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.

7.5 Acknowledgements

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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**				**EIL** [5]	**AT**
	X mean	**XI**	**C** **x** [1] **y** [2]	**V** [3]	**b**	**K** [4] **x** **y**	**x** **y**	**x** **y**
Ramsgate a	No	Yes	R1477.07	R2.25	0.211	0.95	1.47	1.10
			R9179.32			1.00	8.69	6.52
Ramsgate b	Yes	No	R1477.07	R2.25	0.346	0.82	1.04	0.78
			R9179.32			0.90	5.87	4.40
Munster b	No	Yes	R1477.07	R2.25	0.152	0.95	2.05	1.54
			R9179.32			1.00	12.11	9.08
All sites	No	Yes	R1477.07	R2.25	0.251	0.95	1.24	0.93
			R9179.32			1.00	7.33	5.50

[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).

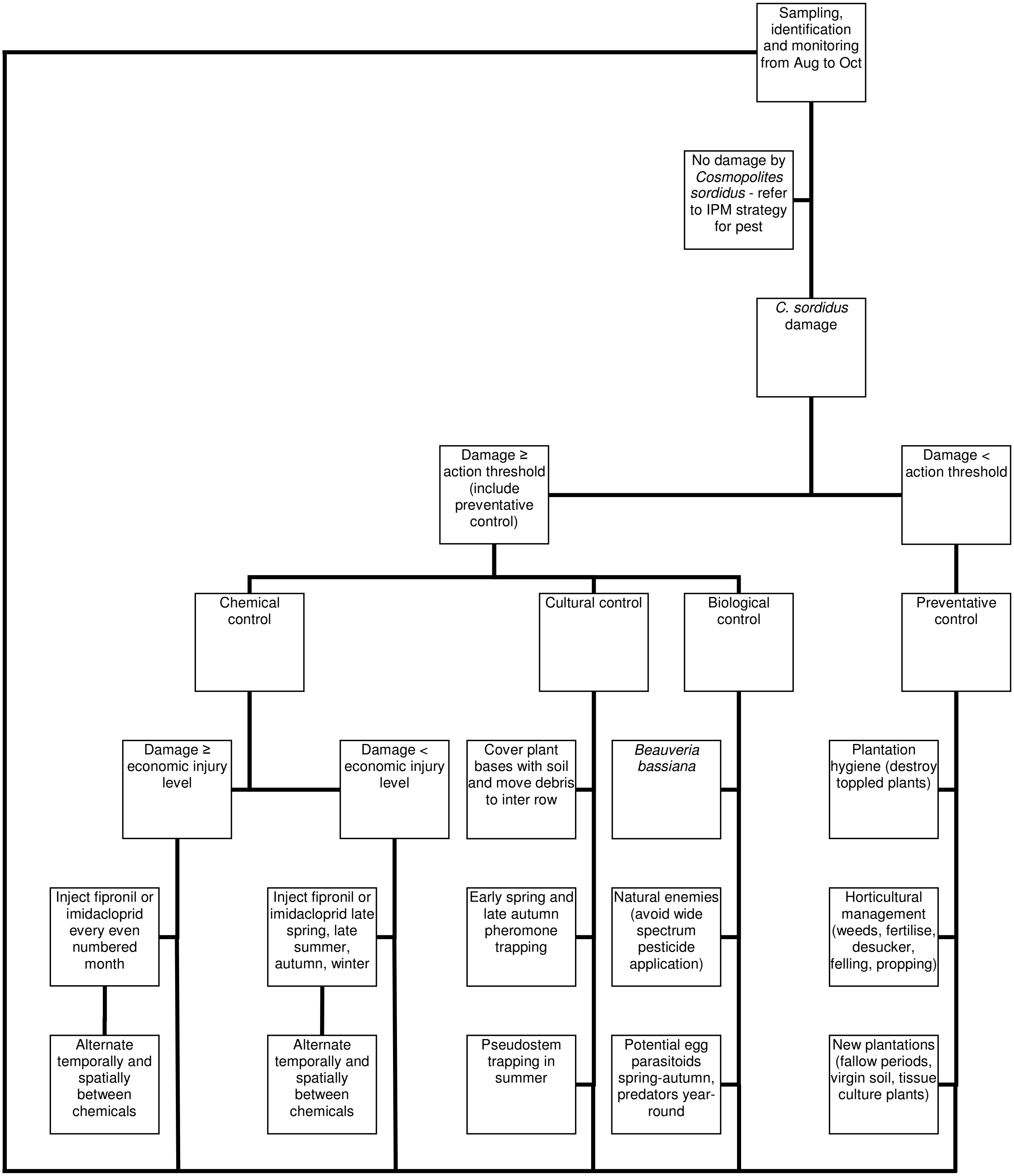
[4] Chapter 6.

[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)