BIOLOGY, ECONOMIC IMPACT AND POTENTIAL FOR SEMIOCHEMICAL-BASED CONTROL OF MAHOGANY SHOOTBORER, *HYPSIPYLA ROBUSTA* (MOORE) (LEPIDOPTERA: PYRALIDAE), AFRICAN RHINOCEROS BEETLE, *ORYCTES MONOCEROS* (OLIVIER) (COLEOPTERA: SCARABAEIDAE) AND MAIZE WEEVIL, *SITOPHILUS ZEAMAIS* MOTSCHULSKY (COLEOPTERA: CURCULIONIDAE)

by

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BASED CONTROL OF MAHOGANY SHOOTBORER,HYPSIPYLA ROBUSTA(MOORE)

(LEPIDOPTERA:PYRALIDAE),AFRICAN RHINOCEROS BEETLE,ORYCTES

MONOCEROS,(OLIVIER)(COLEOPTERA:SCARABIDAE) AND MAIZE WEEVIL

SITOPHILUS ZEAMAIS(MOTSCHULSKY)(COLEOPTERA CURCULIONIDAE)

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Abstract

In tropical Africa, many insects in the orders Lepidoptera and Coleoptera are of major economic importance, including the Mahogany shootborer (MSB), *Hypsipyla robusta* (Moore), the African rhinoceros beetle (ARB), *Oryctes monoceros* (Olivier), and the maize weevil (MW), *Sitophilus zeamais* Motschulsky. This thesis reviews their life history, economic impact and the potential for their semiochemical-based control.

The MSB attacks many mahogany spp. in the Meliaceae, destroying the terminal shoot of the main stem. It restricts the re-establishment of mahogany plantations and reduces the size of merchantable timber, thereby adversely affecting revenue from timber exports. After the identification of the MSB sex pheromone, pheromone-baited traps may be used to detect and delineate MSB populations, monitor MSB population densities, and eradicate populations in small plantations and nurseries through mass trapping of males. Ideally, semiochemical research should be accompanied by investigations to identify and properly manage mahogany varieties non-susceptible to the MSB.

The MW is a stored product pest, infesting grains and cereal, particularly maize. MW feeding reduces the nutritive value of grain and/or renders it unfit for human consumption. With the bulk of the produce stored on small farms, modern procedures, such as X-ray or monitoring for feeding sounds, to detect MW infestations are unavailable and too expensive for the private farmer. Pheromone-based traps, in contrast, should be affordable for the majority of African farmers to reliably detect infestations and assess the efficacy of control measures.

The ARB attacks and defoliates coconut, *Cocus nucifera* L., oil palm, *Elaeis guineensis* Jacq. and date palm, *Phoenix dactylifera* L. The degree of defoliation is

correlated with losses in frond production and revenue. Of the three insects analyzed in this study, the ARB has the greatest potential for semiochemical-based control. The pheromone has already been identified and could become part of a highly effective, multiple tactic control strategy that combines (among others) proper phytosanitation and pheromone-based trapping for elimination or for exposure to viral or fungal diseases and their subsequent spread throughout ARB populations.

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Table of Contents

Table

List of Figures

1.0. General Introduction

The Lepidoptera and Coleoptera are economically important insect orders in sub-Saharan Africa. Vast areas of farm land, forest and natural pasture in many African countries have been devastated by insects from these two orders (Kumar, 1984).

Representatives of the Lepidoptera with serious economic impact on forest resources include stem and shoot boring insects, such as mahogany shootborers (MSB), *Hypsipyla* spp. These moths have restricted the establishment and cultivation of many tropical trees of the Meliaceae (Entwhistle, 1967; FAO, 1958; Whitmore, 1983). Mahogany spp. in the Meliaceae are most valuable export commodities in West Africa (Wagner *et al.*, 1991).

Coleopteran insects are widespread and associated with many crop trees, often attacking trees in all developmental stages (FAO, 1991). The African rhinoceros beetle (ARB), *Oryctes monoceros* (Olivier), for example, attacks oil, coconut and date palm, causing revenue losses. The maize weevil (MW), *Sitophilus zeamais* Motschulsky, attacks grains and cereal which are grown throughout Africa, and constitute the staple food in 50% of the African countries (FAO, 1991). Agricultural production in Africa does not suffice to feed the population (FAO, 1991). Self-sufficiency in food provision can be achieved by increasing production and reducing pre- and post-harvest losses to insects. Insects often degrade the nutritive value of food. Weevils, for example, feed mainly on the carbohydrates of maize grains, thereby removing considerable caloric value and leaving little for human consumption. Wood losses to insects approximate 19 million cubic meters per year in Ghana alone (FAO, 1988). In view of Africa's natural resource-based economy, losses to insects of this magnitude are not tolerable.

Pesticide-based pest management practices are increasingly unacceptable in many societies. As social pressures mount, innovative ideas and tactics are required to reduce the economic impact of insect pests, while maintaining the integrity of natural ecosystems. Semiochemicals have proven to be useful as economically viable tools for the monitoring and control of many different pest insects (Ridgeway *et al.*, 1990).

This thesis describes the natural history and economic impact of important lepidopteran and coleopteran insect pests in Africa. The MSB, ARB and MW - although not ecologically related - were selected for this study because they are excellent representatives of groups of insects that interfere with the production of most valuable crops in agriculture (ARB) and forestry (MSB) and degrade or destroy food stored for human consumption (MW). Ultimate objective of the study is to explore which insect or group of insects has the greatest potential (and should receive research support) to be controlled by semiochemicals.

The choice of these three insect pests was based on the consideration of the two major industries where insect pests are of economic importance, namely forestry and agriculture. The third consideration was based on storage of produce from these industries. Forest products have mostly been preserved by chemical treatment and used without any major concerns. However, about seventy percent of agricultural produce is stored for better market and future consumption during lean seasons. While in storage, the produce is inflicted with considerable damage as a result of insect infestations causing loss of produce and revenue to the industry. *S. zeamais* is one of the major storage insects pests of economic importance representative of storage insects.

The economy of most African countries is based on agriculture and forestry. Therefore, mahogany shootborer *Hypsipyla* species, African rhinoceros beetle, *O. monoceros* and maize weevil, *S. zeamais* are representative of the major insect pest orders in the above industries. Their semiochemical based control will pave the way for managing other major insect pests of these orders with semiochemicals.

2.0. Mahogany shootborer, *Hypsipyla robusta* (Moore)

2.1. Introduction

Mahogany shootborers (MSB), *Hypsipyla* spp. (Lepidoptera:Pyralidae) are serious pests of Meliaceae plantations worldwide. Their damage restricts the establishment and cultivation of many tropical plants in the Meliaceae (Entwhistle, 1967; Whitmore, 1983). This problem is endemic throughout the tropics especially in Africa, where the most important species is *Hypsipyla robusta* (Moore).

2.1.1. Geographical Distribution

H. robusta is widely distributed throughout West and East Africa wherever Meliaceae plantations occur (Entwhistle, 1967), but has not been reported in northern or southern Africa. In West Africa, *H. robusta* attacks moist semi-deciduous forests (Hall and Swaine, 1981).

H. grandella (Zeller) is found throughout Central and South America (except Chile), on many Caribbean islands and in the southern tip of Florida (Entwhistle, 1967).

2.1.2. Host

Throughout the tropics, MSB attacks meliaceous trees in various economically important genera, such as Spanish cedar, *Cedrela* L., African mahogany, *Khaya* spp. (Figures 1 and 2), mahogany, *Swertenia* spp., and others of similar economic status such as *Toona*, *Entandrophragma*, *Lovoa*, *Carapa* and *Guarea* (Grijpma, 1976; Pennington, 1981). In Africa, African mahogany, *Khaya ivorensis*, is most frequently attacked. It

Figure 1. One-year old African mahogany, *Khaya ivorensis*, the host plant of mahogany shootborer, *Hypsipyla robusta,* in Ghana.

Figure 2. A plantation of African mahogany, *Khaya ivorensis,* in Ghana.

Figure 3. Dead apical shoot of a three-year old *Khaya ivorensis* after *Hypsipyla robusta* attack.

generally produces new leaves once a year (Newton *et al.*, 1992), with intraspecific variation in the timing of leaf fall, fruiting and flushing (Grijpma, 1974).

Selective extraction of trees and general deforestation have severely depleted populations (Lamb, 1966; Betancourt, 1987; Collins, 1990; Foster, 1990). As a result of this "genetic erosion" of forest trees, African mahogany is most commonly seen as a short, highly branched tree or bush (Pennington and Styles, 1975). *Hypsipyla* damage to trees is inflicted by the larval stage hollowing out the soft shoots, often causing shoot mortality (Figure 3) and reduction in growth height (Newton *et al.*, 1992).

2.1.3. Biology

H. robusta and *H. grandella* occupy similar ecological niches, but *H. grandella* biology has been more intensively studied (Roberts, 1968; Wagner *et al.*, 1991). The life cycle is completed in one to two months, depending on climate and food availability (Beeson, 1941; Roovers, 1971; Morgan and Suratmo, 1976). While female *H. grandella* oviposit during the evening or early morning, egg hatching occurs at night (Wilkins, 1972; Holsten, 1977). A female lays one to seven eggs singly or in clusters of three to four on or near leaf axils, scars or veins (Ramirez Sanchez, 1964; Grijpma, 1971; Roovers, 1971). She may repeat oviposition over a period of about six days, laying a total of 200-300 eggs (Grijpma, 1971; Samaniego and Sterringa, 1976). Eggs hatch after three days. Neonates move towards new shoots and burrow into the stem or leaf midrib through the leaf axil (Newton *et al.*, 1992). After two to four days the larvae re-emerge and migrate to the terminal shoot of the main stem (Ramirez Sanchez, 1964; Roovers, 1971). About three days after stem penetration, the larvae cover their entrance holes with a web inter-mixed with plant particles and frass (Grijpma, 1974). Most of the larval stage is spent boring in the primary stem and feeding on pith. In *H. grandella* there are five to six larval instars lasting 30 days (Ramirez Sanchez, 1966; Roovers, 1971), whereas in *H. robusta* there are four (Roberts, 1968; 1969) or three to six instars (Atuahene and Souto, 1983). After a pupal period of eight to ten days, adult *H. grandella* emerge during sunset with a common sex ratio of 1:1 (Roovers, 1971; Sterringa, 1973; Sliwa and Becker, 1973). The pupal period of *H. robusta* lasts eight to ten days (Wagner *et al.*, 1991). Adults emerge during the onset of the rains, and diapause during the dry season (Roberts, 1968). There are six to nine generations per year in the high forest zone and three to five generations per year in the Savannah region due to a longer dry period.

2.2. Economic Impact

In Africa, MSBs are among the most important pests that attack mahogany plants (Atuahene, 1970). *H. robusta* is the major pest of Meliaceae, such as *K. ivorensis* (Atuahene and Ofosu-Asiedu, 1974). Up to 100% attack or infestation has terminated projects of mahogany plantation (Newton *et al.*, 1993). In Ghana, for example, up to 100% of *K. ivorensis* stands are commonly affected by *H. robusta* (Atuahene, 1972). In Nigeria, several economically important trees are attacked, including Gedu Nohor, *Entandrophragma angolense* (Roberts, 1961); Omu, *E. Candollei*; Sapele, *E. cylindricum* (Roberts, 1969); mahogany, *Khaya nyassica* (Browne, 1968); African mahogany, *K. senegalensis* (Roberts, 1969); Crabwood, *Carapa grandiflora* (Jones, 1959); Crabwood, *C. procera* (Jones, 1959); African walnut, *Lovoa trichiloides* (Jones, 1959); Cedida, *Pseudocedreal Kotshyi* (Browne, 1968), and mahogany, *Swietenia macrophylla* (Jones, 1959). Young trees depending on the apical meristem for growth are particularly affected by MSB damage. Attacks up to the pole stage are most critical from a silvicultural point of view (Kalshoven, 1926; Lamb, 1966; Grijpma, 1974).

Even though shootborer attack rarely kills mahogany trees, economic losses due to reduced growth can be considerable. Shootborer attack reduces the merchantable size of timber, thereby affecting revenue from timber exports throughout the world. General wood loss to insects in Ghana is estimated at around 19 million cubic meters per year (FAO, 1988). In Africa's natural resource-based economy, this loss is very significant (Wagner *et al.*, 1991). However, accurate estimates of losses due to shootborer attack are very difficult to obtain (Atuahene, 1970; Newton *et al.*, 1993).

2.3. Review of Previous and Current Control Measures

Previous attempts to reduce shootborer infestations to acceptable levels, employing biological, chemical and silvicultural control methods (Grijpma, 1973, 1974; Whitmore, 1976) have largely failed. Biological control of *H. robusta* has been considered with over 50 species of predators and parasitoids, including 17 braconids, nine chalcids, one elasmids, one eulophid, one eurytomid, 13 ichneumonids, two trichogrammids, two tachinids, one nematode, and two coleopterans (Rao, 1969; Rao and Bennett, 1969; Newton *et al.*, 1993). Although parasites have been reared from *H. robusta* pupae, infestation rate of 1% could not exert appreciable control. Fewer natural enemies have been recorded for *H. grandella* in the new world, including five braconids, two ichneumonids, two trichogrammids, two tachinids and one mermithid (Rao and Bennett, 1969). As yet, natural enemies in both the old and new world failed to control

Hypsipyla populations (Newton *et al.*, 1993). Prohibitive cost of rearing *Hypsipyla* as host for natural enemies (Newton *et al.*, 1993) further impeded inundative release of biological agents for *Hypsipyla* control (Newton *et al.*, 1993).

Several modifications in the silviculture of meliaceous trees have been investigated to minimize shootborer attack. These include shading crop trees, different varieties, adjusting planting density and selection for resistant trees. Provenance trials with *Cedrela odorata* in Africa resulted in reduced shootborer attacks particularly in areas where the tree is not native (Burley and Nikles, 1973; Nikles *et al.*, 1978). Resistance in the Meliaceae may be evident by antibiosis, tolerance or antixenosis (Grijpma, 1976). In *Toona ciliata* var. *australia*, antibiosis was expressed through a chemical (cedrelone) which interfered with moults and pupal wing development (Grijpma and Roberts, 1975) in *H. grandella.* Tolerance is evident in pronounced vigor, the ability to produce a single strong leader after attack and increased growth rate (Newton *et al.*, 1993). However, to date there is no evidence of resistant strains within susceptible species based on tolerance and antixenosis (Newton *et al.*, 1992).

In the past, two-weekly applications of insecticidal lead arsenate, DDT and parathion for shootborer control have failed due to inaccessibility of larvae (Grijpma, 1974; Allan *et al.*, 1976; Wagner *et al.*, 1991). Control measures were abandoned due to low success and high costs (Dourojeanni, 1963). In 1966, the above chemicals together with metasystex, endrin, aldrin, parathion were investigated for MSB control. Although application of DDT every six weeks during the oviposition period (Ramirez Sanchez, 1966) was effective, it is impractical on economic and ecological grounds (Wilkins *et al.*, 1976). Systemic insecticides have been successful in shootborer control. Carbofuran was most effective providing complete control for 340 days with low phytotoxicity and high growth rates of treated trees (Wilkins *et al.*, 1976). Controlled-release systemic insecticide application may be economically and ecologically advantageous (Allan *et al.*, 1976). However, the effect of soil and climatic conditions may alter the effectiveness of treatments (Wilkins *et al.*, 1976). Uptake and translocation of insecticide during the dry season, for example, may be ineffective (Grijpma, 1974). Systemic insecticide may also be detrimental to other insects, particularly parasites and predators.

Silviculture, biological and chemical controls by themselves failed to reduce shootborer damage to economically tolerable levels, but may become effective when combined in integrated pest management (IPM) programs. Moreover, semiochemicals often play a role in modern IPM and ought to be identified and tested against mahogany shootborer. The sex pheromone of female *H. grandella* is unknown, but candidate pheromone components of *H. robusta* have been determined (Bosson and Gallois, 1982).

2.4. Potential for Pheromone-based Control

2.4.1. Laboratory Rearing

Mass rearing of the target insect facilitates accumulation of pheromone extract and is often the prerequisite for pheromone analysis. *H. robusta* was successfully reared in Ghana for 3 consecutive generations (Atuahene and Souto, 1983). Field collected larvae were placed on artificial diet and kept under controlled environmental conditions with temperature ranging between 26-28° and relative humidity averaging 80 ± 5%. The diel photoperiod was approximately 12h:12h light:dark. Eggs hatched after 3-5 days. Larvae went through 5-6 instars and formed prepupal cocoons after 21 days. The pupal stage lasted about 9 days. Adults eclosed (sex ratio 1:1) between 17:00 and 22:00 with peak emergence between 18:00 and 19:00 GMT. Males and females were fed a 5% sugar solution soaked in cotton wool. Mated females laid an average of 50 eggs (11-65 eggs). Females separated from males laid infertile eggs.

2.4.2. Pheromone Analysis

Pheromone glands of calling virgin female *H. robusta* were extracted in hexane, and the EAG-active fractions analyzed by capillary gas liquid chromatography (GC) and GC-mass spectrometry (Bosson and Gallois, 1982). The analysis revealed the presence of three major components: *Z*9-tetradecenyl acetate (*Z*9-14:OAc; 30%); *Z*9,*E*12-tetradecadienyl acetate (*Z*9,*E*12-14:OAc; 50%); and Z11-hexadecenyl acetate (Z11:16 OAc; 20%). The structures of these components were assigned by GC retention time and mass-spectrometric comparison with synthetic standards. Double bond geometry was determined by comparative EAG response to standards.

2.4.3. Bioassay of Candidate Pheromone Components

Field testing of synthetic candidate pheromone component of *H. robusta* has not been reported. However, a laboratory-based olfactometric assay of a 7:3 mixture of *Z*9,*E*12:14 OAc and *Z*9-14:OAc elicited a complete behavioral sequence, ending in a display of genitalia comparable to that elicited by an extract of the female pheromone gland (Bosson and Gallois, 1982). To determine which of these candidate pheromone components are indeed part of the *H. robusta* pheromone blend, thorough field experiments need to be conducted. Subsequently, potential of these components for control of shootborer infestation in Meliaceae plantations (Rao and Bennett, 1969; Holsten and Gara, 1974) need to be assessed. Preliminary analyses of female *H. grandella* sex pheromone components are reported in the Appendix.

2.4.4. Pheromone-based Monitoring

Following the identification of *H. robusta* or *H. grandella* sex pheromone, development of pheromone-based trapping becomes possible. There are two main objectives: 1) detecting the presence and distribution of a population; and 2) monitoring changes in population densities and economic impact.

Factors which influence the efficacy of pheromone-baited traps to monitor MSB populations and need to be tested include: 1) dose, ratio and release rate of pheromone components (Sanders, 1981; McLaughlin and Heath, 1989; Jansson *et al.*, 1990, 1992); 2) effectiveness of the pheromone blend at various population densities (Sanders, 1992); 3) species specificity of the pheromone blend (Pivnick *et al.*, 1988; McLaughlin and Heath, 1989); 4) lure type (Sanders and Meighen, 1987); 5) longevity of the lure over the trapping period (Ramaswamy and Carde, 1982; Jansson *et al.*, 1990; Sanders, 1992); 6) trap type (Lewis and MaCaulay, 1976; Houseweart *et al.*, 1981; Ramaswamy and Carde, 1982; Angerelli and McLean, 1984; Sanders, 1986, 1992; Jansson *et al.*, 1992; Polavarapu and Seabrook, 1992); 7) trap position (Lewis and MaCaulay, 1976; Howell *et al.*, 1990; Sanders, 1992); 8) trap density (Housewearth *et al.*, 1981); 9) repellency of killing agents or dead insects within the trap (Sanders, 1986); 10) effect of weather on trap catches (Sanders, 1981; Knight and Croft, 1987; Pitcairn *et al.*, 1990); and 11) ease of management and the cost of monitoring (Sanders, 1992).

Major use of pheromone-based monitoring for MSB would be the quantitative prediction of population densities. The most common method of determining the relationship between numbers of male moths captured in traps and population density is to correlate numbers of captured males and sampled numbers of other stages of the moth population (Sanders, 1988). By correlating population densities determined from samples of immature stages with numbers of insects captured in pheromone-baited traps a predictive tool may be developed which is less costly or less labor intensive than other sampling methods. Which immature stage of MSB may be best correlated with numbers of trap-captured males needs to be determined following pheromone identification and formulation. Prospects of monitoring MSB populations with pheromone-baited traps are good because successful pheromone-based monitoring has been developed for many insects, including the eastern spruce budworm, *Choristoneura fumiferana* (Clemens) (Ramaswamy *et al.*, 1983; Allen *et al.*, 1986; Sanders, 1988); the gypsy moth, *Lymantria dispar* (L.) (Granett, 1974); the potato tuberworm, *Phthorimaea operculella* (Zeller) (Shelton and Wyman, 1979); the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Daterman, 1980; Shepherd *et al.*, 1985); the tobacco budworm, *Heliothis virescens* (F.) (Tingle and Mitchell, 1981); the orange tortrix, *Argyrotaenia citrana* (Fernald) (Knight and Croft, 1987); the mullein bug, *Campylomma verbasci* (Meyer) (Smith and Borden, 1990; McBrien *et al.*, 1994); the western spruce budworm, *Choristoneura occidentalis* (Freeman) (Sweeney *et al.*, 1990); the pickleworm, *Diaphania nitidalis* (Stoll) (Elsey *et al.*, 1991); the blue berry leaftier, *Croesia curvalana* (Kearfoot) (Polavarapu and Seabrook, 1992); and grape vine moth *Argyrotaenia pulchellana* (Haw.) (Faccioli *et al.*, 1993).

2.4.5. Pheromone-based Mating Disruption

Broadcast release of synthetic sex pheromone can disorient male moths in their search for females. Mating is thus disrupted. Mating disruption has been used successfully to control several species of insect pests (Campion *et al.*, 1989). Possible underlying mechanisms are: 1) false trail following: the disruptant released from many point sources is attractive to the male; 2) camouflage: the female's plume becomes indistinguishable from the intermingling plumes of the background formulation; and 3) neurophysiological effects: the male response declines or the threshold of response rises after exposure to pheromone. When a partial blend of the pheromone is used additional possible mechanisms are: 1) sensory imbalance in males caused by peripheral input from the disruptant component resulting in the male's inability to distinguish the female emission as the natural pheromone blend (Bartell, 1982); 2) alteration of optimal ratio causing males to be preferentially attracted to a blend containing an unnaturally high amount of the disruptant component (Bartell, 1982); and 3) neurophysiological effects in response to partial or off-ratio blends (Bartell, 1982). Assessment of pheromone-based mating disruption for MSB control should be initiated at the onset of MSB flight, usually coincident with the beginning of the rainy season. Nurseries with highly susceptible young seedlings or plantations with equally susceptible 2-3 year old trees constitute ideal experimental sites. In these sites, ten plots of 2 hectares (ha) each and > 500 m apart should be selected, in which 5 plots should remain untreated controls and 5 plots be treated with pheromone. Synthetic pheromone may be released from Polyvinyl chloride (PVC) (Daterman, 1974) or from Hercon laminated tape (HLT) (Hercon Division, Health-Chem. Corp., New York) dispensers suspended from trees at 25 or 50 m intervals and releasing a total of 3.5 - 5 g of pheromone per hectare. This dose and dispenser spacing was effective for mating disruption of the western pine shootborer, *Eucosma sonomana* (Sartwell *et al.*, 1983). However, in the tropics with possible photo- or thermodegradation of pheromone, a higher dose may be required. To monitor "performance" of pheromone, additional dispensers may be placed apart from the test site and retrieved biweekly to assess quantity and quality of pheromone contents.

Assessment of efficacy should be based on numerical change in damage before and after treatment. In addition, field assessment of MSB mating disruption may be conducted by placing into treatment blocks delta traps (Phero-Tech Inc.) baited with synthetic pheromone or equally attractive unmated females. Lack of MSB capture in these traps will demonstrate successful disorientation of mate seeking MSB males. The program should be in continuous operation for 2-3 years to ultimately mitigate MSB damage to mahogany trees. The development of semiochemical-based mating disruption of MSB in Africa is timely due to ineffectiveness of conventional control measures to achieve MSB control. However, possible effects of climatic conditions on the stability and longevity of pheromone lures will need to be investigated. Hot weather, e.g.. may increase pheromone release rates. As a result, dispensers may have to be replaced frequently generating extra cost for dispensers and labour. This may increase the overall expense of the programme, but low cost of pheromone and cheap labour in Africa make mating disruption of MSB an appealing IPM tactic.

Comparatively, pheromone-based mating disruption of insect pests is more applicable for protection of agricultural rather than forest crops. In forestry, the programme may need to be carried out over years to protect a particular stage of trees, and investments for mating disruption programmes may only be recovered decades later, whereas in agriculture short rotation times of crops typically produce annual or even biennial revenue. In the long run, mating disruption of lepidopteran forest pests may help to minimize loss of revenue to insects. In Ghana, for instance, about 19 million cubic meters of lumber is lost to insects which equals the value of logs harvested.

The implementation of mating disruption programmes in forestry is non-affordable for private land owners in Africa. Therefore, potential sources of funding need to be explored or provided by governments of various African countries. Egypt as the first African country to implement a mating disruption programme, solicited funds from international donor agencies such as the Overseas Development Agency (ODA) and chemical companies such as Imperial Chemical Industries (ICI). Therefore, other African countries should emulate to mobilize funds for MSB mating disruption (research) programmes.

Regular pheromone-based control or monitoring reduces the use of chemical pesticides which may be applied only when indicated by significant numbers of moths captured in pheromone-baited traps, thus lowering costs for overall MSB management. Mating disruption is a viable alternative to conventional insecticides in terms of cost and efficacy and may allow eradication of pesticide-resistant pest population (Carde and Minks, 1995).

2.4.6. Pheromone-based Mass Trapping

Pheromone-based mass trapping of moths in limited areas is feasible (Borden, 1993) and may be applicable for MSB. Small isolated MSB populations could possibly be eradicated by persistent mass trapping, especially in nurseries and small plantations commonly found in Africa. To effectively control MSB by mass trapping, all MSB pheromone components need to be identified through basic analytical research. Efficacy of mass trapping may depend on optimization of trap design and density, and pheromone formulation.

Unitrap traps (Phero Tech Inc.) may be usable for mass trapping MSB males. This non-sticky reusable trap ($11.99 Can.) could be baited with the pheromone lure and provided with an insecticidal agent to retain captured insects. Efficacy of mass trapping with Unitraps may be assessed by mark-release-recapture experiments with laboratory-reared insects. A reduced ratio of wild (unmarked) males captured over time would be indicative of successful MSB mass trapping. Correlating numbers of MSB larvae and/or pupae per area with MSB males captured in pheromone-baited traps would further allow monitoring of possible reductions in damage as a result of adult mass trapping.

Currently, mass trapping of males is a preferred tactic used by the United States Department of Agriculture to eradicate localized gypsy moth populations (Kolodny-Hirsch and Schwalbe, 1990). If current populations are too high, they may be sprayed with insecticides prior to implementation of pheromone-based mass trapping.

3.0. African Rhinoceros Beetle, *Oryctes monoceros* (Olivier)

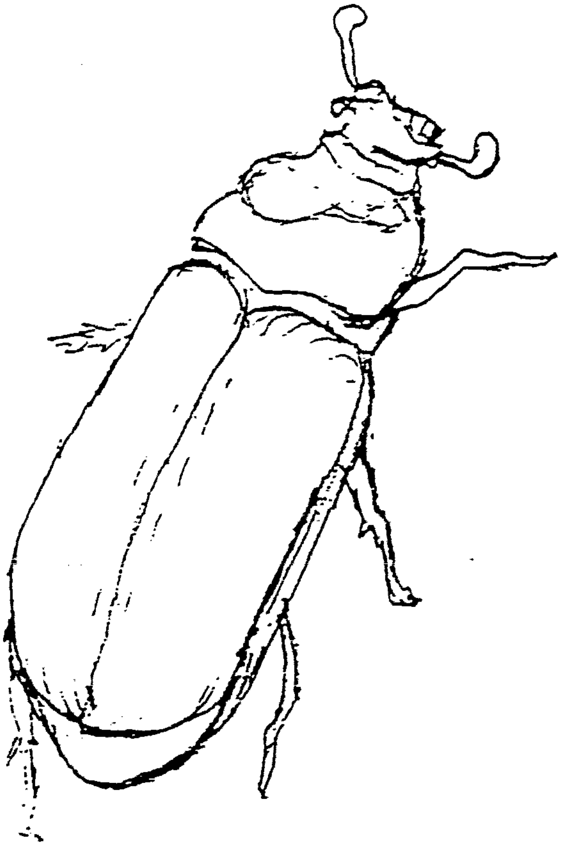
3.1. Introduction

The African rhinoceros beetle (ARB), *Oryctes monoceros* (Olivier), (Figure 4) is one of the most destructive pests of commercial coconut, *Cocus nucifera* L., oil palm, *Elias guineensis* Jacq., and date palm, *Phoenix dactylifera* L., in Africa (Hill, 1983). Adult ARB attack these hosts in decreasing order of preference (Bedford, 1980) and feed inside unopened fronds, while the larvae develop in decomposing organic matter (Bedford, 1980). Beetle attack kills young palms, provides entry holes for lethal pathogenic diseases and other destructive insects, damages inflorescences and reduces photosynthetically active foliage, ultimately diminishing revenue of oil and coconut production (Mariau *et al.*, 1981).

3.1.1. Geographical Distribution

ARB is endemic to the coconut and oil palm growing regions of East and West Africa (Bedford, 1980). It is mostly found in the palm and coconut belt along the west coast of Africa. Within this region, countries with documented ARB damage include Sierra Leone, Ghana, Nigeria and Ivory Coast (Bedford, 1980). In East Africa, serious ARB damage has been reported in Tanzania (in the Tanya region) and Kenya (Purrini, 1989). Lack of systematic insect surveys in Africa, however, make it difficult to obtain precise information of past and current ARB geographical distribution.

Figure 4. Male and female African rhinoceros beetle, *Oryctes monoceros.*



3.1.2. Biology

In West Africa, wet and dry climatic seasons (April to September and November to March, respectively) affect ARB populations (Hoyt, 1962). Female ARB oviposit in moist, decomposing vegetable matter (Bedford, 1980). Female fecundity averages 90-100 (Kalschoven, 1951) and 25 eggs (Bedford, 1980) under natural and laboratory conditions, respectively. Spermatozoa remained viable in the spermatheca for three months (Hurpin and Fresneau, 1973). Eggs are whitish brown, tough and 3-4 mm long (Nirula, 1955). Hatching occurs after 7-18 days (Hurpin and Fresneau, 1973). Larvae develop preferably in decaying coconut palm stems, stumps, compost heaps, sawdust and refuse dumps (Bedford, 1980). Larval development takes 80-130 days in nature (Nirula, 1955) and 107 days under specific laboratory conditions (Hurpin and Fresneau, 1970). Formation of a roomy cocoon (Bedford 1975, 1976) mostly in the soil and sometimes in standing rotten coconut trunks (Gressitt, 1953 and Bedford, 1980) initiates a non-feeding prepupal period of about 8 days (Bedford, 1980). The prepupa moults into a yellow brown pupa 4-5 cm in length (Hurpin and Fresneau, 1970). Emergent adults leave the chamber after one to four weeks (Hurpin and Fresneau, 1970). The entire development from egg to adult lasts 4-9 months, averaging 6 months (Hurpin and Fresneau, 1973).

The beetle lives mainly in the breeding sites and spends relatively short periods in the crown of palms, for feeding. Longevity of ARB approximates 3 months.

3.2. Economic Impact

Coconut, oil and date palm are of superior economic importance. As nontraditional cash crops (FAO, 1989), their parts/produce are of multiple use for

Africans. Fronds provide roofing material for indigenous thatched houses, coconut oil is used for cooking, and palm oil for both cooking and soap manufacturing. Africa significantly contributes to the world's production and export of palm produce. In 1990, for example, Africa produced $240x10^3$ metric tonnes of copra, $667x10^3$ tonnes of palm kernels and $1,767x10^3$ tonnes of palm oil, amounting to 0.05%, 0.19% and 0.15%, respectively, of the world's total production.

Devastating impact of ARB on coconut, oil and date palm has been recognized since the early 1900's when attempts were made to use natural enemies for ARB population suppression (Hoyt, 1959). As trade in copra, coconut oil, palm oil, kernel and date palm increases, losses attributed to ARB become less tolerable. ARB attack on coconut palms reduced yield and occasionally caused death of trees (Zelazny, 1979). Beetle-damaged inflorescences were linked to crop losses (Young, 1975). Defoliation of central palm crowns ranging from 0-100% was correlated with nut losses of 1-23%, respectively (Bedford, 1980). Because young trees have time to recover from foliage loss, defoliation of young trees has a lesser effect on yield than defoliation of older and mature trees (Liau and Ahmad, 1991). Simulating defoliation and crop loss in Malaysia, 50% defoliation in one-, two- and eight-year old palms resulted in crop losses of 30-40%, 12-24% and < 4%, respectively (Liau and Ahmad, 1991). Although foliage losses were quantitatively higher in one- and two-year old trees than eight-year old trees, young trees had about 1.5 years to recover from the stress prior to nut production (Liau and Ahmad, 1991). Defoliation induced hermaphroditism and failure of fruit bunch production (Liau and Ahmad, 1991). According to defoliation levels palms regrew fronds at the expense of fruit bunch production (Liau and Ahmad, 1991).

Correlating defoliation and crop production and simulating resulting losses in foreign currency for young palms bearing 15 tonnes of free fruit bunches (ffb)/ha/annum, 30-76% of crop loss over two years after defoliation corresponded to revenue loss of US $425-1,080 per hectare (Liau and Ahmad, 1991). Produce per hectare and total hectarage of palms grown in Africa is not known, but total revenue losses due to ARB defoliation must be substantial.

3.3. Review of Previous and Current Control Measures

Control of ARB has been based on sanitation burning, pesticide application, biological agents and physical and biotechnical practices (O'Connor, 1953; Vestal, 1956).

3.3.1. Sanitation Burning

Sanitation burning of decaying palms destroys potential oviposition sites (Huger, 1973) and is commonly implemented. For instance, large scale sanitation burning in Western Nigeria and Sierra Leone was practiced to control beetle infestation (Hoyt, 1962), but ARB damage to oil palm was not significantly reduced. Instead, it adversely affected predators and parasites which would have contributed to limiting ARB infestation. Applicability of sanitation burning in general may depend on climatic and vegetative conditions of the geographical location.

3.3.2. Pesticide Applications

Attempts to control ARB larvae and adults with insecticides have met with limited success and proved to be costly (Huger, 1966). For example, the application of

0.001 percent gamma-benzene hexachloride (BHC)[1] was effective against adults and larvae (Nirula, 1951). Also 0.01 percent aldrin has been successfully used for the treatment of infested compost (Kuran and Pillai, 1964), and in Ghana, an application of a five percent DDT preparation gave good protection to young palms against ARB adults and larvae (Frohlich and Rodewald, 1970). However, BHC and DDT accumulate in mammalian tissues and are toxic to humans (Kumar, 1984). Insecticidal drenches of breeding sites and routine application of granular insecticides, such as Carbofuran, to the leaf axil of young oil palms is frequently recommended (Ho and Toh, 1982). These are considered economically viable (Liau and Ahmad, 1991) but present environmental and health risks (Bedford, 1980).

3.3.3. Use of Natural Enemies

Important natural enemies of ARB include predatory insects, parasitic nematodes and pathogens (Bedford, 1980). Parasitic nematodes, such as *Oryctonema genitalis* (Poiner, 1970), *Rhabditis adenobia* (Poinar, 1971) and *Thelastoma pterygoton* (Poinar, 1973) occur in ARB populations of the Ivory Coast (Poinar, 1973) but their effect on ARB and its reproductive potential is not known.

Natural diseases played an important role in limiting ARB population densities (Bedford, 1980). They include *Rickettsiella* spp., and *Helicosporidium* spp., neogregarine *Ophxyocystis oryctesi*, protist *Oryctospora alata* and seven microsporidians in the genera *Nosema*, *Toxoglugea* and *Pleistophora* (Purrini, 1989; Purrini and Kohring, 1986, 1987). Unfortunately, field applications of these microorganisms have been very difficult. Use

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[1] The actual amount of active ingredient per hectare of plant or infested compost could not be determined from the references.

of the pathogenic fungus *Metarrhizium anisopliae* for ARB control required its spread in compost heaps. Fungus-infested ARB larvae leave the compost and die, dried up and mummified by fungal mycelia which eventually form an extracuticular crust for release and wind dispersal of spores. Pupae and adults may need to be repeatedly infected (Nirula, 1955). Fungal development is favored by 70% humidity and temperature of about 27° (Bedford, 1980), as is typical for the African climate.

Introduction of *Baculovirus oryctes* (Purrini, 1989) constitutes a successful attempt of ARB control with biological agents. Release of *B. oryctes* into ARB populations in Vuo-Grezani and Magawa (Tanzania) exemplifies classical biological control of ARB in East Africa (Purrini, 1989). The virus was first observed in body cell nuclei of ARB larvae (Huger, 1966) and was later found in nuclei of midgut epithelium of larvae and adults (Hurpin, 1969; Payne, 1974), and in adult ovarian sheath and spermatheca (Monsarrat *et al.*, 1973). In adult ARB, *B. oryctes* multiplies in nuclei of midgut epithelial cells. The gut eventually fills with disintegrating cells and virus particles (Huger, 1973 and Monty, 1974). Infected adults become virus reservoirs through the release of the virus with feces, contaminating the habitat (Zelazny, 1972). Up to 0.3 mg of virus/day may be produced in the feces of an infected adult (Monsarrat *et al.*, 1973).

Different strains of the virus with different pathogenicity have been recorded from the Philippines, Malaysia, Western Somoa and Seychelles. The major difference between isolates was found to be the presence or absence of small pieces of DNA varying between 30 and 150 bases in size (Crawford *et al.*, 1986).

Although insect viruses have been successful in augmentative biological control (Entwhistle and Evans, 1985), they, unlike most classical insecticides, do not immediately kill the target insect. Genetically engineered, non-occluded baculioviruses (rather than wild type viruses) reduced the time by 30% from beetle infection to death, lowered food consumption of beetles by 75% (Hammock *et al.*, 1993), and were implemented for ARB control in Tanzania (Purrini, 1989). Costs for release of virus-infected ARB adults are low compared to overall costs caused by the beetle (lost revenue, expenses for sanitation control, replanting and quarantine procedures) (Purrini, 1989). Improved formulation of non-occluded viruses for general use is, however, critical (Hammock *et al.*, 1993).

3.3.4. Mechanical and Silvicultural Methods

Traditionally, ARBs have been removed from feeding holes in young palms with hooked or barbed wires, but often only after damage had been inflicted (Gressitt, 1953; McKenna and Shroff, 1911). ARBs were also cut out of holes, usually causing further damage and wounds, attracting more ARBs or secondary pests such as palm weevils (*Rhynchophorus)* (Bedford, 1980). In addition, traps consisting of heaps of compost or wood (sometimes treated with *M. anisopliae*) (Plank, 1948) or split palm logs laid on the ground (Gressitt, 1953) were employed. However, these methods are laborious, expensive, unpopular and frequently ignored.

Vegetative barriers were employed to interfere with the beetle's perception of palm crowns sought for feeding, to conceal breeding sites, and to provide a physical flight barrier. Rotting oil palm trunks were covered with dense ground vegetation (Wood, 1976), concealing potential breeding sites and reducing the frequency of attack on young palms. These cover plants provided effective and inexpensive means of controlling the pest during the critical early period of palm replanting. In the Ivory Coast the legume *Pueraria javanica*, for example, was used to cover rotting palm trunks in clearcuts for 7-9 months, thereby eliminating ARB breeding sites and greatly reducing attacks on young coconuts (Julia and Mariau, 1976).

Currently, low and monocultural undergrowth such as cassava, *Manihot esculenta* (RANTZ), is maintained to conceal possible breeding sites.

3.4. Potential for Semiochemical-Based Control

3.4.1. Previous Attractants for *Oryctes* spp.

Several compounds, including ethyl chrysanthemate (rhinolure) and ethyl dihydroxychrysanthemate (chrislure) have been recommended as lures for trapping *Oryctes* (Barber *et al.*, 1971; Vander Meer *et al.*, 1979). Ethyl dihydroxychrysanthemate in metal vane traps attracted *O. rhinoceros* (Bedford, 1980). Commercially available and cheaper ethyl chrysanthemate was almost as effective (Maddison *et al.*, 1973) but overall both compounds were only moderately attractive (Vander Meer *et al.*, 1979; Young, 1986). In Nigeria, ethyl chrysanthemate was indeed ineffective in attracting ARB in coconut palm plantation with known ARB infestations (Asiagbonhi, personal communication)[2]. Moreover, in the Ivory Coast, ethyl chrysanthemate was not competitive with synthetic ARB pheromone in luring beetles to buried bucket traps (Gries *et al.*, 1994).

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[2] **Asiagbonhi, Integrated Pest Management Centre, Palm Project, Ubiaja Edo Estate, Nigeria.**

3.4.2. Pheromone Analysis

Oryctes adults are gregarious with more than one beetle attacking a given palm at the same time, while a neighboring tree is not attacked (Gressitt, 1953; Bedford, 1980). Congregation of adults in decaying palm trunks to mate, and co-occurrence of both single and multiple pairs of adults in the same breeding site (Zelazny and Alfiler, 1991) suggested that ARB is attracted to host kairomones and/or employs either an aggregation pheromone, a sex pheromone or both.

For pheromone analysis, male and female ARB were collected in oil palm plantations 40-50 km northeast of Abidjan, Ivory Coast, and were placed together or separately in modified Nalgene desiccators (Oehlschlager *et al.*, 1992). An aspirator-driven, charcoal-filtered airstream was maintained through the desiccators, collecting ARB-released volatiles on Porapak Q. Volatiles were eluted from Porapak Q with pentane, concentrated by distillation and subjected to gas chromatographic (GC) analysis with flame ionization (FID) and electroantennographic detection (EAD). Of two male specific compounds, the early eluting compound elicited antennal responses from both male and female beetles. Coupled GC-mass spectrometry (MS) of the antennally-active compound indicated ethyl 4-methyloctanoate. Identical retention and mass spectrometric characteristics as well as comparable antennal activity of synthetic and male-produced ethyl 4-methyloctanoate confirmed the structural identification (Gries *et al.*, 1994).

3.4.3. Field Testing of the Identified Candidate Pheromone

Field testing of synthetic ethyl 4-methyloctanoate was conducted in a 3-4 year old oil palm plantation at the La Me Research Station, Ivory Coast. In 1992, weekly removal of adult ARB in these plantations had revealed 9 beetles per hectare per month. The experiment employed 15 liter plastic bucket pitfall traps (Oehlschlager *et al.*, 1993) in randomized complete blocks with traps at 27 m intervals and blocks 27-500 m apart, and tested attractiveness of the candidate pheromone released at 3 doses (0.3, 3 or 30 mg/day, at 25°C). Petrolatum on the inner bucket surface below side entrances and a wet sponge treated with 3% Thiocylam-hydrogenoxalate in water at the bottom of buckets retained captured beetles. While the known non-beetle produced attractant ethyl chrysanthemate (Bedford, 1973) released at 30 mg/day did not attract any ARB, ethyl 4-methyloctanoate released at 30 mg/day attracted 6 males and 5 females in 9 days. Gries *et al.* (1994) hypothesized that capture rate of ARB might be improved by addition of as yet unknown plant volatiles, and refinement and optimization of pheromone formulation, trap design and placement.

3.4.4. Potential for Pheromone-based ARB Control

The development of semiochemicals (Nordlund, 1981) as tools for insect pest management in the past 3 decades has been encouraging. Although pheromone-based control has enormous potential for suppression of beetle population, its adoption at the socio-economic level generally requires a necessity for insect control, unavailability of alternative control methods, efficacy, market size, patentability, regulatory registration, institutional arrangements and effective cooperation between the government and private sector (Kydonieus and Beroza, 1982).

Necessity for ARB control is self-evident. With copra, kernel and palm oil being major export items of the African economy, and ARB being one of the most destructive insect pests in commercial oil, coconut and date palm in Africa, ARB control is warranted. Other control methods, such as silvicultural practices and the use of Baculovirus as biological agents, are available and may be implemented together with pheromone-based control.

Market analysis indicates potential for use of synthetic insect pheromones in Africa (Jackson, 1989). With the expansion of the agricultural sector, especially the production of oil palm and copra, and the development of insect resistance to conventional insecticides, the market share of pheromones in Africa may further increase.

To avoid "piracy", new discoveries are often patented. For the same reason, use of the Asian rhinoceros beetle, *Oryctes rhinoceros*, pheromone in Malaysia has been patented (Gries *et al.*, 1994). Patent protection is a key feature of pheromone development and requires good cooperation between member countries and the chemical company producing and developing the pheromone. Formal registration of pheromones may be granted after completion of toxiological tests and field trials demonstrating efficacy. ARB pheromone may be registered upon successful demonstration of its efficacy and reliability in pheromone-based ARB management systems.

Multinational agrochemical companies such as Imperial Chemical Industry (ICI) and Mayor and Baker (M&B), have already collaborated in African agrobased research with institutions like the Overseas Development Natural Resources Institute (ODNRI), the Overseas Development Agency (ODA) and the Food and Agricultural Organization (FAO) of the United Nations. ICI and ODNRI collaborated in the pink bollworm, *Pectinophora gossypiella* (Saund) pheromone project in Egypt. Thus, ODNRI has already had considerable experience in the application of pheromone and may be willing already had considerable experience in the application of pheromone and may be willing to enter into a joint ARB pheromone development programme with African governmental organizations involved in ARB management.

Efficacy, the final socioeconomic requirement for adopting pheromone-based ARB control, may be best demonstrated in a mass trapping program.

3.4.5. Mass Trapping

Mass trapping is a viable tactic to suppress pest populations (Borden, 1993). It has been well developed and fine tuned for ambrosia beetle management on the west coast of North America (Borden, 1990). Its greatest advantage is a built-in monitoring feature for population densities (Kydenieus and Beroza, 1982). Efficacy of mass trapping depends on the following factors: 1) identification through basic research of all semiochemicals used by the target species, and 2) commitment to apply the tactic intensively for as long as it is necessary. Further pertinent factors include optimization of trap design, and pheromone formulation. Efficacy of three trap types, pitfall, vane and barrier traps, have been tested for trapping *O. rhinoceros* (Hallett *et al.*, 1995). Capture of *Oryctes* in buried pitfall traps depends upon a crawling response for entry, whereas above-ground traps depend upon a flying response by the beetles (Hallett *et al.*, 1995). *Oryctes* responds well to vertical silhouettes, and above ground light traps with vanes are effective in capturing *O. elegans* in the Arabian peninsula (Bedford, 1980). Superior efficiency of vane and barrier traps for capturing *O. rhinoceros* (Hallett *et al.*, 1995) may mostly be attributed to the vertical silhouettes which are lacking in pitfall traps. Optimal pheromone release rates for attracting and trapping were assessed in a series of experiments (Hallett *et al.*, 1995), using standard vane traps. Of seven different release rates tested (0, 0.3, 3, 6, 9, 18 or 30 mg per day), the latter 4 release rates were similarly attractive, and the 9 mg per day rate was adopted for an operational trapping trial.

Plant kairomones may further enhance the efficacy of *Oryctes* mass trapping. Synergism between aggregation pheromone and plant volatiles has been shown for *Rhynchophorus* palm weevils (Oehlschlager *et al.*, 1992; Gries *et al.*, 1994; Hallett *et al.*, 1993; Giblin-Davis *et al.*, 1994) and for the scarab beetle, *Anomala octiescostata* (Leal *et al.*, 1994). Addition of freshly milled fruit bunches, but not decomposed palm tissue, enhanced pheromonal attraction in *O. rhinoceros* (Hallett *et al.*, 1995). Attractive oil palm volatiles were apparently produced early in the decomposition process.

Following their identification, synthetic plant volatiles need to be tested singly at various doses, and in combination with the pheromone to develop the most attractive semiochemical lure. Potential for pheromone-based mass trapping of ARB may be assessed in experiments analogous to those currently conducted for *O. rhinoceros* in Indonesia (R. Hallett, personal communication). In plantations with ARB incidence, pheromone-treated and control plots should be laid out. In pheromone plots, 6 and 24 traps per hectare (low and high density, respectively) should be set up and baited with the optimal semiochemical lure. ARB inflicted palm damage should be assessed in control and treatment plots prior to, and during, mass trapping in weekly intervals. Differential evaluation of ARB damage in control and treatment plots would indicate the potential of pheromone-based ARB mass trapping to lower palm damage below economic thresholds.

For long term ARB control, various tactics may need to be integrated. For example, ARB may be attracted to pheromone/kairomone-baited traps to be exposed to pathogenic fungus *Metarrhizium anisopliae* or *Baculovirus oryctes*. Subsequent release of pathogen-infected ARB would help to spread the disease throughout the population.

4.0. Maize Weevil, *Sitophilus zeamais (Motschulsky)*

4.1. Introduction

The maize weevil (MW), *Sitophilus zeamais* Motschulsky (Coleoptera:Curculionidae), (Figure 5) is a destructive storage pest of grains and cereals in tropical Africa (Dobie, 1977). Infestations often start a few weeks before crop harvest in the field (Walgenbach and Burkholder, 1986) and may spread to storage facilities (Keever *et al.*, 1988). Hot and damp climatic conditions have promoted continuous attack of MW, causing heavy economic losses in grain production.

4.1.1. Geographic Distribution

Cosmopolitan MW is most commonly found in warm tropical and subtropical areas in Africa (Figure 6) (Sinha and Watters, 1985). In West African Ghana, Nigeria, Benin, Ivory Coast and Togo it is a major storage pest. In Eastern and Southern Africa it is a storage pest in Kenya, Tanzania, Malawi, Zambia, Zimbabwe, Mozambique, Botswana, and the Republic of South Africa.

4.1.2. Host

The MW feeds mostly on cereals and starch grain crops, such as wheat, *Triticum aestivum* L., rice, *Oryza sativa* L., sorghum, *Sorghum bicolor* (L.), and millet, *Eleusine coracana* (L.) with maize, as the primary host in Africa (Sinha and Watters, 1985). MW feeds on the germ and endoplasm of the kernel (Miracle, 1966; FAO, 1991). The ripe kernel of maize is larger than that of millet, sorghum, rice and wheat. The hull which

Figure 5. Maize weevil, *Sitophilus zeamais*.

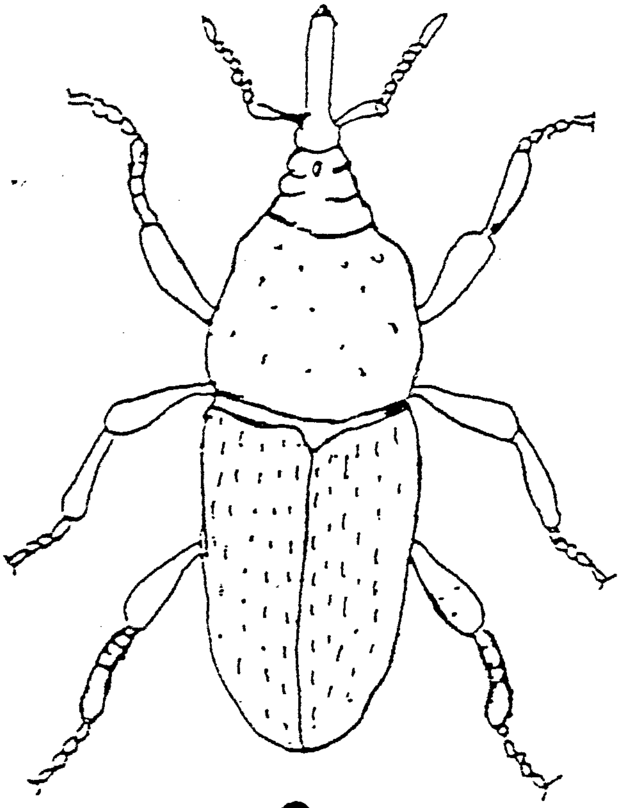

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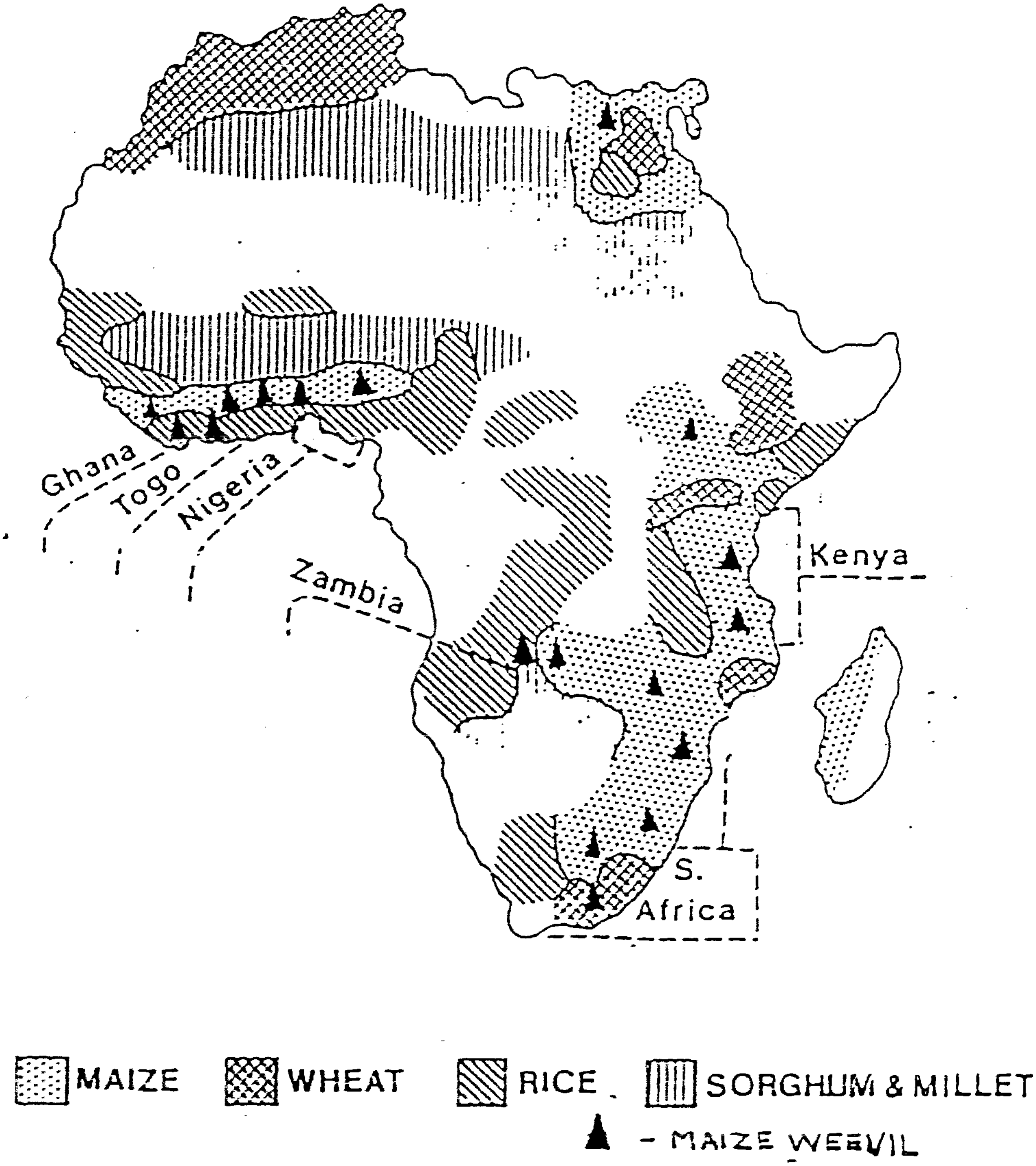
Figure 6. Distribution of cereal crops and maize weevil, *Sitophilus zeamais,* in Africa.


Ghana
Togo
Nigeria
Zambia
Kenya
S. Africa
MAIZE
WHEAT
RICE
SORGHUM & MILLET
- MAIZE WEEVIL

forms the outermost covering of the grain contributes 6%, the endosperm 82% and the germ about 12% of the total kernel weight (FAO, 1991).

The FAO agro-ecological zones project (1970) indicated that maximum suitability for maize cultivation is generally found in the same area as for cereals. It is cultivated in almost all African countries even though it is a staple food in only about half of them (FAO, 1991). Female MW chew a hole through the endosperm in which it deposits its eggs. Both larvae and adult MW feed on the endosperm, leaving very little for human consumption.

4.1.3. Biology

The preferred host of MW in Africa is maize (Zeamais), but it also frequently infests standing corn (Van DerSchaaf *et al.*, 1969; Williams and Floyd, 1970; Taylor, 1971). MW may fly 800m (Singh *et al.*, 1978) from the field to infest a storage facility and vice versa (Chesnut, 1972). Outbreaks occur primarily in pre-harvest, semi-dried, grain kernel and the grain kernel of storage maize.

Females oviposit eggs singly (Arbogast and Mullen, 1990) inside the grain, mostly one and sometimes two eggs per grain (Sharifi and Mills, 1971). Each female is capable of laying 300 to 400 eggs, suggesting enormous potential for population increase within a few months (Hall, 1970). Upon hatching, the larva burrows into the grain and forms a winding tunnel that increases in size as the larva grows (Arbogast and Mullen, 1990). The four instars (Urrelo and Wright, 1989) are completed in corn in about 29 days, with the first three instars each taking 20% and the fourth instar 40% of the time for larval development (Arbogast and Mullen, 1990). Pupation occurs at the end of the tunnel in a cell formed of frass and larval secretion (Arbogast and Mullen, 1990). Pupation lasts five to six days (Urrelo and Wright, 1989). Adult MWs may remain inside the kernel for one to two days after eclosion and emerge by chewing their way out. In corn with 14.4% moisture content, development from egg to adult is completed in 31 to 64 days at 30° (Arbogast and Mullen, 1990). The sex ratio of emergent adults is skewed toward females (Dix and All, 1985), but the flight abilities of males exceed that of females (Bishara, 1968).

4.2. Economic Impact

Food losses due to insect pests are one of the major constraints to increased food supplies (Maredia *et al.*, 1992). Grains and cereals such as maize, sorghum and rice are the important staple foods for the people of Sahara and sub-Sahara Africa (FAO, 1980). Today, maize constitutes 73% of the total cereal crop with annual consumption rates of 83 kg per person (CIMMYT, 1990). However, food production has been hampered by insect pests (Table 1). The low productivity of about 0.8 tons per hectare (Kossou *et al.*, 1993) is primarily due to MW infestation in the field and in storage (Dobie, 1977). Of the small scale farm production, about 70% of cereal grain produced is retained and stored for consumption and sale (Boxall, 1986). Only part of the stored grain finds its way to the table due to losses incurred in storage (Nyambo, 1993).

MW feeding reduces the nutritive fraction of the grain and encourages a high moisture content and development of micro-organisms such as *Aspergillus penicillin*, streptomyces and bacteria (Nyambo, 1993). Because of possible contamination with aflatoxins, growth of these micro-organisms renders the grain unfit for human consumption (Nyambo, 1993). Weevil damage in farm stores also leads to weight loss of stored grain, after 6 months of storage ranging between 0.2-11.8% in Togo (Pantenius, 1988), 1-3% in Malawi (Schulten, 1987) and 4-5% in Kenya (MacFarlane, 1988).

In a 1990-91 study in Kenya, four months-stored grain and sorghum suffered weight losses of 2.2% and 5.6%, respectively, in improved granaries, whereas 3.6% and 6.1% weight loses were recorded in traditional granaries (Nyambo, 1993). However, in Kendu Bay, traditional granaries were superior in minimizing weight losses due to MW (Nyambo, 1993).

Weight loss during storage not attributable to moisture loss is a direct measure of food loss (Hall, 1970), representing a decline in the quality of the product. MW-damaged grains or kernels deteriorate through chemical changes within cells (Hall, 1970). Through hydrolysis and oxidation of oil, acidity in plant cells (e.g. free fatty acid) increases to the point of rancidity (Pingale *et al.*, 1954). The fatty acid content of cereals rises after prolonged storage, particularly when ground into meal or flour or when infested by MW. Thus, pre-milling MW-infested cereal will result in free fatty acid concentration of the meal exceeding that of, and rising to levels higher than in, uninfested cereal (Hall, 1970). Typical of African grain storage, MW fragments and excreta contaminate and degrade cereal quality.

Market analysis and availability of facilities for properly drying and storing cereal would allow farmers to sell their produce to the most favourable market. Because pre- and post-harvest cereal prices may differ by a factor of two (Hall, 1970), MW-free cereal storage to await higher prices may double the farmers' income. It would provide

Table 1. Losses of stored produce due to maize weevil, *Sitophilus zeamais*, in Africa

Country	Commodity	Damaged Grains/Kernels	Weight Loss	Storage Period
Ghana	Maize	--	20%	8 months
Benin	Maize	30 - 50%	--	5 months
Togo	Maize	30%	--	5 months
Uganda	Maize	45 - 75%	20%	7 months
Zambia	Maize	90 - 100%	--	12 months
Ivory Coast	Maize	5 - 10%	--	12 months
Nigeria	Sorghum	11 - 88%	6 -27%	26 months
Kenya	Wheat	58%	2%	6 months
S. Africa	Maize	--	12 - 19%	24 months

(Ref FAO, 1980:21)

incentive to grow more than is needed for consumption by their families, and would provide food for urban populations, in turn generating income for the farming community and minimizing the need for food imports.

The importance of seed is recognized by all farming communities. Use of chemical insecticides and fumigants for MW control leads to considerable losses of seeds (Hall, 1970). It adversely affects germination, growth of rootlets and strength and vigor of resultant plants (Hall, 1970), suggesting that alternative methods of MW control are indicated. Moreover, with the advent of nationhood in Africa, there is and will continue to be growing pride in the ability to provide produce of high quality. Because import and export of produce will rely on collaboration of countries, all countries must maintain equally high standards of hygiene and quality of produce, including proper methods of MW control.

4.3. Review of Previous and Current Control Methods

MW infestations may begin in the field (Dobie, 1974) and, if not controlled, may spread to grains in storage causing extensive damage (Sedlacek *et al.*, 1991). The degree of infestation is mainly determined by the completeness of the husk covering the cob (Giles and Ashman, 1971). In Africa, the traditional method of storing maize unshelled with the husk intact (Kossou *et al.*, 1992) results in substantial losses to insect pests, primarily to MW (Dobie, 1977).

Control of MWs both in the field and storage has been based on cultural practices, insecticide applications, biological agents and the use of MW-resistant maize varieties. Cultural MW controls include drying and threshing of grains which greatly reduce MW populations going into storage (Keever *et al.*, 1988). African farmers traditionally spread out their grain harvest in the sun to dry it and to rid it of insects. This shelling and drying of crops may indeed reduce insect populations through physical separation and increased insect mortality. Changing the micro-environmental conditions, such as moisture content and texture of the commodity, reduces the biotic potential of the insects (Hindmarsh and MacDonald, 1980; Takahashi and Mizuno, 1982). Another traditional cultural method of MW control comprises the mixing of storage grains with sand, limestone, ash or herbs. In addition to forming barriers against movement of the insect through the grains, these materials abrade or absorb the wax coating of the insect's protective cuticle, causing a loss of body moisture (FAO, 1991).

In the last few decades, MW control has been based on conventional insecticides. Despite their thermal instability and lack of persistence (Hall, 1970) especially in hot and humid sub-Saharan Africa, malathion and lindane are commonly applied. Their frequent use in Zimbabwe, for example, has lead to the development of MW resistance (Giga and Mazarura, 1990). Other groups of insecticides, such as chloropyrifosmethyl (Arthur, 1992), tralomethrin (Halliday *et al.*, 1992), primiphosmethyl and fenitrothion (Beasley *et al.*, 1993) have been recommended for long-term MW control. Fumigants commonly used for protection of bagged grains (Hall, 1970) are more efficient than contact insecticides. As highly volatile chemicals they penetrate grains, killing any infesting insect including eggs and immature stages (FAO, 1991). Toxic specificity of the fumigant depends on the insect species, whose susceptibility in turn is stage-dependent (i.e., egg, larva, pupa and adult). Pre-adult MWs are least susceptible, requiring high doses to induce mortality (Bowden, 1960). Under tropical conditions the effect of fumigants may be calculated as the product of fumigant concentration x time (Hall, 1970). Fumigant efficiency may further depend on absorptive properties of the cereal under higher temperature. While liquid and solid (tablet) formulations are available, most farmers in Africa apply the tablet form - phostoxin. Fumigation by phostoxin results from liberation of phosphine gas due to its interaction with temperature and moisture in the grain (FAO, 1991). Methyl bromide, the most commonly used fumigant, requires special equipment and specially trained personnel, and is therefore applied only for fumigation of large scale stored produce. As a result of chemical interaction between fumigants and food products, permanent residues may be formed (Hall, 1970). Fumigation of sorghum with methyl bromide on several occasions, left residues of 200 ppm, greatly exceeding the tolerance level of 50 ppm (FAO, 1969).

Hazardous and negative environmental effects of pesticides have evoked worldwide concern to minimize their usage and to develop and utilize less hazardous pest control methods (Luna and House, 1990). Moreover, there is increasing need in developing nations to implement pest control methods that are economically feasible and require minimal technical knowledge to be adopted by the farmer (Zelazny *et al.*, 1985). Chemicals of plant origin may provide alternative, readily available, safe and inexpensive pest control agents (Maredia *et al.*, 1992). The neem tree, *Azadiracta indica* A. Juss (Family: Meliaceae), of tropical Asia and Africa possesses insect repellent and anti-feedant properties (Saxena, 1983, 1987) with selective activity against pest species (Jacobson, 1986). In a laboratory bioassay, 5 and 10 ml of neem oil per kg of infested maize induced significant MW mortality (Maredia *et al.*, 1992). Further research, however, is indicated to fully evaluate the potential of neem-based MW control.

Increasing insect resistance to conventional insecticides (Wang and Ku, 1982; Evans, 1985; Taylor and Halliday, 1986; Zettler and Cuperus, 1990), limited availability of new insecticides, and safety concerns over fumigants (White *et al.*, 1983) has renewed interest in developing biological control methods for stored product pests such as MW (Arbogast, 1984).

Reported MW parasites/parasitoids include *Anisopterormalus calandrae* (Howard) (Hymenoptera: Pteromalidae) and *Choetospila elegans* Westwood (Arbogast and Mullen, 1990). *A. calandrae* is a cosmopolitan parasite. It feeds on the haemolymph of immature MW using a tube formed around the ovipositor (Arbogast and Mullen, 1990). Inserting its ovipositor through the shell of the grain, *A. calandrae* paralyzes the host to deposit a single egg on or near the host larva (Arbogast and Mullen, 1990). *A. calandrae* in stored corn seems to affect MW populations (Arbogast and Mullen, 1990). *C. elegans*, in contrast, appearing late in the storage period, may not contribute to suppression of MW in storage.

In preliminary studies, with either *C. elegans* or *A. calandrae*, both parasites reproduced successfully on MW (Williams and Floyd, 1970). *A. calandrae* reduced MW populations by more than half in storage facilities, whereas *C. elegans* did that in the field (Williams and Floyd, 1970). Introduction of parasitoids sufficiently early in the storage period may suppress MW populations and allow storage of cereals for longer periods, but re-introduction of parasitoids may be required to prevent rebounding of weevil populations (Press *et al.*, 1984; Cline *et al.*, 1985). Although parasite/parasitoid-based control has not been reported in Africa, it could be introduced because MW and parasite may occupy the same ecological niche in storage throughout the world.

Maize bred for disease-resistance and high yield remains susceptible for MW attack (Kossou *et al.*, 1993) in the field and in traditional maize storage facilities. African countries are alerted that many of the new, higher-yielding maize varieties without MW-resistant characteristics may result in greater losses, if harvested and stored in traditional ways (Kossou *et al.*, 1993). According to Ghana's Grains Development Project yield-improved rather than local maize is more susceptible to storage losses (Badu-Apreku *et al.*, 1992). The Benin variety, for example, is less susceptible to MW attack due to high husk quality, such as husk extension beyond the ear, husk tightness and number and thickness of husk leaves (Kossou *et al.*, 1993). Weevil resistance, particularly husk cover, should be an important objective of maize breeding programs in Africa, wherever crop pre- and/or post-harvest MW resistance is required (Kossou *et al.*, 1993).

None of the above mentioned control measures has achieved absolute MW control. Integration of various control measures may be required to effectively manage infestations in storage. Proper timing may be accomplished through pheromone-based monitoring which has been reported for a number of stored-product pests (Burkholder, 1984).

4.4. Potential for Semiochemical-based MW Control

4.4.1. Pheromone Analysis

Evidence for a male MW-produced aggregation pheromone has been reported (Walgenbach *et al.*, 1983) and its chemical structure been identified (Schmuff *et al.*, 1984). For pheromone identification, volatiles from two hundred unmated males were collected on highly absorbent antibacterial assay disks. Hexane extracts of these disks were concentrated and chromatographed [hexane (1): ether (1)] on Florisil. The bioactive fraction was further purified by preparative gas chromatography (GC), and was subjected to GC-mass spectrometry in both electron impact and chemical ionization modes. Mass spectrometry and nuclear magnetic resonance (HNMR) spectroscopy of the bioactive compound indicated a 3-keto alcohol with formula $C_8H_{16}O_2$ and molecular weight 144.

Synthesis of all 4 isomers revealed that (5*R*,4*S*)-5-hydroxy-4-methyl-3-heptanone had GC, GC-MS and HNMR characteristics identical to the male MW-produced compound. The *RR*-isomer was present in < 5% relative to the *RS*-isomer, which was produced at 6 µg per day per weevil. Chirality of the candidate pheromone was determined by acetyl lactate derivatization (Slessor *et al.*, 1985) and by GC and GC-MS analyses of weevil-produced and synthetic 5-hydroxy-4-methyl-3-heptanone.

4.4.2. Bioassay of the Identified Candidate Pheromone

In a dual-choice pitfall Petri-dish assay (Philips and Burkholder, 1981), attraction of MW to (4*S*,5*R*)-5-hydroxy-4-methyl-3-heptanone was demonstrated (Walgenbach *et al.*, 1987). Both male and female MW were strongly attracted to (4*S*,5*R*)- or (4*R*,5*R*)-5-hydroxy-4-methyl-3-heptanone or a 1:1 mixture thereof. 3-Pentanone was found in small quantities in MW volatiles and was hypothesized to be a degradation product of 5-hydroxy-4-methyl-3-heptanone. In young MW, however, it may enhance pheromonal response (Philips *et al.*, 1985). Aged weevils responded best to 3-pentanone when starved (Philips *et al.*, 1985). Thorough field experiments need to be conducted and thereafter potential of these components for MW control be assessed.

4.4.3. Potential for Pheromone-Based Monitoring of MW

The isolation and identification of MW aggregation pheromone (Philips and Burkholder, 1981; Faustini *et al.*, 1982; Walgenbach *et al.*, 1983) has rekindled interest in pre-harvest MW control tactics (Dix and All, 1985). Detection and monitoring of pest insects is a key component of successful integrated pest management (IPM) in environments of stored agricultural commodities such as grains and cereal (Rice, 1993). Pheromones are effective monitoring tools for a number of stored-product pests (Burkholder, 1984), and several effective trapping systems are commercially available (Walgenbach *et al.*, 1987). For trapping Coleoptera in stored products, corrugated cardboard is effective because the insects hide in the corrugations just as they do in cracks of floors or walls (Burkholder and Ma, 1985). Barak and Burkholder (1985) have therefore designed a four layer corrugated cardboard trap for stored product Coleoptera that can house up to four pheromone septa as well as a dispenser for food attractants. Wheat germ oil, oat oil or other natural oils serve as food attractant, and as killing agent when insects stumble into the dispenser cup (Walgenbach *et al.*, 1985). Adults of *Oryzaephilus surinamensis* (L.) and *Tribolium confusum* (Jacquelin du Val), and larvae of *Trogoderma variabile* are effectively trapped in this device (Barak and Burkholder, 1985).

In preliminary studies with corrugated cardboard for trapping MW, 300 mg of synthetic pheromone plus 1 ml of wheat germ oil in the absence of food constitute a strongly attractive bait (Walgenbach, 1985). Whether it is effective in storage facilities of grain and cereal remains to be investigated. Optimal use of pheromones in monitoring programs requires studying production of and response to pheromone in relation to insect age, mating and diet (Lopez *et al.*, 1978; Khorramshahi and Burkholder, 1981; Lloyd *et al.*, 1981; Leggett and Moore, 1982; Pierce *et al.*, 1983) to properly interpret variable trap catches (Walgenbach and Burkholder, 1986). Young MW, for example, are significantly more attracted to synthetic pheromones than are older MW (Walgenbach and Burkholder, 1987), and starvation and crowding of young MWs enhanced their responsiveness to pheromone. Therefore, the interpretation of laboratory bioassays and trap catches in storage facilities may depend on knowledge of the insect behavior and physiology.

For pheromone-based MW monitoring in African storage facilities or warehouses, pheromone/kairomone-baited traps should be placed in a grid pattern away from open doors and windows to prevent MW entry. Weekly recordings of trap catches will allow to determine sites of infestation and development trends. Because the tolerance for stored product insects is low (Burkholder, 1984), pheromone-based MW-monitoring should be implemented together with thorough sanitation procedures. Capture of only one MW may justify special cleanup and control efforts.

Although grain bins as a closed system are often considered convenient for trapping, inserting traps at the bottom is difficult. Perforated plastic probe traps (Burkholder, 1984) baited with a synthetic MW lure have been developed to monitor the presence of MW. However, these traps will effectively monitor only the presence of adult, and not immature, MWs. Competitiveness of grain producing African countries on the international market requires zero tolerance of pests of all kinds, and the ability to detect and destroy developmental stages of MW.

Accurate, sensitive, expeditious and nondestructive procedures for detecting MW (and other beetle) larvae are commercially available (Vick *et al.*, 1988) and comprise X-ray analysis of grains (Milner *et al.*, 1995) and detection of feeding sounds (Brain, 1924, Adams *et al.*, 1953, Bailey & McCabe, 1965; Street, 1971; Webb & Landolt, 1984). The more recently developed acoustic detection system (Webb *et al.*, 1988) is most suitable for hidden insect infestations in fruit, nuts and grain (Vick *et al.*, 1988) through detection of moving sounds by early instar larvae (Webb *et al.*, 1988). The system comprises a low noise amplifier, acoustical coupler and sample holder, digital voltmeter (A/D converter), universal counter, vectra (IBM compatible) computer and graphic printer.

The A/D system detects insect activity by recording sound of about 100 Hz, disregarding non-biological frequencies. The system is valuable for obtaining basic information such as time and frequency of larval feeding, and growth rates inside of various grains. It may facilitate or even replace labour-intensive and destructive dissection and visual inspection of grains for evidence of insect infestations.

Despite development of state-of-the-art monitoring devices, they may not be available, affordable or beyond the comprehension of African farmers. The bulk of produce is stored on small private farms and in homes, not justifying purchase and maintenance of technically advanced monitoring devices. Only private companies involved in grain storage may be able to afford modern monitoring devices. Pheromone-baited traps, in contrast, should be affordable and most appropriate for the majority of African farmers to reliably detect MW infestations and to assess the efficacy of control measures.

Discussion

The present study was undertaken 1) to review the biology and economic impact of three major African insect pests, the Mahogany Shootborer (MSB), *Hypsipyla robusta*, the African rhinoceros beetle (ARB), *Oryctes monoceros*, and the maize weevil (MW), *Sitophilus zeamais*, and 2) to study the potential of their semiochemical based control. The three insects are ecologically unrelated, but are excellent representatives of groups of insects that have major economic impact on agricultural and forest crops or food stored for human consumption. Although some control tactics for these insects are already implemented, semiochemical-based control alone, or as a part of multi-tactic, integrated pest management, may offer a more reliable, efficacious, cheaper or environmentally more compatible control option. Because basic semiochemical research is expensive and monetary resources are limited, primarily those (groups of) insects should be investigated that have indeed the greatest potential to be controlled by semiochemicals.

African mahogany constitutes one of the most valuable commodities in forestry and provoked the establishment of mahogany plantations. The MSB attacks and destroys the terminal shoot of the main stem, restricts the re-establishment of mahogany plantations and thereby reduces revenue from timber exports. Severe attacks of these plantation trees may be attributed to greatly enhanced foraging success of gravid MSB females that locate host trees more readily in monocultural settings than in tropical rainforest. If females were attracted to kairomones emanating from the many susceptible host trees, and if males were strongly attracted to female-produced pheromone, the following objectives for semiochemical research and subsequent implementation of semiochemicals for MSB control are conceivable: 1) identify, synthesize and formulate host plant kairomones to attract and trap foraging females; 2) identify, synthesize and formulate the MSB sex pheromone to detect and delineate MSB population (infestations), 3) monitor MSB population densities, 4) eradicate the population in small plantations and nurseries through mass trapping of males, and finally 5) disorient mate seeking males through pheromone-based mating disruption.

Identification and use of kairomones for attracting and trapping gravid MSB females is appealing, but prospects of succeeding are low. Many research efforts to reveal kairomones mediating foraging and/or oviposition of Lepidopteran pests have failed. Antennally-active compounds may have been identified (Holsten and Gara; 1974) but behavioral activity of these compounds in field experiments could hardly be demonstrated. Only Phelan *et al.* (1991 who worked on the chemical ecology of the navel orange worm, *Amyelois transtella*(W.) succeeded in the identification of kairomones from almond fruits and their implementation in almond orchards to disorient gravid, oviposition site-seeking females. Even though technology to identify plant kairomones has greatly improved, kairomones *per se* may not be the only cues to mediate host selection behavior. Visual cues, such as size and shape of the terminal mahogany leader, may be as or even more important than kairomones emanating from susceptible trees. Because extensive research would have to be conducted to elucidate the foraging ecology of the MSB, and because there has been only moderate previous success of using kairomones to manipulate Lepidopteran pests, identification of mahogany kairomones for trapping MSB does not appear appealing.

Prospects of using the MSB sex pheromone for MSB pest management seems to be more promising. Bosson and Gallois (1982) revealed a two-component pheromone blend (*Z*9, *E*12-14: OAc and *Z*9-14: OAc) that, equivalent to female MSB pheromone gland extract, elicited attraction of MSB males in the wind tunnel. It is suspicious, however, that attractiveness of these compounds was never demonstrated in the field. Candidate pheromone components have also been identified for *H. grandella*, but in the field hardly attracted any males (appendix). Assuming nonetheless that the identified MSB pheromone components will be attractive in the field, commercial formulations should be explored for their potential to monitor MSB population densities and to predict damage. Before pheromone-based mass trapping of MSB males in small plantations and nurseries can be recommended, research needs to address whether MSB males and females typically have one or multiple matings, and whether mass trapping of males indeed reduces the incidence of oviposition and of mahogany damage. Because MSB attacks mahogany trees from their nursery stage to early stages of transplants, effective mass trapping would have to be implemented for a period of about 3-5 years. Although the optimal number of traps per hectare and number of lures per year has yet to be determined, expenses for intensive mass trapping are probably high. Pheromone-based disorientation of MSB males (mating disruption) would require even more pheromone and dispensers, and resulting costs would greatly exceed those for a mass trapping program. Because forests, unlike agricultural crops, do not provide annual returns for pest management investments, prohibitively expensive mating disruption is not a viable option for MSB control.

While pheromone-based monitoring and, to a lesser degree, mass trapping of MSB has limited potential to become part of an integrated pest management program, research into the susceptibility or non-susceptibility of mahogany for MSB appears promising.

MSB females apparently discriminate between and selectively oviposit on preferred varieties of Meliaceae spp. (Grijpma and Gara, 1970). Varieties or provenances of Meliaceae spp. rejected by MSB females for oviposition should be identified, the mechanisms of non-susceptibility be studied and through selective breeding be enhanced. Because plantations with only one or few susceptible mahogany varieties would likely generate selection pressure for MSB females to overcome mechanisms of non-susceptibility, new plantations should be intermixed with both susceptible and non-susceptible trees. While non-susceptible trees could grow unaffected by MSB and become high valuable crop trees, susceptible trees could become the oviposition target for MSB females. Intermixing mahogany varieties even with non-host species could further reduce the foraging success of gravid females. Repeated removal of infected terminal leaders of susceptible varieties could help to prevent population build-up. Extensive pheromone-based monitoring of MSB population densities may facilitate decisions whether removal of infested leaders is necessary.

The MW is a representative of insect pests that attack crops before harvest in the field and during storage, reducing the nutritional value of food and rendering it unfit for human consumption. Unlike the MSB, the pheromone of the MW has been well analyzed. Pheromone chirality has been determined and pheromonal attraction of MW been demonstrated. Pheromone formulations, food sources enhancing pheromonal attractiveness and even traps have been tested and developed (Walgenbach et. al. 1987). Because the chemical communication system for the MW is sufficiently well described, future semiochemical research could focus on the implementation of previously acquired knowledge. While pre-harvest control of the MW seems difficult to achieve, pheromone-based monitoring and/or even control in confined environments of storage facilities are conceivable. The same pheromone-based trapping system could also be used to reliably assess the efficiency of any (non-pheromone based) control measure.

However, even if MW populations in storage facilities were successfully monitored or even controlled through effective trapping, there are still many other insect pests that inflict damage to stored food. Combined food losses due to feeding by red flour beetle, *Tribolium castaneum* (H.), rice weevil, *Sitophilus oryzae* (L.) and flat grain beetle, *Cryptolestes pusillus* (S.), for example, may be equal to, or exceed, damage caused by MW. Moreover, successful elimination of a key insect pest, such as the MW, from storage facilities may make "secondary pest insects" enter the "vacated" physical space or ecological niche. For example, in the past broad spectrum insecticides have controlled the codling moth, *Cydia pomonella* (L.), and the many other secondary Lepidopteran pests in apple orchards. With the onset of pheromone-based mating disruption of the codling moth (Charmillot, 1990), and the discontinuation of insecticide sprays, formerly controlled secondary lepidopteran pests, such as leafrollers or leafminers, have become a major problem and now also need to be managed by pheromone. Applying this example to the MW system, pheromones of associated grain/maize-feeding insects would also have to be identified, tested, formulated and implemented for control. Even if this formidable task were accomplished, the many private African farmholders could hardly be supplied with, or be expected to purchase, all the required pheromone lures. Assuming, however, that the MW is indeed the most important insect pest of stored food and, at least in part, indicates the presence of associated insect pests, MW pheromone-baited traps may be appropriate to reliably detect pest insect infestations and/or assess the efficacy of non-pheromone-based control measures.

Of the three insects analyzed in this study, the ARB has the greatest potential and meets all the prerequisites to be controlled in a semiochemical-based integrated pest management program. The reasons are as follows: 1) The need for ARB control is self-evident. Copra, kernel and palm oil are major export items of the African economy. Because the ARB is one of the most destructive pests of commercial oil, coconut and date palm, ARB control is essential; 2) Unlike the MW, only one developmental stage of the ARB, the adult, inflicts damage; 3) The carrying capacity of palm plantations for the very large ARB is limited; 4) There are only 1-2 generations of the ARB per year; 5) The ARB pheromone has been identified (Gries et al., 1994) and attracts both male and female ARBs; 6) The Asian rhinoceros beetle uses the very same aggregation pheromone. Any experience regarding optimal pheromone formulation , trap design and placement currently being gathered for the Asian rhinoceros beetle (Hallett et. al., 1995) may directly be applicable for the ARB; 7) Current studies investigate the number of pheromone-baited traps required to mass trap the Asian rhinoceros beetle and to reduce its damage below economic threshold. Because the ARB occupies a very similar ecological niche as the Asian rhinoceros beetle, results gathered in Asian palm plantations (Hallett, unpublished) may again directly be applicable for mass trapping of the ARB; 8) Many tactics have already been implemented to control the ARB, including silvicultural methods and use of natural enemies (virus). Although neither of these tactics singly yielded satisfactory suppression of ARB populations, in combination with pheromones, as part of an integrated pest management program, they may become highly effective. For instance, ARB may be attracted to pheromone/kairomone-baited traps to be exposed to pathogenic fungus *Metarrhizium anisopliae* or to *Bacolovirus orcyctes*. Subsequent release of pathogen-infected ARB would help to spread the disease throughout the population. Furthermore covering rotting oil palm trunks with dense ground vegetation (silvicultural method; Wood 1976) would conceal potential breeding sites and thereby help to reduce ARB population densities.

In conclusion, because the pheromone of the ARB has already been identified and can readily be formulated and combined with other control tactics, development of pheromone-based, integrated pest management for the ARB has excellent potential, and among the three insects (MSB, MW, and ARB) studied should receive first priority.

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Appendix

5.0. Analysis of Female *H. grandella* Sex Pheromone

5.1. Materials and Methods

Pheromone analysis of *H. grandella* was conducted at Simon Fraser University (SFU) within the framework of this thesis. Insects were reared in Costa Rica and pupae shipped to SFU. Pupae were reared to adults at 27°C, 70% relative humidity and a photoperiod of 12L:12D. Male and female pupae were kept separately in filter paper lined Petri dishes to avoid mating of emergent moths. Pheromone glands of two to three day-old virgin females were removed and extracted for 5 minutes in hexane. Aliquots of one female equivalent of gland extracts were subjected to gas chromatographic-electroantennographic detection[3] (GC-EAD) (Arn *et al.*, 1975), employing a Hewlett Packard 589OA gas chromatograph equipped with DB-210 or DB-23 coated, fused silica column (30m x 0.25mm ID) (J & W Scientific, Folsom, California 95630).

Coupled GC-mass spectrometry (MS)[4] (Hewlett-Packard 5985B fitted with the DB-210 column) with isobutane for chemical ionization (CI) was conducted to confirm the identification of EAD-active components in pheromone extracts. Full-scan CI mass spectra of synthetic candidate compounds were obtained to select diagnostic ions. Two hundred pg of synthetic compounds, hexane and a concentrated pheromone gland extract were then analyzed in SIM mode, each time scanning for diagnostic ions.

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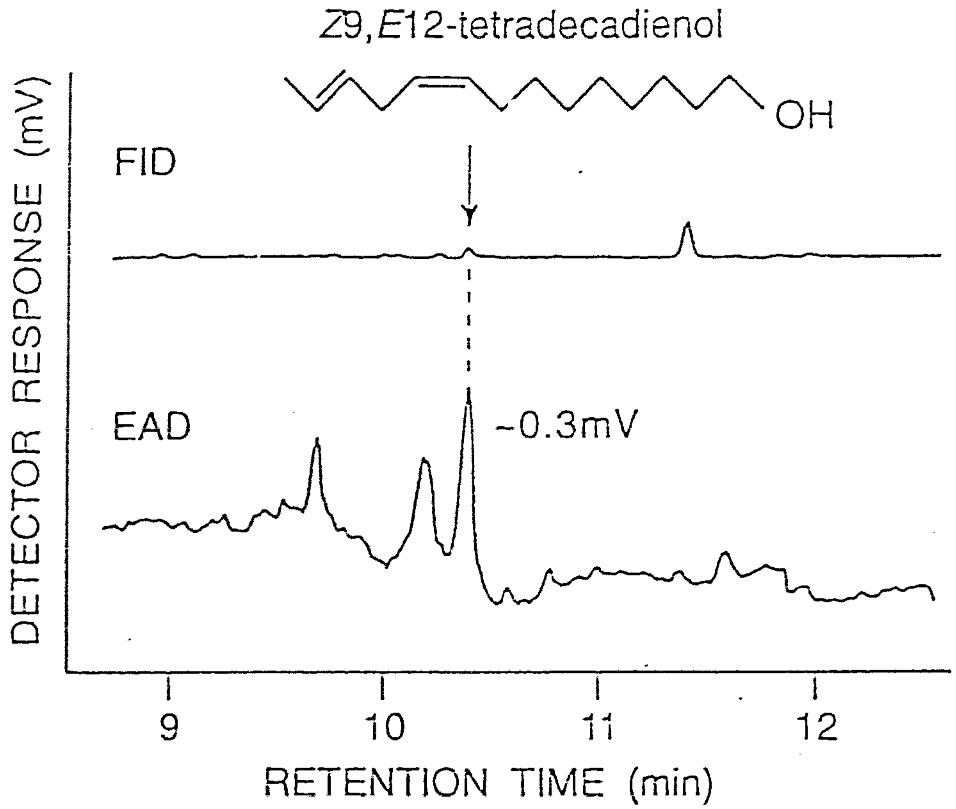
[3] Conducted by R. Gries, Department of Biological Sciences, Simon Fraser University, Burnaby, B.C., Canada.

[4] Conducted by G. Own, Department of Chemistry, Simon Fraser University, Burnaby, B.C., Canada.

5.2. Results

GC-EAD analysis of female pheromone gland extract revealed several EAD-active compounds that elicited antennal responses by male *H. grandella* antenna (Fig. 7). Based on retention index (RI) calculations on DB-210 and DB-23 columns, EAD-active compounds 1, 2, and 3 were hypothesized to be *Z*9-tetradecen-1-ol (*Z*9-14:OH), *Z*9,*E*12-tetradecadien-1-ol (*Z*9,*E*12-14:OH) and *Z*9,*E*12-tetradecadienyl acetate (*Z*9,*E*12-14:OAc). Synthetic *Z*9-14:OH, *Z*9,*E*12-14:OH and *Z*9,*E*12-14:OAc coincided with antennal responses to gland extract on DB-210 and DB-23 columns and elicited comparable EAD-responses. GC-MS-CI-SIM of 25 female equivalents of pheromone extract and synthetic compounds resulted in retention time and ion ratio matches of synthetic and female-produced compounds except for *Z*9-14:OH; synthetic *Z*9,*E*12-14:OH [*m/z* (%)]: 211 (M+1, 100), 193 (35); extract: 211 (100), 193 (33); synthetic *Z*9,*E*12-14:OAc: 193 (100), 253 (41); extract: 193 (100), 253 (38). Diagnostic ions for *Z9-14:OH* were detected at the exact retention time, but quantities were too small to accurately determine ion ratios. Field tests in Costa Rica with these pheromone components singly or in combination at appropriate ratios resulted in very few captures of male MSBs. Only *Z*9,*E*12-14:OH at 100μg per septum attracted a few males. These low trap catches may be attributed to one or several of the following factors: 1) low MSB population level during the experiment, 2) as yet unknown synergistic pheromone components, and 3) inappropriate trap type (Phero Tech Wing trap). Furthermore, premating flight by female MSBs seems to be a prerequisite for the production of fertile eggs (Fasoranti, 1985), and may also be necessary for pheromone production. Because emergent females in this study were not given the opportunity of flying, they may have failed to produce critical pheromone components. In future MSB pheromone analyses, use of pre-flown females should be considered.

Figure 7. Flame ionization detector (FID) and electroantennographic detector (EAD: male *H. grandella* antenna) responses to 25 female equivalents of female *H. grandella* pheromone gland extract. Chromatography: Hewlett Packard 5890A gas chromatograph equipped with a fused silica column (30m x 0.25mm ID) coated with DB-23 (J&W Scientific, Folsom, California 95630); temperature program: 1 min at 70°C, 20°C/min to 140°C then 2°C/min to 200°C.



*Z*9,*E*12-tetradecadienol
OH
FID
EAD
-0.3mV
DETECTOR RESPONSE (mV)
9
10
11
12
RETENTION TIME (min)