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).

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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