Alternatives to synthetic pesticides for the management of the banana borer weevil (*Cosmopolites sordidus*) (Coleoptera: Curculioniidae)

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Received: 5 November 2019
Accepted: 20 March 2020

doi: 10.1079/PAVSNNR202015026

The electronic version of this article is the definitive one. It is located here: http://www.cabi.org/cabreviews

Abstract

Bananas and plantains are important staple crops for many people in developing countries, but these crops are severely affected by biotic constraints that reduce productivity. A major biotic stress is the banana corm borer weevil (*C. sordidus*) whose larvae eat corm/pseudostem tissues that eventually weaken the plants and cause toppling. To manage these borer weevils, most farmers use synthetic pesticides with active ingredients from different pesticide groups. Over reliance and abusive use of pesticides result in detrimental effects on the environment and human health. These effects together with ecological backlashes such as development of resistance by the pest have led to numerous advocacies to minimize the use of these chemicals. To achieve this, there has been increasing number of researches to seek sustainable alternatives that could be used to replace these synthetic pesticides or be integrated with less toxic chemicals to effectively manage the pest. This review summarizes global research on the use of synthetic pesticides and alternative management techniques such as the use of appropriate cultural practices (e.g., clean planting materials, fallowing, mulching, intercropping, and trapping), botanical pesticides (e.g., from Solanaceae, Asteraceae, and Meliaceae), entomopathogens, predators/parasitoids, and the use of resistant crop varieties, as well as possibilities of engineering phytocystatins to produce transgenic varieties that will be harmful to weevil. The review ends with conclusions, limitations/gaps, and recommendations for future research for the different alternative options.

Keywords: musa, pest, integrated pest management

Review methodology: To successfully carry out this review, we collected lots of information from different sources including internet search engines, libraries, consultation of experts from different parts of the world via individual emails, yahoo groups (e.g., pestnet@yahoogroups.com), and Whatsapp groups. The information collected were mainly primary research (peer-reviewed manuscripts published in journals) as well as scientific reports or articles in conference proceedings or annual reports. Secondary literature especially from news bulletins, magazines, and books were also consulted. Focus on all these was on the banana borer weevil (*C. sordidus*) and the different management options that have been tested or implemented in the laboratory and/or on the field. The information collected was categorized to form a table of content that guided the write up. Aspects of the content focused on general information on pests of bananas and plantains, bioecology of *C. sordidus*, and management options (use of synthetic pesticides, cultural practices, biotechnological options—genetic engineered plants/use of resistant varieties, botanicals, microbials, predators/predators, mass trapping/pheromones, and use of cystatins).

Introduction

Bananas and plantains (*Musa* spp.) are cultivated in many countries in the world, especially in tropical developing countries. According to Ploetz *et al.* [1], these crops rank among the world's most valuable primary agricultural commodities. According to FAO [2], bananas and plantains together serve as a staple food for at least 400 million people globally. These food crops have therefore been rated as the fourth most valuable food after rice, wheat, and milk [3]. Bananas and plantains provide about 25% of food-energy requirements for about 70 million people in Sub-Saharan Africa (SSA) and since the fruits are produced all year round, these crops play an important role in food security and income generation to many resource-poor farmers especially during low production periods of local cash crops like cocoa, coffee, and oil palms [4]. These crops are mainly cultivated in backyard gardens, smallholder farms, and commercial plantations that represent a valuable source of employment to thousands of peoples [5]. Worldwide, the production of *Musa* spp. is usually constrained by biotic factors such as pests and diseases. The common pests are corm borer weevils (*Cosmopolites sordidus*), stem borer weevils (*Odoiporus longicollis* and *Metamasius* spp.), skippers (*Erionota thrax* and *Erionota torus*), lesion nematodes (e.g., *Radopholus similis*), mealy bugs (*Pseudococcus* spp. and *Dysmicoccus* spp.), thrips, aphids (*Pentalonia nigronervosa*), huntsman spider, red spider mites, white flies, snails (*Limacolaria* spp.) while common diseases are black sigatoka (*Mycosphaerella fijiensis*), banana wilt (*Xanthomonas* spp.), fusarium wilt (tropical race 4), banana streak viruses, and banana bunchy top [4, 6–13]. Borer weevil is the most important pests with serious damage on plantains and usually found in most banana/plantain producing zones [4, 14–20].

Brief on the bioecology of *C. sordidus*

Morphology and life cycle

There are three main species of borer weevils that affect *Musa* spp. including *Cosmopolites sordidus*, *Metamasius sericeus*, and *Pollytus mellerborgii*, although *C. sordidus* is the most economically important. Young adults of *C. sordidus* are reddish-brown in color while the older ones are dark or black, and adults are slow walkers. The insect undergoes holometabolous development and after mating, females use their rostrum to create tiny holes and then lay a single egg in each hole [21]. These eggs are white, oval in shape and may hatch within 5–8 days. Larvae from these eggs pass through 5–6 instars lasting 30–50 days. A mature larva is about 10–12 mm long, apodous, creamy white, has dark brown and well developed mandibles, as well as a curved body [21]. After intense feeding, the larvae undergo a dramatic change to form pupa. Adult longevity of up to about 15 months has been reported in the laboratory [22].

Distribution and dispersal

The borer weevils occur in fields throughout the year and adults are free-living. Among the 28 borer pests associated with bananas and plantains worldwide [23, 24], banana corm weevil borers are most widely distributed [6, 7, 25]. Generally, adults are negatively phototropic, and are active in the night and are not commonly seen in the fields unless caught in traps. The adults are usually found in soil around mats, within leaf sheaths of living pseudostems and harvested stumps/corms [8, 17, 26, 27]. Messiaen [26] suggested that movement from and to adjacent fields by walking is limited. However, Rannestad *et al.* [28] showed that the migration potential of banana weevil is greater than previously reported and this should be taken into account when new banana fields are established with clean planting materials.

Damage and damage signs/symptoms

Even though adults feed on decomposed corms in banana fields, the larvae usually cause damage. The economic importance of borer weevils varies with agroecological region, cultivars, production system, and level of implementation of crop protection practices. Corm damage and percentage of plants attacked in the fields is usually assessed or estimated using Coefficient of Infestation (CI) of Vilardebo [29] or Percentage Coefficient of Infestation [26]. Damage is usually assessed by observing the periphery of corms (external damage) and/or the cross section of corms, that is, cortex and central cylinder (internal damage). Damage in the central cylinder showed greater effect on yield than damage in the cortex in highland cooking banana in Uganda [16]. In addition, corm damage is common in farms with poor soil nutrient status, inappropriate agronomic practices, and poor phytosanitary measures, with severe damage reported on small-scale plantain farms compared to commercial plantations [4, 15, 30, 31]. Larvae are the most destructive stage, using their strong mandibles to escavate and create tunnels or galleries in the rhizome (corm) and sometimes extending to the pseudostem. Larval feeding usually results in weak growth, poor anchorage and toppling especially during windy periods and infestation is usually low in the first cycle, but increases significantly during older cycles [32, 33]. Infested plants show stunted growth, delayed maturation [34], reduced bunch weight, and can snap or topple [35–37].

Population dynamics

Generally, population dynamics involves changes in numbers of an organism as well as the biological and environmental processes influencing such changes [38–40]. Concerning *C. sordidus*, the main method used to monitor or estimate the population is trapping (pseudostems or pheromones). The dynamics of this pest varies from one country to another, but with some common determinants such as presence of predators, soil type, agronomic practices, farming season, and temperature [4, 17, 26].

Justification/Objective of the review

Cosmopolites sordidus is an important economic pest on *Musa* species in the world, especially in smallholder farms. To minimize the damage caused by this biotic constraint, most smallholder farmers often use synthetic pesticides while commercial or agro-industrial plantations mainly integrate cultural techniques with different types of synthetic pesticides [4, 41–43]. In addition, these synthetic pesticides are frequently misused, which could be detrimental on the environment and human health, with emergence of ecological backlashes such as resurgence, replacement, and resistance [44–49]. Based on these over reliance and misuse of synthetic pesticides, there has been global advocacy to minimize their use for crop protection and to increase the search for sustainable alternatives, especially for the highly hazardous pesticides [44, 50, 51]. This review therefore was intended to search the literature on primary/secondary researches on alternatives to synthetic pesticides that have potential to manage the banana borer weevil. Furthermore, the review points out limitations for these alternatives and recommends areas for future research or that needs improvement.

Options for managing *Cosmopolites sordidus*

Like many other important pests on staple crops, lots of researches have been conducted to provide more bioecological information on *C. sordidus*—its structure, life cycle, and population dynamics. Also, with this knowledge, researchers have been testing different techniques that can reduce the population below economic thresholds and minimize or delay damages caused by the pest. These management options that have been evaluated in laboratories, screen houses, research experimental stations, and farmers' farms can be grouped into chemical (synthetic and botanicals), microbials (entomopathogens), infochemicals, biological control (parasitoids andpredators), genetical (resistant varieties, manipulation of cystatins), physical (trapping), and cultural (sanitation, use of clean planting materials, mulching). While some of these options comprise techniques that have been validated on-farm, some have only shown their potential under controlled conditions in laboratories and in screen houses.

Use of synthetic pesticides

Many active ingredients from different groups of synthetic pesticides have been tested and/or used for the management of *C. sordidus*. The efficiencies of several chemical formulations of classical pesticides have been evaluated for the management of borer weevils infesting bananas and plantains. These groups of pesticides include organochlorines (e.g., chlordecone), organophosphates (e.g., chlorpyrifos, terbufos, ethoprofos), carbamates (e.g., carbofuran), pyrethroids (e.g., cypermethrine), neonicotinoids (e.g., imidacloprid, thiamethoxam), and phenyl pyrazoles (e.g., fipronil) [4, 26, 41, 42, 52–57]. First pesticides used against the borer weevils were Paris Green and organochlorines such as BHC, dieldrin, lindane, chlordecone, and DDT [58, 59]. Although these were effective, they were persistent and therefore had potential for bioaccumulation and weevils were reported to develop resistance against these pesticides [60]. These led to the use of organophosphates (e.g., chlorpyriphos, pirimiphos-ethyl, ethoprofos, terbufos, cadusofos, isophenfos), carbamates (e.g., carbufuran, aldicarbe, oxamyl), and some pyrethroids (e.g., deltamethrine, bifenthrine and zeta-cypermethrine) [4, 10, 41, 43, 61–65]. With the continuous development of resistance of the weevils to organophosphates, carbamates, and pyrethroids, new formulations have been developed and tested including the neonicotinoids and phenyl pyrazoles that are commonly used in large commercial or agro-industrial plantations.

Generally, chemical formulations of pesticides are in the form of granules, wettable powders, suspension concentrates, dustable powders, and aqueous solutions. Most of the chemicals that have been evaluated have contact and/or systemic effects and are usually neurotoxic and their effectiveness varies from weak to excellent results. The mode of application of these chemicals are (i) on the soil around corms, (ii) on corm surfaces, (iii) on pseudostem traps, (iv) in planting holes, (v) planting materials soaked in insecticide solutions (especially emulsive solutions) before planting, and (vi) application at plant collar upto height of 45 cm [4, 10, 41, 55, 66, 67]. In addition, the application rate varies from once to thrice per year and the dose applied per plant also varies as follows: (i) for active ingredients it ranges from 0.1 to 2 g, (ii) for commercial products it ranges from 2 to 100 g or 1.25 to 50 mL per plant [4, 10, 41, 42]. These variations are based on the group of insecticide used, the agroecological zones and probably the level of resistance by the weevils. Of all these classical pesticides evaluated, those with excellent efficacies are dieldrin, chlordecone, isophenfos, ethoprophos, terbufos, furadan, aldicarbe, zeta-cypermethrine, imidaclopride, thiametoxam, and fipronil [4, 10, 41–43, 61, 64, 68]. However, fipronil and imidacloprid are relatively new formulations that have been reported with excellent efficacies, having relatively less effect on non-target organisms, and with little or no resistance developed by the weevils [4, 41, 43, 69, 70].

Although these synthetic pesticides have been shown to play an important role in modern agriculture and are relatively easier and effective for the management of *C. sordidus*, there are reports on the resistance development [4, 26, 61] and on the general adverse effects of pesticides on human health and on the environment [44, 45, 50, 51, 71, 72]. Because of these issues, there has been an increasing advocacy for the reduction of these pesticides in food production [72, 73] and these have led to the growing concerns and/or tendencies to search for alternatives that could replace them completely or that could be combined with the least toxic chemicals too in an integrated pest management program. For the case of *C. sordidus*, commonly evaluated alternatives are use of infochemicals, entomopathogens, predators/parasitoids, botanical pesticides, inhibition by protein enzymes, cultural, and genetic techniques.

Alternatives to synthetic pesticides

Use of cultural methods

Pest management using cultural techniques involves manipulation of the environment or implementation of preventive practices with the aim to reduce pest population and their damages. Cultural techniques are the oldest methods for managing pest populations although they have been over shadowed by synthetic pesticides. These techniques are dependent on detailed knowledge of the bio-ecological relationships with crop systems. Generally, there have been lots of speculations or hypotheses on the benefits of these techniques especially to smallholder farmers. Such techniques include mulching, fallowing, crop rotation, intercropping, sanitation; cover cropping, trapping, and use of clean planting materials. In this review, we focused on techniques that have been tested in the laboratory, screen houses or in the fields.

Clean planting materials

Using pest and disease-free planting materials (clean planting materials) is a common technique and has been widely reported to reduce spread of plant parasitic nematodes and different life stages of the banana borer weevils [15, 74–83]. InfoMusa [84] also mentioned that a combination of several cultural techniques is the best available approach to resource-poor farmers as it is likely to reduce weevil and nematode pressure. The different clean planting materials are those resulting from tissue culture (micropropagation), plantlets from corm bits (macropropagation), and treated traditional suckers. According to Viljoen [85], tissue culture plantlets are very clean since they are produced under sterilized laboratory conditions and often indexed to ensure they are virus-free. These plantlets are free of soil-borne pathogens and perform well when planted in the field [86]. In spite of these advantages, only large agro-industrial plantations or large commercial farms mainly use tissue culture plantlets. Although in vitro plants showed vigorous growth and were taller, they did not show superior performance and higher yields compared to conventional suckers [87]. Smallholder farmers who cannot afford and/or have access to these micro-propagated plantlets are now shifting from their common use of untreated traditional suckers to treated ones or to macro-propagated plantlets. In these small farms, high proportion of plantains fail to produce due to early toppling as a result of root boring nematodes and borer weevils [75]. Disinfected or treated suckers by paring and using hot or boiling water has been shown to significantly reduce contamination by pathogens and pest [75, 76, 79, 85, 88]. Paring of suckers before planting, paring of suckers in combination with sun-drying for 3 days and use of hot water treatment of pared corms before planting have been widely used and shown to have some benefits including vigorous growth of the plants, reduced corm damages and root necroses as well as increase in bunch weights [76, 88, 89]. Pared and sun-dried plants showed 17% increase in bunch weight [88]. Messiean [26] mentioned that paring helps to expose larval galleries and therefore allowing the farmer to reject heavily damaged suckers. Hot water treatment at 50–55°C of peeled or pared suckers for 15–27 min have been reported to significantly reduce weevil and nematode infestations [4, 79, 90–92]. However, due to the difficulties in managing and practical implementation of this hot water treatment technique, IITA [93] and Hauser (2010) reported an improved method involving immersing pared suckers into boiling water for about 20–30 s. Suckers treated with boiling water produced more bunch than the control [75, 76].

Fallowing

Generally, fallowing involves destroying the crop at a particular piece of land for at least a year before cultivating again. In the case of bananas and plantains, this practice is very common in large commercial plantations and fallows are prepared by injecting plants with herbicides before plowing the field [4, 94]. In plantations, after about 3–5 years of cultivation, plots are fallowed for about 1–2 years [4, 12]. In some cases, other non-*Musa* crops such as sweet potatoes and pineapples are cultivated in the fallow areas before replanting of bananas/plantains. Price [95] recommended at least 1 year of fallowing or growing a non-*Musa* crop before replanting of bananas. Besides suppression of nematodes, some researches have shown limited effects of this practice on the weevils [41, 96]. Price [12] showed that weevil damage was lowest (CI = 0.5) in the weed-fallow micro-plots while highest damage (CI = 2.25) occurred in micro-plots previously planted with plantains. Based on these results, it was concluded that *C. sordidus* can cause serious damage to young plants planted directly into infested land. New plantings nearer to fallows usually have weevils from the fallow fields. To make fallows more effective in reducing weevil population and damage to new plantings nearby, Rhino *et al.* [94] introduced the use of pheromones traps (9–16 traps per hectare) within banana fallows and significantly lower catches of adults recorded in new plantations adjacent fallows. Also, these catches decreased with the distance from the fallow. Duyck *et al.* [97] reported that 12 months fallow decreases *C. sordidus* and mass trapping is effective during the dry season between 40–80 days after planting. Mass trapping with pheromones within fallows therefore allows adequate sanitation, preventing a large part of weevil population leaving fallows and getting into the new plantings, causing damage to the young plants.

Use of organic manure/mulching

Mulching is a process of adding a layer of material to the surface of soils during cultivation. Such materials have demonstrated the ability to protect and improve soil, and therefore enhance crop growth and yields [98–100]. In addition, mulching can play an important role in the management of pests and diseases [98–102]. Organic and inorganic mulches suppressed pests (e.g., insects, nematodes, and weeds) and diseases (e.g., blight, mosaic viral, and curling diseases). Living/non-living organic mulches have been used to manage pests and diseases on *Musa* species and improve their growth and yield. According to Matkovic *et al.* [98], living mulches are plants grown in the field to provide various ecological benefits to the main crop but are not the main crop. McIntyre *et al.* showed that leguminuous crops such as *Canavalia muzinna* and *T. vogelli* intercropped with bananas repelled borer weevils although the yield was unaffected. McIntyre *et al.* [99] intercropped some legumes (*Canavalia ensiformis*, *Mucuna pruriens*, and *T. vogelii*) with bananas and found out that they did not affect weevil population or damage as well as fruit yield. The cover crop (*Paspalum notatum*) reduced adult weevils but it did not reduce damage to corms while the bunch weight was significantly lower in cover crop plots than the bare soil, probably due to competition. Gold *et al.* [103] reported that weevil populations were higher in mulched that unmulched systems, while damage caused varied with site. They also mentioned that mulching favors growth and yield but with no advantage for managing *C. sordidus*. Young adults were higher in cover crop and negatively correlated with abundance of earwig (*Euborellia caraibea*) that is an important generalist predator of *C. sordidus* in French West Indies [104]. Salazar *et al.* [105] intercropped plantains with *Mucuna* legume cover crop and found that *Mucuna* attracted *C. sordidus* although it did not affect plantain height, stem diameter, or sucker production when the legume was eliminated 4 months after planting. Dassou *et al.* [106] showed that using cocoyam, maize and gourd (*Lagenaria siceraaria*) as intercrops for plantains had clear effects on ant abundance, which negatively correlated with *C. sordidus* damage for ants of the family Myrmicinae and positively for Formicine and Ponerinae. Duyck *et al.* [14] and Carval *et al.* [101] reported that abundance of *C. sordidus* and generalist predators such as *E. caraibea* are affected by addition of cover crop. Generally, this intercrop did not affect damage to plantain corms by *C. sordidus* larvae, although it increased the number of some ant species while decreasing others.

Banana weevil population has also been found to be lowest when banana is intercropped with millet while yield losses are higher with intercrop and mulch [107–109]. Coffee-banana intercropping was much more profitable and beneficial than banana monoculture [110]. The corm damage and yield did not differ between the monoculture and intercrop. The cover crop (*Brachiara decumbens*) was very useful in providing resources that attracted and supported a community of insect herbivores that are alternative prey for potential predators of *C. sordidus* [14]. Poeydebat *et al.* [111] mentioned that lower strata species richness had a positive bottom-up effect on herbivore-prey abundance, which in turn enhances abundance of predators. Therefore, regulation of *C. sordidus* is enhanced through field-scale plant diversification, which increases predators such as ants. Use of living mulch or intercropping is a common practice in developing countries, and it is practiced by many farmers due to declining land sizes and for food security needs [112].

Non-living mulches are made up of non-living plant materials that are mostly biodegradable (e.g., straws, saw dust, wood ash, paper, wood chippings, tree backs, grass, plant residues, and composted animal dung/manure). The use of such mulches in cropping systems is very common as they are cheaper, available, easily acquired, and relatively easy to apply on crops. Unlike living mulches that may compete for resources with the main crop [113], and mainly reduce pest abundance and/or damage on the main crop indirectly (by encouraging the presence of predators and parasitoids), non-living mulches do not only encourage diversity of beneficial soil-dwelling macro-and micro-organisms, but also break down to release nutrients that enhance soil fertility and ultimately crop vigor and yield. Tinzaara *et al.* [114] used grass mulches (mix of *Panicum maximum*, *Imperata cylindrica*, and *Brachiaria* spp.) at thin (75 kg per plot) and thick (150 kg per plot) levels. Mulching had no effect on the number of adult weevils caught in pheromone traps and the ratio of male to females captured. However, more weevils were caught in pheromone traps in thick mulch plots than the control, especially during the rainy season. Gold *et al.* [115] reported that *C. sordidus* is more active and move longer distances in mulched than unmulched areas.

Residue removal

These techniques keep the farm or crops clean such that conditions favoring competitors and pests are minimized to allow healthily crop growth. According to Masanza [78], corms of bananas and plantains are most attractive to weevils than any other crop residues with high oviposition on freshly harvested residues of up to 30 days. He concluded that residues are important source of infestation to standing crops. Okolle and Mbouenda [17] also reported more adult weevils on cut pseudostems, stumps, and bunched plants. Although there are many suggestions/beliefs on the importance of residue removal, weeding, and pruning for managing *C. sordidus*, very little research (supported with data) has been carried out on this. In his field experiment, Masanza [78] showed that removal and chopping of crop residues in farmers' fields helped to keep *C. sordidus* populations and damage lower than when residues were left to accumulate, leading to a 34% reduction in yields. However, he reported that complete removal of residues lead to significant reduction in arthropod natural enemies compared to leaving residues. Inzaule *et al*. [116] reported that experimental plots with cultural practices such as desuckering, detrashing, chopping of pseudostems decreased weevil, and nematode damage.

Trapping

Trapping is a physical technique intended to exclude a pest such that it does not reach the target and cause damage. Generally, traps are used to catch and either destroy or poison adult weevils. An old trapping method in research stations and most farms is the use of classical split pseudostems [15, 26, 95, 108, 117]. Classical pseudostem traps are usually about 30 cm in length and cut from harvested pseudostem stumps or pseudostem residues on the soil. Although at present it is difficult for most farmers (small-scale) to adopt this technique, most plantations (large-scale) adopted it but soon abandoned it because it is labor-intensive, costly and time wasting [118]. Other traps called disc-on-corm traps [4] have been made from corms of harvested stumps by cutting out a small pieces of corms from harvested stumps, removing it and placing it again on the cut spot such that an allowance is left for weevil entry. Similarly, Ogenga-Latigo and Bakyalire [119] described a disc-on-stump trap made by cutting harvested stump 15–25 cm above-ground level and placing a 5–10 cm thick pseudostem disc on top of the stump. Although disc-on-corm and disc-on-stump catch more weevils than the classical split pseudostem traps, they are still labor-intensive, relatively difficult to set, and are inflexible. To overcome this problem, many researchers and large-scale plantations are now using pheromones as lure for banana borer weevils [54, 120–125]. Sordidine is a male-produced aggregation pheromone isolated from banana borer weevils and was identified by Beauhaire *et al*. [126]. This pheromone is commonly sold in commercial packs with trade names such as Cosmolure®, CosmoPlus®, and Cosmotrak®, and Budenberg *et al*. [127] first provided evidence for this pheromone.

In addition to sordidine, Uzakah *et al*. [128] provided evidence for the presence of a female produced sex pheromone. However, they mentioned that this pheromone is only active within a short range and essentially for mating purposes and therefore weak as compared to sordidine. Generally, pheromones have been used to monitor and to mass-trap *C. sordidus* in attract and kill programs. Pheromone-bated pitfall traps are commonly used and are very effective in reducing adult weevil population compared to all the variants of pseudostem traps and other pheromone-baited traps [4, 118, 120, 125, 129]. To retain adult weevils that fall into the trap, water containing 1–3% dish washing detergent is placed in the traps. A major setback for pheromone-baited pitfall is that they are easily flooded during the rainy season, very expensive and not affordable or easily accessible for smallholders. In South Africa, De Graaf [41] reported that there were no significant differences between normal pseudostem traps and the control (pit fall traps without baits or lures) with over 65.3% female weevils caught. The efficacy of pheromone-baited traps is enhanced when they are integrated with some plant parts. Tinzaara *et al*. [130] reported that *C. sordidus* responded significantly stronger to the combination of synthetic pheromone and fermented pseudostem (AAA-EA) than to pheromone or pseudostem alone. Osorio *et al*. [121] found that with the exception of corms, there were no statistical differences between pheromone traps mixed with other plantain parts and pheromones alone, while pheromone traps mixed with corms captured more weevils. In Ghana, Jallow *et al*. [120] did not find any significant differences between corm and pseudostem traps, although the corm traps caught more weevils. Dead banana leaves have also been found to be more attractive to weevils than pseudostem and rhizome materials [131, 132].

Use of plants with insecticidal properties

Plants with bioactive properties are also referred to as botanical pesticides or they can be categorized as biorational pesticides [4, 133]. Generally, these type of pesticides should have low toxicity to non-target organisms and suppress pest populations by affecting their orientation and reproductive behaviour. In addition, these botanical pesticides also pose little threat to the environment and human health [134]. Although many smallholder farmers commonly and quickly adopt synthetic pesticides for the management of pests, plants with insecticidal properties have been used and are now gaining more support as more evidences arise on the threats of synthetic pesticides on the environment and human health. Table 1 below shows 31 different plant species from 15 Families have been evaluated for the management of *C. sordidus*, with many of the experiments conducted in the laboratory. Of these plant Families, the most frequently evaluated have been Solanaceae, Asteraceae, and Meliaceae. However, commercial products for the management of *C. sordidus* have been developed mainly from Meliaceae (e.g., neem plant) and Solanaceae (e.g., chili pepper).

Table 1. Different plant species screened and tested for their potential to manage *C. sordidus*.

References	Plants evaluated	Common name	Family	Parts used	Effects on *C. sordidus*
Bwogi *et al*. [135]	*Capsicum frutencesis*	Chili pepper, bird pepper; cayenne pepper; tabasco pepper	Solanaceae	Not mentioned	• No significant differences in fields where synthetic pesticides and ethnomedicinal plant extracts were used.
	Nicotiana spp.	Tobacco	Solanaceae	Not mentioned	
	Phytolaca dodecandra	African soapberry	Phytolaccaceae	Not mentioned	
	Tithonia diversifolia	Wild sunflower	Asteraceae	Not mentioned	
	Tephrosia vogelii	Fish poison bean	Fabaceae	Not mentioned	
	Crassocephalum crepidiodes	Fireweed, Okinawa Spinach	Asteraceae	Not mentioned	
Musabyimana *et al*. [136]	*Azadirachta indica*	Neem	Meliaceae	Seed in powder form, cake and oil.	• Feeding deterrence for larvae. • Larval mortality. • Surviving larvae with significantly smaller sizes and weight. • Oviposition deterrence.
Sahayaraj and Kombiah [137]	*Azadirachta indica*	Neem	Meliaceae	Commercial product—Neem Gold®	• Repulsive to weevils. • 6.7% mortality. • Significantly reduced the total haemocyte counts for weevils.
Tinzaara *et al*. [133]	*Melia azedarach*	Chinaberry tree, Pride of India, Bead-tree, Cape lilac, Syringa berrytree, Persian lilac, Indian lilac,	Meliaceae	Ripe seeds	• Oviposition significantly low on corms treated with the plant extracts. • Limited toxicity on adults (only 5.5% mortality). • Repellent properties also limited.
	Tagates spp.	Mexican marigold	Asteraceae	Leaves	
	Eichornia crassipes	Water hyacinth	Pontederiaceae	Leaves	
	Ricinus communis	Castor oil	Euphorbiaceae	Leaves	
Tinzaara *et al*. [124]	*Nicotiana tabacum*	Tobacco	Solanaceae	Leaves	• Oviposition significantly reduced. Good repellents although very weak for ash.
	Capsicum spp.	Pepper	Solanaceae	Fruits/seeds	

Continued

Table 1. Continued.

References	Plants evaluated	Common name	Family	Parts used	Effects on *C. sordidus*
Debonnaire [69]	*Piper nigrum*	Black bush pepper	Piperaceae	Seeds	• *P. nigrum* powder and solution caused 100% mortality and over 90% repulsion. • *P. nigrum* reduces oviposition on corm surface by 50%.
	Aframomum melegueta	Grains of paradise or alligator pepper	Zingiberaceae	Seeds	
Inyang and Emosairue [138]	*Allium cepa* and *Allium sativum*	Onion and Garlic, respectively.	Amaryllidaceae	Leaves	• All extracts showed repellent effects which were dose-dependent. • However, only *Piper guineense* and *S. aromaticum* elicited repellence of class IV (60.1–80%).
	Azadirachta indica	Neem	Meliaceae	Seeds	
	Cymbopogon citratus	Lemon grass	Poaceae	Leaves	
	Dennetia tripetala	English pepper fruit	Annonaceae	Seeds	
	Garcinia kola	Bitter cola	Clusiaceae or Gluttiferae	Seeds	
	Mondora myristica	Calabash nutmeg	Annonaceae	Seeds	
	Ocimum gratissimum	Clove basil or African basil	Lamiaceae	Leaves	
	Piper guineense	Ashanti pepper, Benin pepper, false cubeb, Guinea cubeb	Piperaceae	Seeds	
	Tetrapleura tetraptera	Aidan tree	Leguminosae or Fabaceae or Mimocaceae	Fruits	
	Syzygium aromaticum	The clove tree	Myrtaceae	Fruits	
	Zingiber officinale	Ginger	Zingiberaceae	Stems	
Manka and Okolle [70]	*Capsicum annuum*	Chili pepper	Solanaceae	Extracts in the form of a commercial product Bromorex®	• Very poor repellence and mortality for weevils but higher efficacy for mealy bugs (73.3% compared to 53.3% for Fipronil).
Mukassa *et al*. [139]	*Tithonia diversifolia*	Wild sunflower	Asteraceae	Whole plant material	• All the plant parts for fresh and dry crude extracts caused high mortality (>70%) for eggs and larvae. • Had significant deterrence and repellence effects on adults. • Significantly affected oviposition on treated corms (less eggs laid).
	Phytolacca spp.	Pokeweeds, Pokebush, Pokeberry, Pokeroot, Poke sallet, and Ink berry	Phytolaccaceae	Whole plant material	

With the exception of *Piper* spp. with very high mortality on adult weevils, most evaluated plants had little or no direct toxicity on adult weevils. In one study, neem caused mortality of larvae while *T. diversifolia* and *Phytolacca* spp. caused high mortality to eggs and larvae. However, most of the plant extracts showed significant indirect or non-mortality effects such as repellency, oviposition deterrence, feeding deterrence, significant reduction in weight and size of larvae, as well as a case that resulted to reduced number of haemocytes in adult weevils. Most experimental screening and testing of these plants with bioactive properties have been conducted in the laboratory (with few field tests) and we could not find any that tested the effects of botanicals on non-target beneficial organisms within banana agroecosystems. An important finding from Messiaen [26] is that the collection site of neem plants affects its effectiveness, and those from North Cameroon were better than those from South Cameroon.

Use of pathogens, predators, and parasitoids

The use of living organisms (microscopic or macroscopic) and/or their products to manage pests is referred to as biological control. Of particular importance is the use of parasitoids, pathogens, predators, antagonists, or competitors to suppress pest population, making their population less abundant and less damaging than it will be in the absence of biocontrol agent [140]. For *C. sordidus* management, most researches have focused on entomopathogens and predators.

Entomopathogenic organisms

Entomopathogens or microbial agents that have been tested against *C. sordidus* include entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae*, entomopathogenic nematodes such as *Steinernema* spp. and *Heterorhabditis* spp. and endophytes such as non-pathogenic *Fusarium* spp. Entomopathogenic fungi and nematodes are mostly used to kill adult weevils, while endophytes effectively control the immature stages of the pest. Entomopathogens reportedly established following applications in banana fields in some cases but without adequate establishment, entomopathogens would require repeated applications as a biopesticide and this entails continued production, distribution, and storage costs.

Entomopathogenic fungi andendophytes

Studies exploring the potential of entomopathogenic fungi (EPF) in biocontrol indicate a striking asymmetry between above- and below-ground target pests. While, studies on EPFs have focused on above-ground pests [141, 142], there is increasing interest of EPFs for controlling root-feeding pests [143, 144]. The common commercially available EPF-based products to control root pests include three genera of opportunistic insect pathogens: *Beauveria* or *Cordyceps* [145] (Hypocreales: Cordycipitaceae), *Metharizium* (Hypocreales: Clavicipitaceae), and *Isaria* (Hypocreales: Cordycipitaceae). Delattre and Jean-Bart [146] were the first to evaluate different strains of entomopathogenic fungi on *C. sordidus*. Of the several researches conducted, many have tested the potential of EPFs to manage d *C. sordidus* in the laboratory [147–156] and field [152, 153, 157–161].

Although different results were obtained based on the strains of *B. bassiana* and *M. anisopliae* used, concentration, method of application or delivery of the fungi, integration with other management options, environmental conditions and even length of storage, *B. bassiana* has shown strong potential to manage *C. sordidus*. Table 2 shows some tested isolates, concentrations, and their effects on *C. sordidus*. With particular interest on the high potential of enhancing efficacy of entomopathogens by using conventional host plant traps and pheromone traps [152, 156, 161]. Compared to pseudostem traps, incision traps on corms attract more weevils and therefore when treated with *B. bassiana*, caused higher mortality. Generally, indigenous strains are more pathogenic to adult weevils [149, 152, 164] and those on insect body are more persistent than those on substrates. Commonly used substrates are bagase rice, bagase beans, maize grains, soil, vegetable oil, although higher efficacy was recorded on maize and soil formulations. An inportant factor that makes *B. bassiana* an effective biological control agent for *C. sordidus* is that infected living adult weevils can spread and transmit the infection to other healthy weevils. In the laboratory, Omukoko [155] recorded 24–26% mortality of weevils as a result of such transmission of infection. According to Fancelli *et al.* [148], several factors account for variation of effectiveness of *B. bassiana* in the field, such as strain, variety of crop, climate, and method of application of fungus. In addition to traps, *B. bassiana* can be integrated with pesticides. Sirjusingh *et al.* [159] reported that reduced doses of pesticides combined with fungal spores resulted in higher mortality of adult weevils but not a better development of mycosis a synergistic effect. Similarly, Okolle and Lombi showed that combination of imidacloprid and commercial *B. bassiana* (Botanigard®) reduced weevil damage in the field.

Besides the direct use of *B. bassiana* as biopesticide, these entomopathogenic fungi and other non-pathogenic fungi provide bioprotection services to banana and plantain plants. By performing this role, they are referred to as endophytes—microscopic organisms that colonize plant tissues internally for at least part of their life cycle to form mutualistic relationships with their host plants including antagonism to pests and diseases. According to Tixier *et al.* [165], bioprotection of banana vitro plants with endophytic fungi such as non-pathogenic *Fusarium oxysporium* is an innovative

Table 2. Different entomopathogenic fungi isolates evaluated for the management of *C. sordidus*, their concentration, and major results obtained.

Fungal isolate/strain	Concentration used	Key results	Reference
B. bassiana (G41) (indigenous)	3.4×10^{11}spores/mL (in the laboratory) 1.25×10^{8} spores/mL (in pot experiment) 3.54×10^{12} spores/mL in the field applied on top soil around plants	Significantly more pathogenic to the adult weevils than foreign isolates Reduced hatchability of eggs Significantly reduced weevil population and damage and persistent on soil	[152]
B. bassiana (CG1013)	2.6×10^{8} spores/mL (in the laboratory)	Caused mortality of 90–93.7% to adult weevils	[162]
B. bassiana	$3.1–3.2 \times 10^{9}$ conidia/g cultured on cracked maize grains (in the laboratory)	Caused adult weevil mortality of 80% in 30 days and a 20% drop in mortality after 180 days in storage	[163]
Cordyceps bassiana (Cb171, Cb190, Cb174)	LC_{50} of 6.4×10^{6} and 5.4×10^{6} conidia/mL (in the laboratory and field) at LT_{50} of 9.49–9.55 days	In the laboratory: Caused adult mortality of 77.5–80.2%. Reduced weevil population by 48.5% and with over 50% mycosis of trapped weevils in the field	[145]
M. anisopliae (Ma148)	LC_{50} of 8.6×10^{6} conidia per mL at LT_{50} of 12.6 days	Virulent and causing 76.9% adult mortality in the laboratory. Reduced weevil population by 48.5% with over 50% mycosis of trapped weevils in the field	
B. bassiana (G41)	3×10^{9} conidia/g in the lab and on-station field	Weevils captured from plots where conventional traps were treated with G41 showed significantly higher percent mycosis (25.9%) compared to those where the fungus was applied around banana mats	[156]
B. bassiana (ICIPE 237, M353, M207)	10^{8}, 3×10^{8}, 10^{9} in the laboratory	Pathogenic to adult weevils although virulence was significantly different with different concentrations. ICIPE 237 as the most virulent at LC_{50} of 4.22–8.89 × 108 conidia/mL and LT_{50} of 31–51 days	[154]
B. bassiana (ICIPE 273, ICIPE 645, ICIPE 281)	1×10^{8} in the laboratory	All were pathogenic although ICIPE 273 was the best causing weevil mortality of 50–70% in 40 days	[155]
B. bassiana (CNPMF 407, CNPMF 218, CNMPF 416)	1×10^{8} in the laboratory and then in the field	In the laboratory, these isolates caused about 96% mortality. In the field, CNMPF 218 was most efficient causing about 20% mortality leading to 40% reduction in weevil population size after 12 months	[148]

option for controlling *C. sordidus*. The role of different isolates of non-pathogenic fungi as endophytes that can manage banana borer weevils have been studied [166–168]. Dubois *et al.* [169] evaluated 15 strains of *Fusarium* spp. isolated from corms and roots of banana plants. The endophytes from roots that were inoculated into plants caused higher mortalities (up to 50%) of *C. sordidus* eggs with strains V2w2 and V5w2 as the best. In the field, Ochieno [170] showed that *C. sordidus* has low preference for plants inoculated with two endophytes—*F. oxysporum* V5w2 and *B. bassiana* G41 while corm damage was low for *F. oxysporum* V5w2-treated plants. Paparu *et al.* [171] showed that isolates of *F. oxysporum* served as endophytes with root colonization highest in inoculated plants, with better colonization and significant weevil damage for V5w2 isolate. In addition to their pathogenicity, some *Metarhizum* spp. and *Beauveria* spp. have evolved as characteristic root endophytes [142, 169, 172–174], facilitating nutrient absorption, and offering substantial protection against tunneling insect pests. In a screen house experiment, 15 days after weevil infestation and endophyte of plants, Akello *et al.* [175] recorded 53.4–57.7% mortality of adult weevils as a result of *B. bassiana* infection resulting in reduction of plant damage by 29.1–62.7%. They also reported that this endophyte can colonize tissue cultured plants for at least 4 months after inoculation. In addition, in a screen house experiment, Akello *et al.* [176] at inoculation rate of 1.5×10^{7} conidia/mL for 2 h and 2 weeks after larval infestation, reported that *B. bassiana* endophyte significantly reduced larval survivorship (23.5–88.9% mycosis) resulting in 42–86.7% reduction of plant damage.

Entomopathogenic nematodes

Among the most promising biocontrol agents of root pests are the soil-borne entomopathogenic nematodes (EPNs) in the families Steinernematidae and Heterorhabditidae that are obligate parasites of arthropods [177–180]. The third juvenile stage is the "infective juvenile" that is free-living in soil and used in biocontrol [181, 182]. Entomopathogenic nematodes are soil-dwelling and naturally occurring organisms but they can be isolated from soils and produced commercially [183, 184]. EPNs have received attention as biocontrol agents because of their wide host range, ability to kill host rapidly, can easily be mass produced and applied, and long-term efficacy with no adverse effect on the environment [185, 186]. Generally, once EPN infective juveniles get into an insect's hemolymph, it releases highly specialized symbiotic bacterium (*Xenorhabdus* spp.) found only in EPNs. The bacterium multiplies rapidly to kill the insect, making the cadaver more suitable for nematodes to feed on.

Most studies on the use of EPNs to manage banana borer weevils are laboratory based with few in the field. Laboratory trials demonstrated susceptibility of adult *C. sordidus* to *Neoaplectana carpocapsae* [187, 188] while Figueroa [189], mentioned the genus *Steinemema* as a potential biocontrol agent for *C. sordidus*. These nematodes have demonstrated efficacy to destroy a wide range of soil-borne and stem-boring insects that attack agricultural crops [190–192]. Treverrow and Bedding [193] developed a delivery system that involved releasing nematodes into conical shaped cuts made in residual rhizomes that developed mutualistic relationships with plants, and act as antagonists to pests and diseases. Although these nematodes reduced weevil numbers, they were not economically competitive with pesticides [194]. Bortoluzzi *et al.* [195] tested the pathogenicity of different isolates of EPNs (at 100 infective juvenile (IJ)/cm^2 applied on cut pseudostem placed in plastic containers in the laboratory) from the families Heterorhabaditidae and Steinernematidae. They recorded variations in mortality (0–36.7% within 2–7 days) of adult *C. sordidus* with highest mortality from *Heterorhabditis* spp. isolate IBCBn40. Combination of EPNs with insecticide (carbofuran) did not affect viability of IJ, although it caused reduction in infectivity.

In another laboratory experiment, Amador *et al.* [196] evaluated the susceptibility *of C. sordidus* adults and larvae to *H. atacamensis* isolate CIA-NEO7. No mortality on adult weevils while different concentrations of 100, 500, and 1000 IJ per larva were significantly different from the control and resulted to LD_{50} of 52 IJ/larva. When larvae were in the corm, LD_{50} increased to 375 IJ/larva and weevil larvae within banana corms infected with EPN had 80% mortality 10 days after inoculation at 1000 IJ/larva. Kutnjem *et al.* [197] tested local isolates of *Heterorhabditis* and *Steinernema* and showed that mortality of *C. sordidus* adults of the different isolates ranged from 3 to 40% after 12 days after treatment while that for *C. sordidus* larvae was 84% at concentration of 40 IJ/larva 2 days after treatment. Furthermore, weevil larvae were more susceptible to isolates of Heterorhabditidae family. Mwaniki [198] reported that the local EPNs isolated do not infect adult weevils and therefore no mortality was observed. Although the entire test EPNs caused more than 90% mortality for weevil larvae, *S. carpocapsae* was the most virulent at 300, 400, and 500 IJ/larva. In a commercial banana plantation, Schmitt *et al.* [199] applied dose of 5×10^6 IJ/m^2 onto split pseudostems and pseudostem stumps as a baiting technique and recorded 70% mortality of adult *C. sordidus* recovered from the traps 7 days after treatment. Application of EPN to pseudostem traps resulted to significantly greater control of weevils than application on the soil around banana.

Entomopathogenic bacteria and viruses

We found only two researches that evaluated the effect of entomopathogenic bacteria. Kaya *et al.* [151] found that the entomopathogenic bacteria *Serratia marcescens* caused mortality of third instars of *C. sordidus* at LT_{50} of 2.8 days although it did not kill adults even at 10 times the concentration applied for larvae. About 0.24 ppm for *Bacillus thuringiensis* crystal (CRY6A) toxins resulted in 50% mortality (LD_{50}) of neonate larvae [200].

Predators and parasitoids

Banana and plantain farms usually have microenvironments that favor the survival of a complex of natural enemies especially predators. These microenvironments include residues (harvested pseudostem stumps, cut pseudostems, pruned leaves, and patches of weeds), parts of living plants (within old leaf sheaths), and drainage channels in the case of large commercial plantations. Most of these areas have also been reported as most preferred sites/habitats of *C. sordidus* [201]. Several researches were conducted to search for indigenous and exotic predators and parasitoids, as well as testing their abilities to manage borer weevils under laboratory and field conditions [37, 106, 201–209]. Many of these have resulted to a listing of potential predators/parasitoids and few studies actually tested the impact of these predators/parasitoids for managing the pest. Table 3 lists different potential predators of *C. sordidus*, of which most are Coleopterans (beetles), Hymenopterans (ants), and Dermapterans (earwigs). A case has also been mentioned of a vertebrate (the cane toad) that eats adults of *C. sordidus* [210] while upon dissection of toads collected from the fields in Martinque, Okolle [4] also recovered dead weevils from their stomachs.

As far as parasitoids are concerned, attempts to rear them from *C. sordidus* life stages have all been negative. Traore [211] tried to use carrot weevils (*Listronotus oregonensis* and *L. texanus*) parasitoid (*Anaphes sordidatus*) but failed. The parasitoids laid eggs into eggs of *C. sordidus* but no emergence of larvae or adult parasitoids were recorded. After thorough field searches, Tinzaara and

Table 3. List of potential predators of the banana borer weevil (*C. sordidus*).

Predator	Order (Family)	Observations	Reference
Plasius javanus *Plasius laevigatus* *Hololepta* spp. *Belonochus ferrugatus* *Leptochirus unicolor* Earwigs Ants	Coleoptera (Histeridae) Coleoptera (Staphylinidae) Coleoptera (Staphylinidae) Dermaptera (Forfuculidae, Labiidae, Chelisochidae) Hymenoptera—Formicidae (Ponerinae, Formicinae, Ponerinae, Amblyoponinae, Formicinae, Myrmicinae, Dolichoderinae)	Usually found within mats and residues. For the non-social predators, Dermaptera was most abundant. Among ant species, the Formicinae, Ponerinae, and Myrmicinae were most widely distributed and abundant. Chelisochidae consumed more of C.sordidus eggs while larvae and adults of *P. javanus* consumed much of larvae and pupae of the pest	Abera-Kalibata *et al*. [204]
Pheidole spp. *Odontomachus troglodytes*	Hymenoptera—Formicidae (Myrmicinae) Hymenoptera—Formicidae (Formicinae)	In the laboratory, eggs, larvae and pupae of the pest reduced by ants only at low densities. In the field, at full crop cycle, ants reduced densities of the weevil eggs only.	Abera-Kalibata *et al*. [202]
Ants	Hymenoptera—Formicidae (Dorylinae, Dolichoderinae, Formicinae, Myrmicinae, Ponerinae)	*Pheidole* spp., *Lepisiota* spp & *Paratrechina* spp. were most abundant in the field. *O. troglodytes* and *Pheidole* spp. were most significant in consuming the pest immature life stages in plants and residues. These ants could remove 33–68% eggs from naturally infested corms	Abera-Kalibata *et al*. [203]
P. javanus Earwigs Ants	(Histeridae) Dermaptera (Chelisochidae) Hymenoptera—Formicidae (Dolichoderinae, Formicinae, Myrmicinae, Ponerinae)	The ant species *Myopopone castanea* (Ponerinae) seen attacking the weevil larvae in crop residues in the field. *P. javanus* larvae and adults were best in consuming the pest larvae and pupae (53–87% while the Chelisodid earwig was the best for eggs (42%)	Hasyim *et al*. [207]
Eutachia pulla *Euborellia annulipes* *Dactylosternum abdominal*	Coleoptera (Tenebrionidae) Dermaptera (Anisolabidae or Caroinophoridae) Coleoptera (Hydrophilidae)	These predators reduced weevil eggs population in the field at a rate of between 20.5–44%	Koppenhofer [37]
Pheidole megacephala *Tetramorium guineense.* *Azteca* spp. *Solenopsis geminata* *Wasmannia auropunctata* *Pheidole fallax*	Hymenoptera—Formicidae (Myrmicinae) Hymenoptera—Formicidae (Myrmicinae) Hymenoptera—Formicidae (Dolichoderinae) Hymenoptera—Formicidae (Myrmicinae) Hymenoptera—Formicidae (Myrmicinae) Hymenoptera—Formicidae (Myrmicinae)	*P. megacephala* and *T. guineense* had best results in the field. *P. megacephala* caused 55% reduction of weevil population and 65% reduction in corm damage. *T. guineense* causes 83% mortality of weevil larvae in low infested fields and 67% in highly infested fields	Castineiras *et al*. [206]

Continued

Table 3. Continued.

Predator	Order (Family)	Observations	Reference
Axinidris spp.	Hymenoptera—Formicidae (Dolichoderinae)	Intercropping banana with maize had clear effects on ant abundance, which was negatively correlated with *C. sordidus* damage for Myrmicinae and positively correlated for Formicinae	Dassou *et al*. [106]
Camponotus spp.	Hymenoptera—Formicidae (Formicinae)		
Odontomachus mayi	Hymenoptera—Formicidae (Myrmicinae)		
Paratrechina longicornis	Hymenoptera—Formicidae (Formicinae)		
Pheidole spp.	Hymenoptera—Formicidae		
Tetramorium spp.	(Myrmicinae)		
Odontomachus spp.	Hymenoptera—Formicidae (Formicinae)	Most common predators were *Odontomachus* and Dactylosternum.	Tinzaara and Karamura [18]
Dactylosternum spp.	Coleoptera (Hydrophilidae)	*Euborellia, Labia* and *Thyreceophalus* were most promising as they consume more eggs, larvae and pupae	
Euborellia spp.	Dermaptera (Anisolabididae)		
Odontomachus spp.	Hymenoptera—Formicidae (Formicinae)		
Labia spp.	Dermaptera (Spongiphoridae)	*Labia* spp. had highest searchability based on consumption of hidden eggs in the laboratory	
Thyreceophalus spp.	Coleoptera (Staphilinidae)		
Bufo marinus—Cane toad	Anura (Bufonidae)	Feeds on the weevil in the field	Pinese *et al*. [210]
Dactylosternum abdominal	Coleoptera (Hydrophilidae)	These generalist predators used volatiles from fermented banana pseudostem tissues as the major chemical cue when searching for prey	Tinzaara *et al*. [209]
Pheidole megacephala	Hymenoptera—Formicidae (Myrmicinae)		
Euborella annulipes	Dermaptera (Anisolabididae)		
Thyreocephalus interocularis	Coleoptera (Staphilinidae)		

Karamura [18] did not find any parasitoids of the pest and no parasitism for *C. sordidus* eggs, larvae, and pupae. Koppenhofer [212] did not also find any parasitoids from all the indigenous natural enemies recorded, which is probably due to the cryptic nature of weevils (the larvae and pupae hiding and found deep into pseudostem or corm). In Indonesia (one of the native places of the weevils), Hasyim *et al*. [213] obtained phorid parasitoids from both larvae and pupae of *C. sordidus* although parasitism was very low. Abera-Kalibata *et al*. [204] and Hasyim *et al*. [207] not only reported no parasitism of weevil eggs and larvae, but also recovered phorids (*Megaselia* spp.) and drosophilids from larval rearings, which most likely were scavengers.

Resistant varieties and genetic modification

According to Seshu-Reddy and Lubega [214] and Haubruge and Amichot [46] host-plant resistance is a potential long-term intervention to control banana borer weevils on small-scale farms within an integrated pest management perspective. Although the use of synthetic pesticides is usually effective, most pesticides easily become ineffective due to the quick development of resistance by the weevils or insects in general [4, 61, 215]. Several researches have therefore focused on breeding programs that develop cultivars that are resistant to pest through identification of resistant cultivars, resistance mechanisms, crossing, and possibilities of engineering genes that are deleterious to weevils ([16, 214–231].

Screening for resistant varieties

Kiggundu *et al*. [231] highlighted the importance of identifying resistance and its incorporation into breeding programs for improving the available germplasm. Generally, field screenings using damage scores resulting from weevil attacks are used to identify resistant or susceptible cultivars. Although plantains and East African Highland bananas have been found to be more susceptible to weevils, there are some exceptions and variations. In India, two plantain cultivars (Karumpoovan and Poozhachendou) and in Cameroon the plantain Kedong Kekang were found to be resistant [216, 232]. Table 4 shows the response of different genomic groups to banana borer weevil. Ocan *et al*. [225] reported that genotypes with "B" genome are more tolerant to banana weevils than genotypes with only "A" genomes, while Mesquita *et al*. [240] mentioned that AA genome progenitor *M. acuminata* is more susceptible to weevils than BB progenitor *M. Balbissiana*. Many hybrids have been reported display high levels of

Table 4. Different Musa genomic group response to banana borer weevils.

Genomic response	Reference	Country
AAB Susceptible	Haddad *et al*. [233]	Venezuela
	Seshu-Reddy and Lubega [214]	Kenya
	Speijer *et al*. [234]	Kenya
	Gold *et al*. [235]	Uganda
	Fogain and Price [216]	Cameroon
	Musabyimana [236]	Kenya
	Kiggundu *et al*. [231]	Uganda
	Teixeira de Oliveira [227]	Brazil
AAB Resistant	Irizarry *et al*. [237]	Pueto Rico
	Kiggundu *et al*. [231]	Uganda
ABB Susceptible	Viswanath [238]	India
ABB Resistant	Seshu-Reddy and Lubega [214]	Kenya
	Speijer *et al*. [234]	Kenya
	Gold *et al*. [235]	Uganda
	Ortiz *et al*. [218]	Nigeria
	Musabyimana [236]	Kenya
	Abera [239]	Uganda
	Rwekika [220]	Tanzania
	Kiggundu *et al*. [231]	Uganda

Source: Kiggundu *et al*. [231] with additions and light modifications by the present authors

resistance [222, 226, 227, 231], but few were susceptible. Some varieties reported with high resistance to the weevil are Yangambi Km5 (AAA), Sanna Chenkadali, Sakkah, Senkadali, Elacazha, Njalipoovan, Pisang Awak (ABB), Kivuvu (ABB), FHIA 03, TMBx612-74, TMBx6142-1, TMB2x8075-7, Long Tavoy, Njeru, Muraru, Calcutta-4 (AA-wild type), Bluggoe, *M. balbissiana*, Cavendish (AAA), Gros Michel (AAA), Kayinja (ABB), Ndiizi (AAB), Kisubi (AB), FHIA-03 (AABB), Nalikira (AAA-EA), Prata Ana (AAB), Pacovan (AAB), M3, M4, M5, M6, M8, CRBP-60, CRBP-39, CRBP-969, Karumpoovan, Poozhachendu, Kedong Kekang [4, 215, 216, 222, 226, 227, 231, 241].

Resistance mechanisms

Kiggundu *et al*. [231] described three possible resistance mechanisms in insect-host plant relationships:

i. Non-preference or antixenosis—ability to locate and accept to feed or oviposit on a particular plant.
ii. Antibiosis—adverse, usually biological effects to the insect trying to utilize a plant species.
iii. Tolerance—a variety being able to survive a pest population that would otherwise be destructive to another susceptible variety.

Mesquita [240] found that banana weevil preferred particular cultivars for feeding and oviposition, and that susceptibility of *Musa* spp. varies both between and within genomic groups. In most studies, there was no case that supported antixenosis as the main resistance mechanism for *C. sordidus* because weevils were found to be able to search, locate and oviposition on both susceptible and resistant varieties and there was no significant difference on egg laying on/into the varieties [127, 218, 220, 226, 239, 242]. Rwekika [220] found that salicin (a phenolic glucoside) and glucose were significant feeding attractants to banana weevils with higher levels found in susceptible cultivars as compared to the resistant ones. Similarly, Ndiege *et al*. [243] identified another chemical (1,8-cineole) as the active component of volatiles released from some susceptible varieties. Results from laboratory studies have shown that the main mechanism for resistance of *Musa* spp. to the pest is antibiosis [17, 217, 231, 239]. In these studies, egg/larval mortality was lowest on resistant varieties and highest on susceptible ones. In some, the developmental cycle from ovipostion to adult emergence is lengthened in resistant varieties. Corm hardness and latex quantity/viscosity were reported to have negative effect on egg hatchability and survivorship of first intars [231].

Engineering of chemicals deleterious to the weevils

There exist genetically modified *Musa* species but the use and acceptability or adoption of these transgenics has been very controversial especially for biosafety concerns and these are usually resistant to different diseases and nematodes that attack bananas and plantains but not *C. sordidus*. However, researches have identified and tested the toxicity of phytocystatins on banana borer weevil larvae [200, 223, 224, 228, 244]. These researches showed natural susceptibility of *C. sordidus* to some identified phytocystatins. Phytocystatins are proteinaceous inhibitors of plant origin that inhibit specifically cysteine proteases by forming tight irreversible bonds, thus preventing the hydrolysis of proteins by proteases. According to Kiggundu [224], cysteine protease inhibitors (cystatins) are expressed in response to wounding and insect herbivory and they form part of the native host plant defense system. Cysteine proteases are enzymes usually found in the mid-gut of coleopteran insects such as *C. sordidus* with an important role of breaking down dietary proteins. Any substance that inhibits the functioning of proteases has direct effect on protein digestion of the insect, resulting in protein deficiency and affecting insect development and survival.

Montesdeoca *et al*. [244] found that neonate larvae of *C. sordidus* fed on diets containing 0.2% (w/w) of soybean Kunitz trypsin inhibitor (STI) experienced lower survival rates and displayed significant reduction in growth. Larvae reared on this STI diet also had reduced trypsin activity. Kiggundu [224] reported that phytocystatins resulted to 60% reduction in body weight of young larvae and reduction in growth rate. Elyeza [200] showed that 50% mortality (LD_{50}) of neonate larvae was observed at 0.24 ppm and 0.15 ppm for *Bacillus thuringiensis* crystal (CRY6A) and *Carica papaya* cystatin (CPCYS) toxins, respectively. This research also resulted in a modified artificial diet that could sustain 70% of *C. sordidus* as well as using the diet to establish efficacy of these recombinant proteins, which is a basis for developing transgenic bananas with improved resistance against borer weevil.

Conclusions, gaps/limitations, and recommendations for further research

Generally, banana or plantain corm borer weevil (*C. sordidus*) is the most reported economically important insect pest on *Musa* species.

Use of synthetic pesticides

- It is the oldest method for *C. sordidus* control/management and many different active ingredients have been used with varying results (moderate to excellent).
- *C. sordidus* has been reported in most areas that *Musa* species are grown and it is commonly managed using synthetic pesticides (mainly of organophosphorus, carbamate, phenylpyrazole, and neonicotinoid groups).
- Pesticides that are normally not registered for use in banana or plantain farms are often misused.
- There is a need to periodically assess common pest management practices performed by farmers, especially in developing countries. In addition, detailed studies are required to elucidate on the effects of pesticides on non-target beneficial organisms within *Musa* spp. agroecosystems.
- In spite of their effectiveness, weevils develop resistance to these pesticides, which leads to ecological backlash coupled with potential harmful effects on the environment and human health, which has necessitated the search for sustainable alternatives to synthetic pesticides. Nonetheless, these alternative management options may also have their limitations that require further research.

Cultural methods

This first line of defense is widely applied in farms (e.g., small-scale, commercial, or agro-industrial), and it is commonly integrated and compatible with other options. Some practices such as mulching can attract or increase activitiy of pest while others can have very slow action, and others such as classical trapping can be labor-intensive. Correspondingly, evidences from field experiments showed that the decrease of *C. sordidus* in living mulch plots does not affect corm damage and fruit yield.

- Clean planting materials (the case of tissue culture) are scarce and relatively expensive for small-scale farmers, which makes its adoption difficult. Hence, many of small-scale farmers are adopting macro-propagated plants while some still rely on pared/unpared traditional suckers. More research is needed to evaluate/compare effects of different clean planting materials on *C. sordidus* damage and yield of *Musa* spp. under field conditions.
- Fallowing and rotation are other common practices with large commercial or agro-industrial plantations, but land scarcity also highlight the need for more research to ascertain the impact on bananas and plantains.
- Cover crops such as *Mucuna* spp. and *Brachiara decumbens* provide useful ecosystem service that attracts hervivorous insects and generalist predators, but detailed studies are necessary to provide insights into the impact of such mulches on weevil population dynamics, corm damage, plant growth, and yield.
- Trapping is an old method with small-scale farmers easily applying the classical split pseudostem traps while large commercial farms are vest with pheromone traps.
- Pheromone-baited traps are very effective in capturing adult banana borer weevils and are very compatible. However, the effectiveness varies with several factors such as exposure to sunlight, relative humidity, temperature, season (wet or dry), irrigation, farm site, rainfall, trap size, trap type (ramp or pitfall), trap color (white, brown, mahogany brown, black, yellow) duration of trapping, trapping material, pheromone release rate, release distance, trap location, and farm management practices [122]. The number of traps per hectare depends on the purpose (detection, monitoring, or mass trapping). Range of 4–25 traps per hectare has been used with a maximum mean trap catch per day of about 60 weevils. Research results also showed variations between the number of weevils caught in traps and the damage on plants. Despite the effectiveness and compatibility, there is need to search for more allelochemicals against borer weevils and testing the effects when these and pheromones are combined. In addition, the synergistic effects of combining male aggregation pheromone with female sex pheromone are other areas that could be exploited.

Use of plants with insecticidal properties

- Several plant species have shown potentials to manage *C. sordidus* with most tested families as Solanaceae, Asteraceae, and Meliaceae, but commercial products have been developed only from Meliaceae (e.g., neem plant).
- Effects on *C. sordidus* are mainly of non-mortality type (oviposition deterrence, feeding deterrence, repellency, reduction in size and weight, and decreased haemocyte counts for weevils).
- Only *Piper* spp. was found to have high mortality for adult weevils while only *T. diversifolia* and *Phytolacca* spp. caused high mortality to eggs and larvae of *C sordidus*.
- *Piper* spp. and *S. aromaticum* elicited very high repellency—Class IV according to the International Organization for Biological Control (IOBC) standard.

- Most of these potential botanical pesticides do not cause direct mortality to adults and many with high potentials have not been formulated as commercial products, and therefore not readily available for use by farmers.
- Although there are claims that these botanical pesticides are environment-friendly, much still needs to be done to test their effects on non-target beneficial organisms in banana or plantain agroecosystems. Additionally, it is important to test the potencies of extracts from the same plant species from different agroecological zones. Also, more effort should be put to develop, test, and register commercial products from plants with proven potencies.

Entomopathogens

- The fungus *Beauveria bassiana* and nematodes *Steinernema* spp. or *Heterorhabditis* spp. are widely used as effective entomopathogens for *C. sordidus* larvae and adults.
- Like non-pathogenic fungi such as *F. oxysporum* and *B. bassiana* also plays an important role as fungal endophyte.
- Even though there are several strains of these entomopathogens, relevant commercial products are scarce. Also, adult weevil mortality caused by these pathogens is more effective and enhanced only when they are applied on pseudostem traps, disc-on-corm traps, and corm incisions or when they are integrated with pheromones.
- Effectiveness of these fungal pathogens in the field varies with the fungal strain, culture medium, variety of *Mus*a spp., climate, method of application, and duration of storage.
- EPNs have broad pest-insect host range, rapidly kill insect host, have active searching behavior using olfactory cues, can be mass produced in vivo and in vitro, safe for non-target organism with strong potential for use in integrated pest management [245]. EPNs can penetrate *C. sordidus* larval galleries and easily reproduce, while weevil mortality varies with the EPN species and concentration.
- It is necessary to formulate commercial products from the most effective EPN strains and test their efficacies under field conditions, and determine their compatibility with commercial pesticides.

Predators and parasitoids

- Although successful parasitoids have not been identified, generalist predators have been recorded with many having limited potential to manage the pest, and only toads were found consuming adult weevils.
- Some ant species (*Odontomachus* spp., *Tetramorium* spp., and *P. megacephalia*) were found with best predation results for eggs, larvae, and pupae of *C. sordidus* in the field. Abera-Kalibata [202] reported that ants are not able to provide economic control of banana weevils under field conditions.
- Larvae and adults of the histerid beetle—*P. javanus* was reported as the best predator on larvae and pupae of the pest.
- Earwigs also reduce the population of *C. sordidus* by consuming eggs, larvae, and pupae.
- Most parasitoids and predators find it difficult to locate larvae and pupae that are usually found within tunnels in residues that are usually blocked with frass or escavated plant materials. In addition, parasitism of weevil eggs is difficult since eggs are usually laid in holes in corms that are covered by the female weevils after oviposition.
- Most of these generalist predators can also feed on non-target beneficial soil-dwelling organisms.
- More searches for indigenous parasitoids and predators are needed to evaluate establishment and effectiveness of predators like *P. javanus* to other areas and to determine the impact of other management options like entomopathogens, synthetic, and botanical pesticides on natural enemies.

Resistant varieties and genetic modification

- Generally, most plantains, East African Highland bananas and hybrids are resistant to borer weevils with antibiosis as the main resistance mechanism.
- Most susceptible varieties found with high quantities of glucose, salicin, and 1,8-cineole.
- Corm hardness and latex quantity/viscosity as factors that negatively affect egg hatchability and survivorship of first instars.
- Some phytocystatins were reportedly deleterious to larvae of the pest.
- Find ways to engineer effective phytocystatins to develop resistant cultivars to borer weevils.

Acknowledgement

Dr. Woin Noe, the Director of IRAD/CARBAP Cameroon for permission to use all documents having information on banana borer weevil's research. Dr. Sama Lang Patrick, soil scientist and former Chief of CARBAP Antenna, Ekona, SW Region Cameroon, for the useful discussions and provision of some literature. The members of pestnet@yahoogroups.com (www.pestnet.org) for the information exchanges and supply of literature. The administration of PRAM Martinique for hosting the first author in 2009 and therefore facilitating access to numerous literatures on *C. sordidus*. Dr. Christopher Mbua Parr, former Research Manager, Cameroon Development Corporation (CDC) Banana plantation for providing useful literature as well as working with the first author on many field experiments.

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