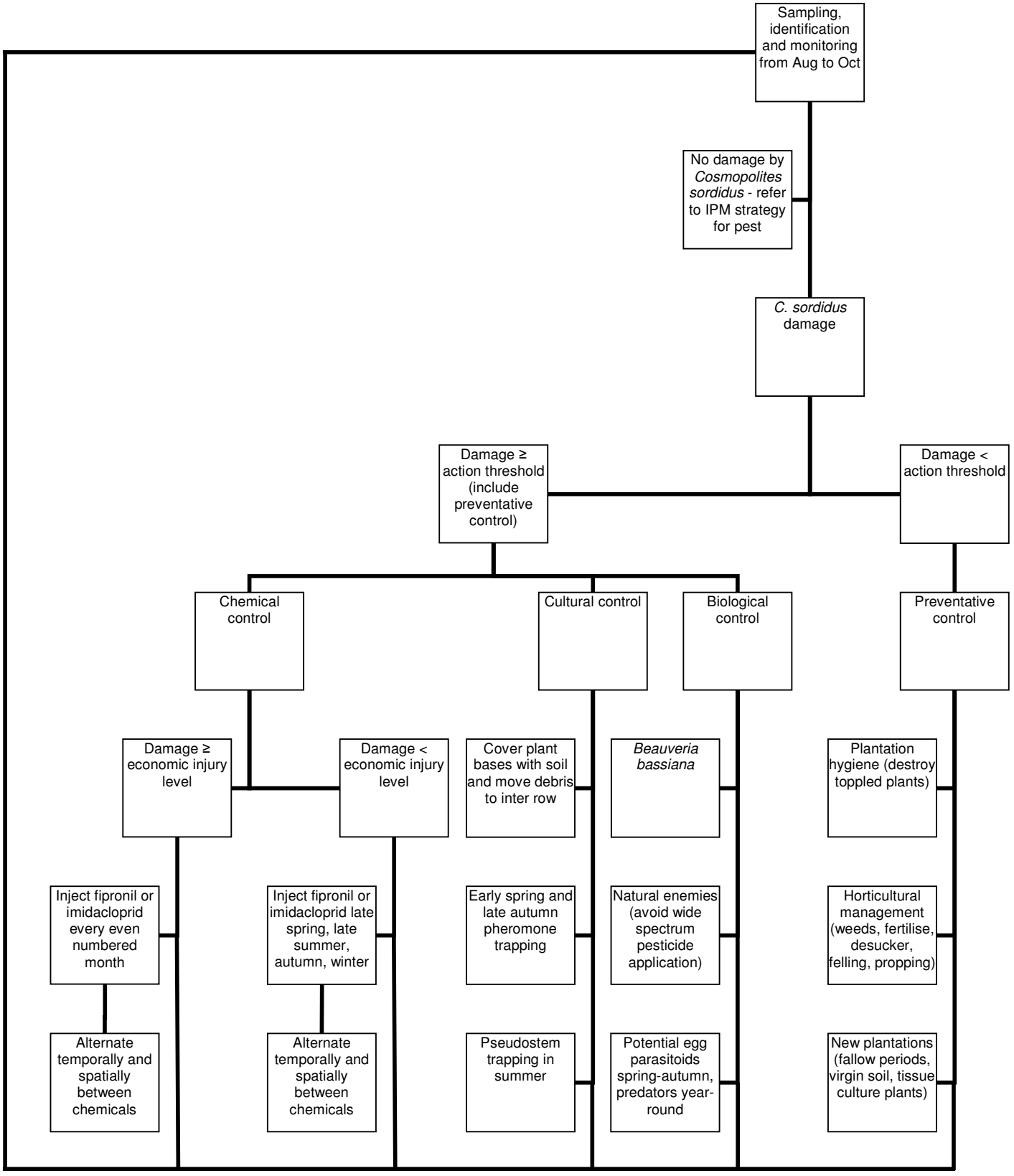
[4] Chapter 6.

[5] Damage $units.ha^{-1}$ ÷ 2222 plants = Average damage percentage per plant.

Figure legends

Figure 7.1. Recommendation algorithm for the integrated pest management of *Cosmopolites sordidus* in South Africa.

Figure 7.1


Sampling, identification and monitoring from Aug to Oct
No damage by *Cosmopolites sordidus* - refer to IPM strategy for pest
C. sordidus damage
Damage ≥ action threshold (include preventative control)
Damage < action threshold
Chemical control
Cultural control
Biological control
Preventative control
Damage ≥ economic injury level
Damage < economic injury level
Cover plant bases with soil and move debris to inter row
Beauveria bassiana
Plantation hygiene (destroy toppled plants)
Inject fipronil or imidacloprid every even numbered month
Inject fipronil or imidacloprid late spring, late summer, autumn, winter
Early spring and late autumn pheromone trapping
Natural enemies (avoid wide spectrum pesticide application)
Horticultural management (weeds, fertilise, desucker, felling, propping)
Alternate temporally and spatially between chemicals
Alternate temporally and spatially between chemicals
Pseudostem trapping in summer
Potential egg parasitoids spring-autumn, predators year-round
New plantations (fallow periods, virgin soil, tissue culture plants)