BIOLOGY AND CONTROL OF THE MANGO SEED WEEVIL IN SOUTH AFRICA

by

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In dedication to my loved ones who believed in me, supported me and graced me with the time and opportunity to fulfill my dreams.

I hereby declare that the dissertation hereby submitted to the University of the Free State for the MSc degree and the work contained therein is my own original work and has not previously, in its entirely or in part, been submitted to any other university for degree purposes.

Abstract

The mango seed weevil (MSW), *Sternochetus mangiferae* (Fabricius) (Coleoptera: Curculionidae), generally causes few problems on early-season cultivars, since the fruit are marketed and consumed before adult emergence from the fruit. Adult emergence from late-hanging cultivars, however, results in unattractive lesions that influence the marketability of the fruit. There is little evidence that MSW influences yield, although some authors argue that MSW development in the seed may lead to premature fruit drop. The economic impact of the MSW is primarily based on the fact that it is a major phytosanitary pest, restricting access to new foreign markets and contributing to substantial rejections of fruit destined for existing export countries.

The MSW has no natural enemies, is monophagous on mango and completes its entire life cycle within the mango seed. The impact of this pest can, therefore, be greatly reduced by orchard sanitation. Sanitation practices, however, are labour intensive, necessitating producers to rely on alternative or additive control measures. Several semi-penetrant and contact pesticides are registered for MSW control. However, with trans-laminar products it is imperative that treatments coincide with, or are applied just after, the onset of weevil oviposition. This requires intensive and accurate scouting programmes, with an in-depth knowledge regarding the duration of oviposition necessary to ensure seasonal control. When using contact insecticides, applications should coincide with seasonal and daily activity peaks to ensure direct contact. Since adult weevils are extremely inactive, this necessitates an in-depth knowledge of MSW activity patterns. It is also imperative to understand the development cycle and life strategies of the insect in order to know at which time intervention would prove to be the most effective. The product most generally used for MSW control in the Hoedspruit magisterial district of the Limpopo Province is fenthion (Lebaycid® EC 500g/ℓ a.i.). This product is very effective, but does not provide 100% control and can lead to secondary infestations of mango scale, *Aulacaspis tubercularis* (Newstead) (Hemiptera: Diaspididae), and mealybug (various species). The use of organophosphates on fruit destined for certain overseas markets is also under investigation by the EU. It is for this reason that Westfalia Technological Services, over the past four years, investigated various aspects of MSW general biology, reproduction and control.

The investigation into the activity patterns of adult weevils indicated that MSW were crepuscular – nocturnal insects. For this reason, applications with contact insecticides aimed at controlling the adult weevil would be expected to be more efficacious when applied at dusk.

During the study investigating MSW development, it was found that the majority of MSW eggs hatched between 7 and 14 days, with some of the first instar larvae already having penetrated into the seeds between 7 and 14 days after oviposition, depending on whether the eggs were laid early or late in the season. This implies that chemical control with contact and semi-penetrant chemicals, aimed at controlling the MSW larvae, should preferably not commence later than 7 days after observing the first eggs in the orchards. However, it was found during the course of this study that MSW oviposition commenced during the latter part of September and continued up to the latter part of January, a period considerably longer than previously stated in the literature. For this reason, more than one chemical application would be warranted.

While investigating alternative chemical control measures, it was found that a single application with the systemic insecticide, thiamethoxam (Actara™ SC 240g/ℓ a.i.), applied during flowering in the root zone, rendered seasonal MSW control. The use of this product, therefore, negates the necessity of tedious fruit inspections and an in-depth understanding of the pest in order to determine the most appropriate time for chemical intervention.

Uittreksel

Die mango snuitkewer (MSK), *Sternochetus mangiferae* (Fabricius) (Coleoptera: Curculionidae), het oor die algemeen nie ‘n groot impak op die vrugkwaliteit van vroeë-seisoen mango kultivars nie, aangesien dié vrugte gewoonlik bemark en geëet word voordat die volwasse kewers die vrug verlaat. Vir laat-seisoen kultivars vind dit egter dikwels plaas dat volwasse snuitkewers vanuit die saad, deur die vrugvlees, na buite beweeg. Die letsels wat so ontstaan verlaag die bemarkbaarheid van die vrug. Daar is nie baie inligting beskikbaar oor die effek van MSK op oesopbrengste nie, alhoewel sekere outeurs van mening is dat die teenwoordigheid van kewers in die saad tot verhoogde vrugafspening kan lei. Die ekonomiese impak van die MSK is meer vervat in die feit dat hierdie insek ‘n baie belangrike fitosanitêre plaag is, wat nie net toegang tot nuwe uitvoermarkte beïnvloed nie, maar ook kan lei tot die afkeur van vrugbesendings na bestaande uitvoermarkte.

Die MSK het geen natuurlike vyande nie, is monofaag op mango en voltooi sy hele lewensiklus binne-in die saad. Om hierdie rede kan boordsanitasiepraktyke infestasievlakke grootliks onder beheer bring. Sanitasie is egter arbeidsintensief, en lei daartoe dat produsente meerendeels staat maak op chemiese beheer. Verskeie kontak en translaminêre produkte is vir mangoes geregistreer om MSK te beheer. Wanneer translaminêre produkte gebruik word, is dit egter baie belangrik dat die aanvangsbespuiting gedoen word sodra MSK eierlegging begin, wat noodsaak dat 'n akkurate verkenningsprogram gevolg word. Dit is ook nodig om kennis te dra van die tydsduur van eierlegging ten einde effektiewe seisoenale beheer te kan verleen. Wanneer kontakmiddels gebruik word, is dit weer belangrik om kennis te dra van seisoenale en daaglikse aktiwiteitspatrone van die insek ten einde direkte kontak te verseker. Dit is ook noodsaaklik om die lewensiklus en lewenstrategieë van die insek te ken, ten einde te kan bepaal wanneer toetrede die grootste effek sal hê. Die chemiese middel wat algemeen in die Hoedspruit omgewing van die Limpopo Provinsie gebruik word is fenthion (Lebaycid® EC 500g/ℓ a.i.). Hierdie middel is effektief, maar verleen nie altyd 100% beheer nie en kan tot sekondêre uitbrake van mango dopluis, *Aulacaspis tubercularis* (Newstead) (Hemiptera: Diaspididae), en wolluis (verskeie spesies) lei. Die gebruik van organofosfate op vrugte wat vir oorsese markte bestem is, word tans ook deur die EU ondersoek. Om hierdie rede het Westfalia Tegnologiese Dienste die afgelope vier jaar verskillende aspekte van die algemene biologie, voortplanting en beheer van die MSK ondersoek.

Daar is, tydens die ondersoek na die gedragspatrone van die MSK, gevind dat die insek skemer- en naglewend is en dat daar veral ‘n toemane in aktiwiteit en voeding tydens skemer plaasvind. Vir hierdie rede sal blaarbespuitings met kontakmiddels, wat daarop gemik is om die volwasse kewer te beheer, meer doeltreffend wees indien bespuitings tydens skemer uitgevoer kan word.

Tydens die studie om MSK ontwikkeling te ondersoek is daar gevind dat die meerderheid van MSK eiers reeds tussen 7 en 14 dae na eierlegging uitgebroei het, terwyl die eerste instar larwes reeds tussen 7 en 14 dae na eierlegging tot in die saad gepenetreer het, afhangende daarvan of die eiers vroeg of laat in die seisoen gelê is. Vir hierdie rede is dit dus noodsaaklik om chemiese beheer van die MSK larwe, met kontak- en translaminêre middels, nie later as 7 dae nadat die eerste eierlegging waargeneem is, te begin nie. Maar, aangesien dit gevind is dat MSK eierlegging tussen die einde van September en die einde van Januarie plaasvind, ‘n periode wat aansienlik langer is as waarvan in die literatuur vermelding gemaak word, sal dit beteken dat meer as een bespuiting nodig sal wees om seisoenale beheer te verleen.

Uit die resultate wat verkry is met die studie waar alternatiewe chemiese beheer vir die MSK ondersoek is, het dit geblyk dat ‘n enkele tiametoksam (Actara™ SC 240g/ℓ a.i.) toediening, toegedien in die wortelsone tydens blom, effektiewe seisoenale beheer van die MSK verleen het. Die gebruik van hierdie sistemiese insekmiddel maak voortdurende vrugverkenning, asook ‘n deeglike kennis van die biologie en gedrag van die insek ten einde die beste tyd vir chemiese beheer te bepaal, oorbodig.

Key words Mango, mango seed weevil, activity patterns, feeding preferences, oviposition, weevil development, eclosion, adult emergence, biological control, chemical control

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CHAPTER 1

A review of mango production and the impact of selected pests and diseases on local and export markets

Economically mango (*Mangifera indica* L.) is the most important of the 41 species of Anacardiaceae, and the third most important crop in the tropics after citrus and bananas (Anonymous, 2006). Mango trees are evergreen with a long tap-root (up to 6m deep) and a dense mass of feeding roots just beneath the soil surface (Anonymous, 2006). Although the ideal soil texture for mango production under irrigation is a sandy loam or loam (i.e. clay content between 15 to 25 %), mango trees easily adapt to grow on a wide variety of soil types, and will even grow in soils with a depth of only 750mm, provided that irrigation scheduling is well planned and excess water can easily drain away from the root zone (Anonymous, 2006). Tree height normally ranges between 9m and 35m, but trees are frequently pruned back to more manageable sizes in order to increase the efficacy of management and pest control measures.

In the tropical and subtropical regions of the world, mangoes grow well at altitudes from sea level to about 1200m above sea level. The elevation of mango growing areas in South Africa ranges between 300m to 950m above sea level (Finnemore, 2000) but, since production decreases as altitude increases, mango production in South Africa above altitudes of 600m is generally not commercially viable (Anonymous, 2006).

Mangoes tolerate a wide range of climatic conditions from very hot and humid, to cool and dry, to very hot and arid. In South Africa cultivation occurs mainly in the northern and eastern provinces, with the major production units in Tzaneen (36%), Hoedspruit (28%) and Malelane and Komatipoort (20%) (Anonymous, 2006). The South African mango season starts in late November and ends around about the middle of April.

For optimum growth and production, the average maximum temperature should be between 27°C and 36°C, with the average winter temperature preferably above 5°C. Temperatures in the main mango growing areas in South Africa generally range from 3°C (winter night) to 40°C (summer day). Temperature differences between the various production regions result in fruit of the same cultivar being harvested at different times, with fruit in the higher lying areas harvested later in the season than fruit in lower lying areas. The time of harvest for a specific cultivar, between the various mango growing regions, may differ as much as 3 to 6 weeks (Anonymous, 2006). The most important cultivars currently under cultivation are 'Tommy Atkins' (26%), 'Sensation' (13%), 'Kent' (12%), 'Heidi' (9%), 'Keitt' (8%) and 'Zill' (8%) (Finnemore, 2000).

Mangoes will grow in areas with an average annual rainfall of less than 300mm if other climatic conditions are favorable, provided that irrigation practices sufficiently supplement the soil moisture. Mangoes will also grow well in areas with an average annual rainfall exceeding 2500mm, but the trees would be inclined to produce poorly as vegetative growth would tend to exceed reproductive growth. In South Africa the average annual rainfall for the main mango growing areas varies from 300 to 1000mm (Anonymous, 2006).

Mangoes are prone to wind damage. Strong winds will not only damage the fruit skin, lowering the esthetic value of the fruit, it can also result in fruit losses, lowering yields. Mangoes can, therefore, only be grown in areas subjected to strong winds when some barrier can protect the fruit from wind damage.

Mango flowers are borne in inflorescences with dense panicles containing up to 2000 minute flowers, at branch terminals (Anonymous, 1996). The mango inflorescence bears both hermaphrodite (functionally female) and staminate (functionally male) flowers (Figs 1 - 3). Only a small percentage of hermaphrodite flowers contain functional pistils (stigma, style and ovary), which can develop into fruit after successful pollination and fertilization. Later in the season, but when the mango fruit are still very young and immature, a great many mango fruit will be shed or weaned despite successful fruit set. This enables the tree to successfully bear the remaining fruit to maturity according to its capacity.

Fruit weaning of nearly full-size fruit may occur during the course of the season under adverse climatic conditions or poor production practices. The majority of these are processed for atchar, a green pickled mango product which is highly sought after by the black population in South Africa (Anonymous, 2006).

About 15% of mango fruit are processed to mango puree, used for different mango juices and blends, while a small proportion is dehydrated and packed as dried mangoes (Finnemore, 2000). About 30% of fresh fruit are sold on domestic markets, while an increasing number of fruit are exported to various countries. The majority of export fruit (90%) are destined for the European markets (Netherlands, United Kingdom and France), with approximately 10% exported to the Middle East, the Far East and Canada (Finnemore, 2000).

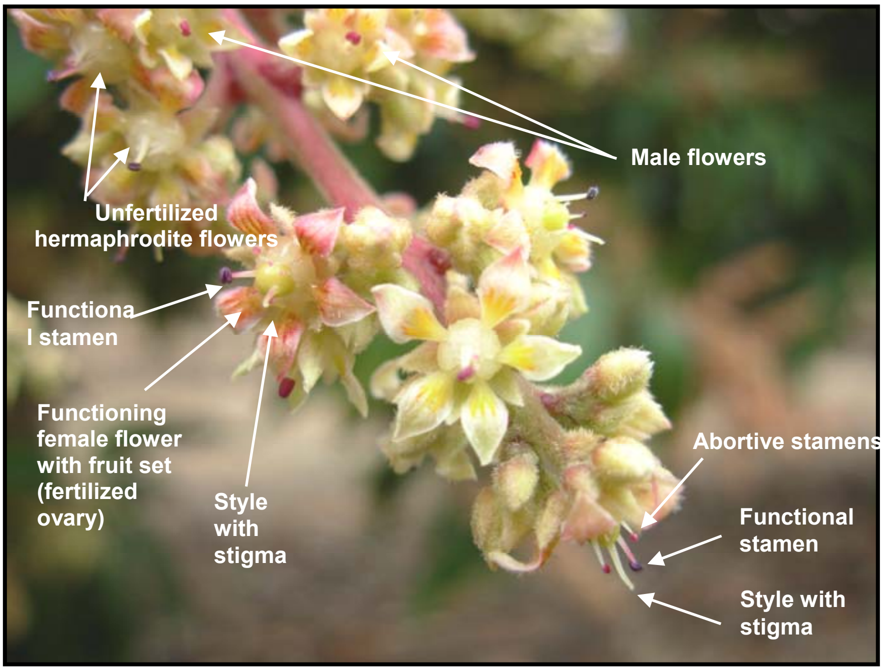

Fig. 1. Mango inflorescence with hermaphrodite (functionally female) and staminate (functionally male) flowers.

Fig. 2. A staminate (functionally male) flower with closely grouped, prominent yellow petals that extend upright.

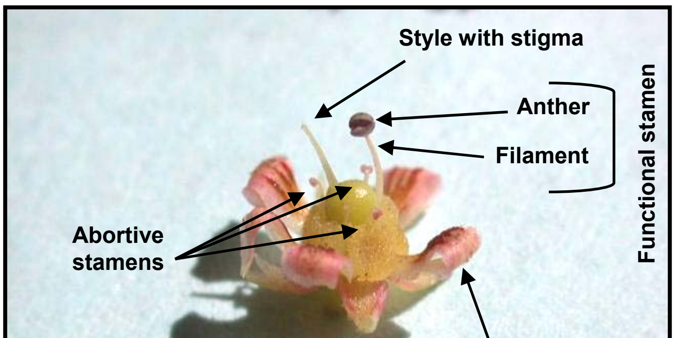

Fig. 3. A perfect hermaphrodite (functionally female) flower with developing fruit (fruit set).

There are numerous diseases affecting mangoes production and influencing yield. Bacterial black spot (BBS), *Xanthomonas campestris* (Fig. 4), caused serious economic losses in the past, to such an extent that this pre-harvest disease threatened the continued existence of many South African mango producers (personal communication with various mango growers, November 2005 – January 2006). BBS, however, have recently been contained mainly through intensive Copper spraying programmes.

Fig. 4. Bacterial black spot, an economic debilitating disease that manifests prior to harvest.

Anthracnose (*Colletotrichum gloeosporiodes*) and soft brown rot and stem-end rot (*Botryosphaeria* complex) are important post-harvest diseases that can influence producer-consumer relationships adversely (Figs. 5 - 6).

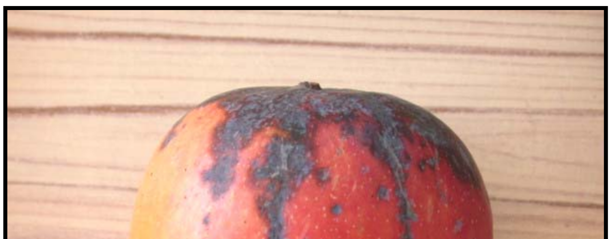

Fig. 5. Post-harvest manifestation of the disease symptoms of anthracnose.

Fig. 6. Stem-end rot (SER) (left) and soft brown rot (SBR) (right), both post-harvest diseases caused by pathogens from the *Botryosphaeria* complex.

The two major insect pests restricting South African producers from exporting to potential new markets are the mango seed weevil, *Sternochetus mangiferae* (Fabricius) (Coleoptera: Curculionidae:) (Fig. 7) and fruit flies, *Ceratitis* spp. (Diptera: Tephritidae:).

Fig. 7. A recently eclosed mango seed weevil adult on a mango seed.

The three fruit fly species of economic importance in South Africa are the Natal fruit fly, *Ceratitis rosa* (Korsch), the marula fruit fly, *Ceratitis cosyra* (Walker), and the Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (Fig. 8).

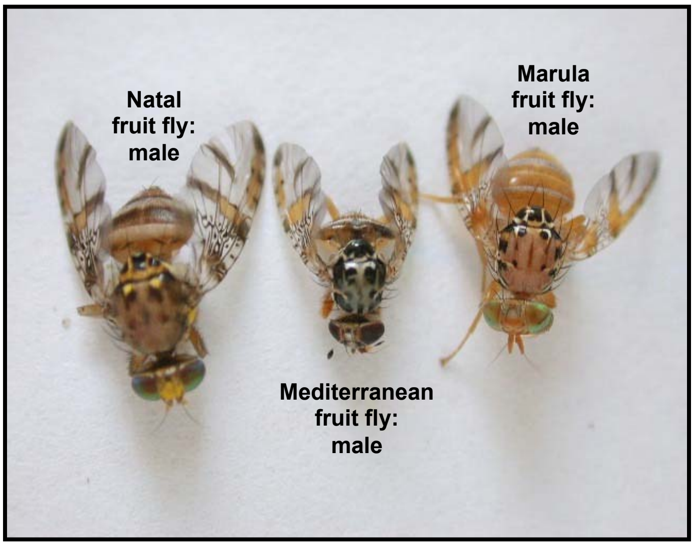

Fig. 8. Three fruit fly species of economic importance for mango production in South Africa.

The mango seed weevil (MSW), *S. mangiferae*, is an important phytosanitary pest for the South African mango industry. The possibility of MSW in mango seeds, along with fruit fly larvae from any of the above mentioned species in the fruit pulp, hinders the South African mango industry from gaining access to new foreign markets such as China and the United States of America. Even in existing export countries such as the Netherlands and Europe, where phytosanitary restrictions are less strict, the presence of adult weevils in mango fruit contributed to a substantial percentage of export fruit rejections in the past (Schoeman, 1988; Joubert & Pasques, 1994). The presence of mango seed weevil within the mango seeds of early cultivars generally causes few problems on local markets, since these fruit are usually marketed and consumed before natural adult emergence from the fruit (Joubert & Pasques, 1994). Adult weevil emergence from late hanging cultivars, however, can lead to large, unattractive lesions or emergence holes (De Villiers, 1987). This not only reduces the number of marketable fruit in a consignment, thereby reducing profit, but it ultimately influences producer-consumer relationships adversely.

The incisions made by the ovipositioning MSW female, as well as larval penetration wounds, generally heal as the mango fruit increases in size, making it difficult to notice these lesions (Schoeman, 1987; Hansen, 1991). With time it may be nearly impossible to distinguish infested from non-infested fruit without opening the seed of the fruit (CABI & EPPO, 2005).

Schotman (1989) stated that the presence of weevils did not seem to affect mango fruit development adversely, but that the mere presence of weevils in fruit can lead to shipments being turned down for export. Weevil incidences in fruit are determined by quality assurance departments who cut a certain number of fruit per consignment prior to shipment, and who guarantee a certain percentage of fruit to be weevil free. This is based on threshold values determined by export countries. For late-hanging cultivars the presence of unattractive emergence holes (lesions) will render fruit unmarketable, whether fruit are destined for overseas or local markets. The presence of developing weevils within the fruit pulp, although rare, will also influence producer-consumer relationships adversely.

Adult weevils are extremely inactive (Joubert & Pasques, 1994) but, since they are nocturnal, activity slightly increases at night (CABI & EPPO, 2005). Although they have well developed wings, adult weevils rarely fly (Schoeman, 1987; Woodruff & Fasulo, 2006). Weevils tend to hide in crevices and other sheltered places during winter, probably in and / or under infested trees, where they are well camouflaged (De Villiers, 1984; De Villiers, 1989). No known natural enemies exist (Schoeman, 1987; Hansen *et al*., 1989). These factors all influence the efficacy of controlling mango seed weevil.

Since mango is the only known host plant of the MSW, with the weevil completing its whole life cycle within the mango seed (De Villiers, 1984; De Villiers, 1987; Hansen *et al*., 1989), the impact of this pest can be greatly reduced by implementing good orchard sanitation practices (the process of removing all weaned fruit out of the orchard) (De Villiers, 1987; Joubert & Pasques, 1994). The effectiveness of sanitation practices, however, is greatly influenced during seasons with high yields. As harvesting becomes more labour intensive as the season progresses, the allocation of labour and time to actions pertaining to sanitation are usually greatly reduced (personal observations, 2005 – 2006 and 2006 – 2007 mango growing seasons). Joubert & Pasques (1994) also found that, since sanitation practices are labour intensive, producers tend to make more use of chemical control measures.

Since no known biological control measures, up to date, have proved effective in controlling mango seed weevil infestations (Schoeman, 1987; Hansen, 1991), control is currently obtained through a combination of good orchard sanitation (cultural practices) and chemical control measures. However, it is important to know the onset and duration of oviposition to determine the best time for chemical intervention, especially with contact and trans-laminar products.

With trans-laminar chemical products, aimed at controlling the developing larvae as they emerge from the eggs and start to burrow into the fruit pulp, it is critical that treatments coincide with, or are applied just after, the onset of oviposition (Joubert & Labuschagne, 1995; Nel *et al.*, 2002). For effective control, this requires intensive and accurate scouting programmes to determine the onset of oviposition. At the same time an in-depth knowledge regarding the duration of oviposition is necessary to determine the period of chemical treatments needed to ensure seasonal control (Joubert & Pasques, 1994).

For effective chemical control of the adult seed weevil by means of contact insecticides, applications should coincide with seasonal and daily activity peaks of the adult weevil (i.e. when the weevils are moving about to feed or reproduce) in order to ensure direct contact, since adult weevils are extremely inactive and tend to hide during periods of inactivity. It is therefore necessary to understand and have an in-depth knowledge about MSW feeding preferences and activity patterns.

It is also imperative to understand the development cycle of the insect in order to know at which time intervention, chemical or physical (cultural), would prove to be the most effective. It is, for instance, important to know when the early instar, miniscule larvae will reach the safety of the seed, where they will be protected by the seed husk, at which time chemical treatments with contact and semi-penetrating products would prove to be ineffective (Verghese, 2000). At the same time it is important to know exactly when adult weevils would be present in the seeds, and more importantly, when the adult weevils would be ready to emerge from the seed, in order to ensure that orchard sanitation is executed effectively to prevent re-infestations.

However, in order to effectively manage any crop and obtain maximum yield, it is important to follow a holistic approach, whereby informed decisions are made based not only on an in-depth knowledge of any specific pest, but also on the effect that control measures of any given pest may have on other organisms that form part of the specific monoculture system. Chemical control programmes should form part of integrated pest management systems, encompassing chemical, cultural, physical and biological control measures and should aim at managing the whole complex of insects and diseases at economic threshold levels. It is thus not only imperative to understand the target specie’s biology, reproductive cycle and dispersal patterns, but also to understand the pest in relation to the complex of interactions existing between all the organisms that occur within the larger agricultural system.

There does not seem to be any direct adverse or advantageous interactions between any insect pest known to attack mangoes and the mango seed weevil (personal observations, 2006 – 2007 and 2007 – 2008 mango growing seasons). Various species of aphids (Hemiptera: Aphididae) feed early in the season on plant sap extracted mainly from very young mango flushes (vegetative shoots), and then again feed after the commercial harvest when the trees are pruned and vegetative growth is induced (Fig. 9). Adult mango seed weevils also feed mainly on very young flushes, consuming small portions of the lamina and feeding along the petiole (Fig. 10).

Although it does seem probable that aphid colonization on young flushes may deter MSW feeding, colonization by aphids usually occurs in isolated patches. And, since a mango tree produces an abundance of flushes, this negates the possibility that aphids may influence or hinder adult MSW feeding.

Fig. 9. An aphid colony colonizing a young vegetative shoot during the early part of the mango growing season.

Fig. 10. Adult seed weevil feeding damage on very young, soft flushes, showing portions of the lamina that have been consumed (left), or where plant sap along the petiole has been extracted (right).

During the early part of the season (spring), when developing fruit is small, aphids may periodically infest mango fruit. Although aphid colonies generally consist of only a couple of individuals, small to medium sized colonies may be found. Colonization usually occurs only on a few isolated fruit, negating the possibility that early aphid colonization may hinder weevil movement and / or oviposition (Fig. 11).

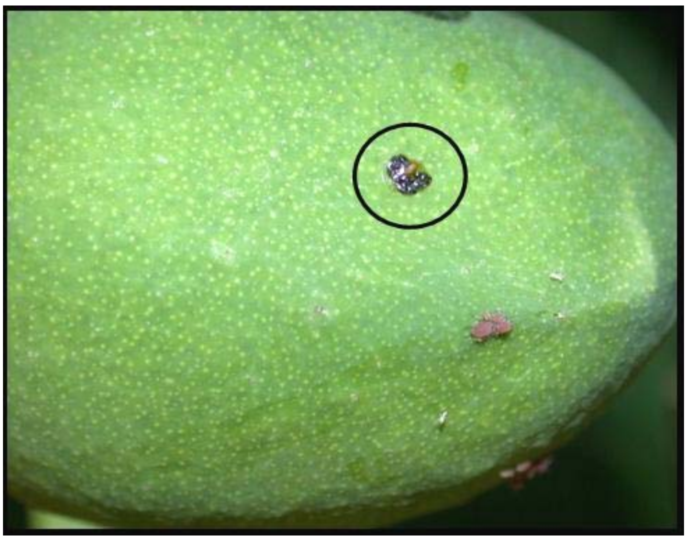

Fig. 11. A mango seed weevil egg (encircled) close to a small colony of aphid nymphs.

During the latter part of the season (December - February), when aphid infestations on mature fruit are more severe and the excretion of honeydew, the presence of ants and the occurrence of black sooty mould could affect adult MSW movement and oviposition, the bulk of weevil oviposition had already occurred (Fig. 12).

Fig. 12. Heavy aphid infestation on a mature mango fruit.

Other insects known to excrete honeydew which lead to the presence of ants and black sooty mould and which, in turn, may influence weevil movement, are mealybug (various species) (Fig. 13) and some homopteran scale insects. These insects are also found, either sporadically and in isolated colonies, or at the end of the season when the bulk of seed weevil activity and oviposition had already occurred. For this reason they do not influence either weevil movement, or oviposition (personal observations, 2005 – 2006, 2006 – 2007 and 2007 – 2008 mango growing seasons).

Fig. 13. Long-tailed mealybug (*Pseudococcus longisporus)* is usually present in large numbers on mango fruit at the end of the mango growing season (February – March).

Heavy mealybug infestations late in the mango growing season (February – March) usually lead to fruit decomposition due to fungal growth, and eventually fruit-drop. These prematurely ripened fruit may indirectly aid adult MSW emergence, since fruit-drop due to mealybug infestations usually occurs when the majority of weevils inside the fruit have already reached maturity. MSW emergence is most probably triggered by this increase in fruit moisture levels due to the ripening and / or decomposition, although no quantitative data is available to support this theory.

Adult weevil emergence has been found to be indirectly aided by the presence of fruit flies (personal observations, 2005 – 2006 mango growing season). Adult fruit flies lay their eggs just underneath the fruit skin of usually physiologically maturing mango fruit, although oviposition may occur on green fruit. The larvae feed and develop inside the fruit pulp, causing decay (Van den Berg *et al.*, 2001) and increasing fruit moisture levels, leading to premature drop of overripe and / or decomposing fruit (Fig. 14).

Adult seed weevil emergence seemed to have been more frequent from these prematurely ripened fruit than from green, tree hanging fruit. Decomposition, and the resultant increase in fruit moisture levels, of mango fruit due to the post-harvest diseases SBR and SER may, therefore, also indirectly aid adult weevil emergence, but this phenomenon has never been investigated.

Fig. 14. Fruit fly infested mango fruit, where larval feeding leads to fruit decay.

Thrips (Thysantoptera, Thripidae) feed mainly on young mango leaves and fruit, extracting chlorophyll (Van den Berg *et al.*, 2001). They are usually found during flowering, during periods of vegetative growth (flushing of trees) when soft leaflets are abundantly present, and during the early stages of fruit set and development.

The presence of this miniscule insect, or the resultant damage caused by their feeding on fruit surfaces, however, does not seem to hinder weevil movement or inhibit oviposition (Fig. 15). Feeding is also just as likely to take place on fruit with thrip feeding damage as on fruit free from the resultant superficial scar tissue on the fruit skin (Fig. 16).

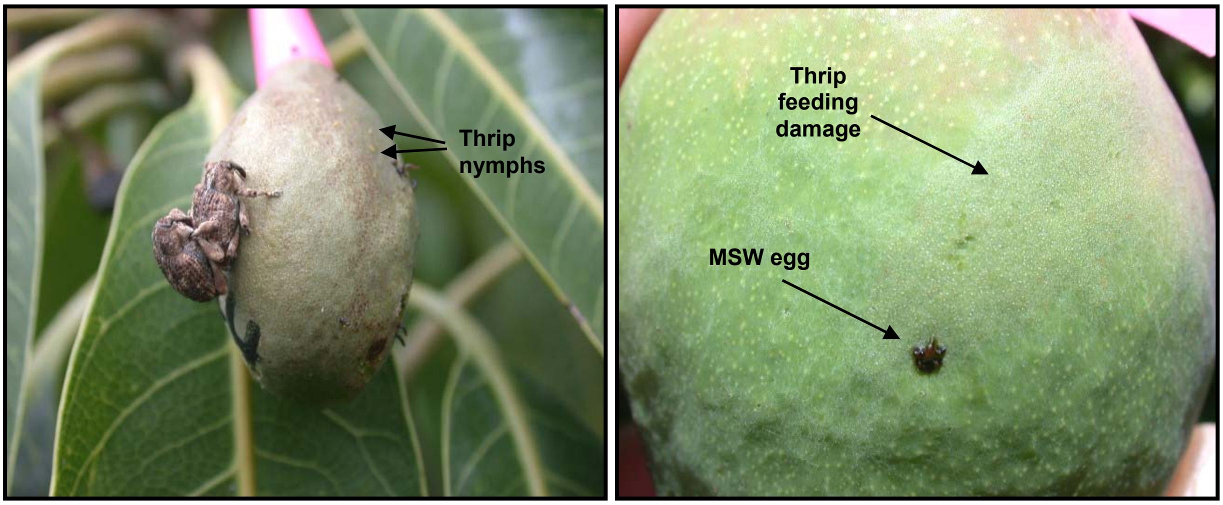

Fig. 15. Weevils mating on an immature mango despite severe thrip feeding damage (left), and oviposition among prominent thrip feeding damage (right).

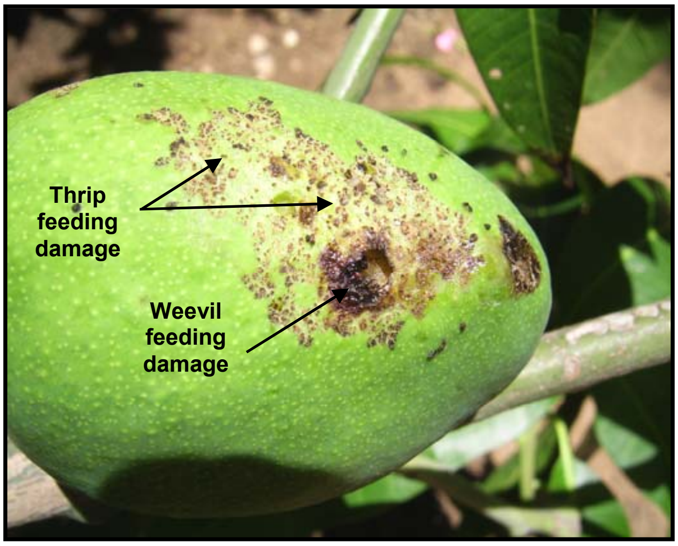

Fig. 16. Mango seed weevil feeding despite prominent thrip feeding damage.

Although the presence of no specific insect seemingly influences the incidence and / or severity of MSW movement, feeding and / or oviposition directly, the presence of some insects or diseases may indirectly aid their emergence. Measures aimed at controlling the MSW, however, may have an indirect impact on the incidence and / or severity of some other insect pests, i.e. mango scale (*Aulacaspis tubercularis*) and mealybug (De Villiers, 1989; Joubert & Labuschagne, 1995). Control measures aimed at controlling the mango seed weevil may eradicate parasitoids keeping mango scale and mealybug populations in check. Alternatively, control measures may impact these insects directly should such control measures, aimed at controlling MSW, also eradicate or control these infestations. Therefore, in order to effectively control MSW, and at the same time retain the integrity of the environment, it is imperative to follow a holistic approach. This means not only having an in-depth knowledge about the target insect, understanding activity patterns, feeding behaviour, procreation and development of the MSW, but also understanding interactions with other organisms and being aware of the impact of control measures on other organisms that forms part of a specific agricultural system.

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CHAPTER 2

Activity and distribution patterns of the adult mango seed weevil

2.1. Introduction

Various authors have investigated mango seed weevil (MSW) behaviour, activity patterns and distribution within mango trees and orchards. Schoeman (1987b) found large numbers of adult seed weevils in tree crotches directly after harvest, although these numbers did not correlate to fruit infestation levels prior to harvest. During the course of the season he observed only a small number of adult weevils, either walking along tree branches within trees (Schoeman, 1987a), or flying to adjacent trees where they landed with ease, disappearing into the foliage (Schoeman, 1987b). He also collected soil and debris samples from beneath infested trees to investigate for the presence of mango seed weevils. These samples, however, yielded no adult weevils. He concluded that the question pertaining to the whereabouts of the mango seed weevil during the course of the season remained unanswered.

In 1994, Joubert and Pasques investigated the activity and behaviour of adult weevils in captivity. They placed over a thousand depulped mango seeds (the fruit flesh removed from around the seeds) in gauze cages, monitoring the rate of adult emergence and weevil activity after emergence. They found that, after emerging from the seeds, the adult weevils tended to move upwards in the gauze cages. Careful sifting of the top soil from the cages yielded only three dead specimens. From this they concluded that emerging adult weevils would probably follow the same pattern under natural conditions, moving from the seed at ground level upwards into the mango tree, and that the mango seed weevil did not hibernate in the soil. The emerged adults were then marked with fluorescent paint and transferred to a gauze cage erected over a young mango tree in an orchard. By observing these adults they found that, although the weevils were extremely inactive and remained in a specific spot for long periods if undisturbed, activity did increase during September when the adult weevils were found mating, and October when the majority of eggs were deposited. On three separate occasions the site was visited at night (about 22h00), using an ultra violet light to determine whether activity levels increased at night. Although they did find more individuals, the weevils were in the same resting positions as was noted during the day. No conclusions could be made regarding day-night activity patterns. Some literature references, however, do state that the adult weevils are nocturnal, feeding, mating and laying eggs at dusk (Balock & Kozuma, 1964; Schotman, 1989; CABI & EPPO, 2005). No weevils in flight were recorded for the duration of the study.

De Villiers (1984) also described adult seed weevils as being extremely inactive and although winged, rarely flying long distances. Such observations generally resulted in the assumption that adult weevils crawl, rather than fly, into the trees after emerging from infested seeds (CABI & EPPO, 2005). However, Joubert and Pasques (1994) and Joubert and Labuschagne (1995) found no evidence to support this theory. They investigated the efficacy of sticky barriers, placed around the trunks and main branches of mango trees in an orchard with previous high levels of infestation, for capturing adult weevils. No adult weevils were found on the barriers, while fruit infestation levels from treated trees were comparative to those of untreated control trees. Schoeman (1987a) also found that sticky barriers, placed around the main trunk of the mango tree, did not yield any adult weevils. He concluded that adult weevils probably fly into trees and between trees, although they tend to walk along branches within trees.

Since varying opinions exist and little conclusive information is available regarding the activity patterns, distribution and behaviour of this very important phytosanitary pest, a study was undertaken by Westfalia Technological Services (WTS) to investigate the behaviour and activity patterns of mango seed weevil adults in captivity, as well as in the field.

2.2. Materials and Methods

2.2.1. Activity and behaviour of adult seed weevils in captivity

2.2.1.1. Seasonal activity patterns of the mango seed weevil

Over a four-year period, from July 2004 to April 2008, the activity and behaviour of adult seed weevils in captivity was monitored continuously. Adult seed weevils that were found in the field, emerging adults from emergence studies, and adults that were removed from infested fruit and discarded seeds in the field, at the same time that natural adult emergence occurred, were placed in containers (0.6m x 0.4m x 0.3m) with glass lids (Fig. 1). These containers, referred to as 'breeding boxes', contained between 200 and 300 adult seed weevils.

Young mango flushes were regularly placed in the breeding boxes for the adult weevils to feed on and to provide shelter. In season, mango fruit were placed inside the containers for feeding and oviposition. The breeding boxes were kept in an office at ambient temperatures and under electrical (artificial) lights. Monitoring was done periodically during the day, measuring activity as the number of weevils, out of the total number of weevils present within a given breeding box, actively moving around, feeding on flushes and fruit or mating. The relative positions of individuals within the breeding boxes were also noted, as well as the onset and cessation of mating and oviposition.

Fig. 1. A 'breeding box' containing mango seed weevil adults, mango flushes (feeding and shelter) and mango fruit was (feeding and oviposition).

2.2.1.2. Daily activity patterns of the mango seed weevil

Weevil activity and behaviour was also monitored at night during the 2005 / 2006 mango growing season, specifically from 12 September (to include the period that adult weevils terminate diapause and become active) to 2 November (to include the period that adult weevils were reported to be most active), since the onset of mating and ovipositioning was most likely to occur within this period. A breeding box with approximately 200 adult weevils was kept indoors at room temperature. The breeding box was positioned in front of a clear glass window to expose the adult weevils to natural light.

Monitoring occurred at irregular intervals from late afternoon to early morning. The relative positions of individuals inside the breeding box was noted, while activity patterns was again established by counting the number of adults in each of the relative positions, i.e. at the glass surface (inactive vs. moving about; clustered vs. single), among flushes (inactive, feeding or moving about), present on fruit (inactive, feeding or moving about) and present on top of the soil surface (clustered and inactive vs. moving about).

With each assessment the mango fruit were removed from the breeding box to count the number of weevil eggs present on the fruit skin. Mating behaviour was noted as the number of weevils mating, irrespective of their position in the breeding box. Overhead electrical lights were switched on for the duration of the evaluation at night. Although the use of electrical lights are not representative of natural conditions and may have influenced behaviour, sufficient light was needed to monitor weevil activity and count the MSW eggs on the fruit. Since assessment periods lasted for only a couple of minutes, the effect of the electrical lights on MSW behaviour was deemed negligible.

2.2.2. Activity and behaviour of adult seed weevils under natural conditions

In the 2004 / 2005 mango growing season a mango orchard (early season cultivar ‘Zill’) with known high seed weevil infestation levels, on the farm Jonkmanspruit (latitude 24^{o}24’S, longitude 30^{o}48’E) in the Hoedspruit magisterial district of the Limpopo Province, was visited on 23 September in order to determine the whereabouts of adult weevils during the day. The orchard was visited early in the mango growing season, corresponding to the onset of adult weevil activity in captivity. Assuming the onset of activity in the field to be the same as that for adult weevils in captivity, the farm was visited at the stage where the majority of weevils were thought to be inactive and most likely to be found in their over-wintering sites. The branches of various trees known to have been

infested by seed weevil in previous seasons was carefully inspected, searching for adult weevils on branches, among foliage and on the marble sized fruit, as well as in the crevices on tree trunks and in tree crotches.
Since no adult weevils were found on 23 September, the time corresponding with the onset of activity of adult weevils in captivity, the orchard was again visited on 13 and 15 October, corresponding to a time that the adult weevils in captivity were found to be more active, frequently mating and consistently laying eggs. During this visit it was decided to shake and / or beat the tree branches after inspections of the tree trunks, branches and foliage in order to try and dislodge adult weevils, if present, from infested trees.

This time around infested trees could be identified by prominent oviposition scarring or weevil eggs on the fruit surfaces of the golf ball sized fruit. A white sheet was placed underneath the trees to collect any weevils, should they be dislodged by shaking and / or beating the branches. Since adult weevils are well camouflaged and quite small compared to the total surface area of the tree, and since no adult weevils could be found during the previous visit, this was done in order to determine whether adult mango seed weevils did reside within infested trees. Soil and debris were also collected from underneath the same trees to determine whether adult weevils resided in the soil or on the soil surface among debris.

In the 2005 / 2006 mango growing season, the method of shaking and / or beating infested trees to dislodge adult weevils was repeated on the farm Murlebrook (latitude 23^{o}52'S, longitude 30^{o}23'E) in the Letsitele magisterial district of the Limpopo Province. This was done on the 25th of October, with the fruit size between that of a golf ball and a tennis ball, and again on the 2nd of November 2005. Isolated trees (cv. 'Long Green'), situated apart from established orchards and where no normal production practices or control measures were followed, were used, since these trees were reported to have had severe infestations in previous years. As in the previous season, infestation was confirmed visually by the presence of oviposition scarring or weevil eggs on the fruit skin before shaking and / or beating the tree branches to dislodge any adult weevils present within the tree, collecting them on a white sheet placed under the tree.

In the 2006 / 2007 season, tree branches were again shaken and / or beaten to dislodge adult weevils. For this study two orchards (early season cultivar 'Tommy Atkins') situated in the Hoedspruit magisterial district of the Limpopo Province were used. The first orchard, Block B46, is situated on the organic farm Moriah (latitude 24°25'S, longitude 30°51'E), with the second orchard, Block GD7, situated on Bavaria Fruit Estates (latitude 24°24'S, longitude 30°53'E), adjacent to a compost site, the drying unit and the pack house. Within each orchard, 10 trees within a single row comprised individual trial plots, with 10 non-data trees within a row, and one non-data or border row between rows, separating the trial plots, resulting in 8 plots (8 replications) evenly spaced throughout the orchard (trial protocol and design courtesy of Dr. Johan de Graaf, Senior Researcher and Coordinator, Phytosanitary Research, Westfalia Technological Services).

From both orchards a single tree from each trial plot was shaken and / or beaten fortnightly (Fig. 2), using subsequent trees in a plot for each consecutive action, and placing dislodged adults back into the same tree after the action was completed.

Fig. 2. Shaking and / or beating mango tree branches to dislodge adult mango seed weevils.

The process commenced with the onset of the mango growing season with the trees in full flower (1 August 2006) and continued up to the time that fruit reached full size (3 December 2006), but did not continue up to the time of commercial harvest (end of December to the beginning of January, depending on the season), since too many non-data fruit were lost during the process.

The number of dislodged adult weevils that were collected on the sheet placed underneath the data tree (Fig. 3) was noted. In order to obtain qualitative data to determine the correlation between adult weevils present within a tree, and oviposition or fruit infestations, fruit were simultaneously collected for evaluation. Three mango fruit were randomly sampled per tree, from all the trees in a plot. Fruit were sampled from the top, the middle and the bottom of a data tree, alternating between the eastern and the western facing sides for adjacent trees.

Two hundred and forty (240) fruit per block or orchard (3 fruit per tree, sampled from 10 data trees, 8 replications) were sampled fortnightly to determine the incidence of weevil eggs on the fruit skin. This was done by noting the presence or absence of weevil eggs per fruit and by counting the number of eggs per sampled fruit to determine the average number of eggs per fruit for each assessment period. Fruit were sampled from the time that the first weevil eggs were noted on the developing fruit, the majority of which were golf ball sized (10 October 2006), up to the commercial harvest of the cultivar (1 January 2008).

Fig. 3. An adult seed weevil dislodged by shaking and / or beating the branches of a weevil infested mango tree.

2.3. Results, Discussion & General Observations

2.3.1. Activity and behaviour of adult seed weevils in captivity

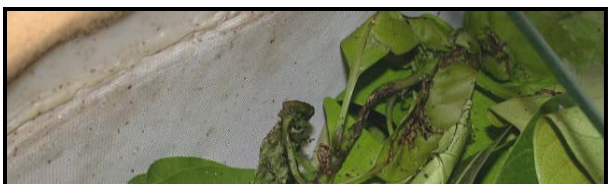
2.3.1.1. Seasonal activity patterns of the mango seed weevil

A few of the captive adult seed weevils terminated diapause as early as late August, although only a very small percentage of all the adults in a breeding box were found to be active, with negligible feeding damage. From the middle to the end of September activity was more pronounced, with more weevils seen among the mango flushes (Fig. 4) and at the glass surface, and with feeding damage more prominent. Some weevils were found mating at this stage (Fig. 5).

Fig. 4. Adult mango seed weevils feeding on the stem of a mango flush.

Fig. 5. Mango seed weevils underneath a mango leaf, with a mating pair on the right.

By the beginning of October many adult weevils were found to be active. Some adult weevils were found feeding or sheltering singularly among the foliage, others were found as mating pairs among the foliage or on the glass cover, while others were found clustered among the mango foliage or at the junction of the glass cover and the side of the breeding box. At this time feeding damage was excessive (Fig. 6), confirming this increase in activity levels.



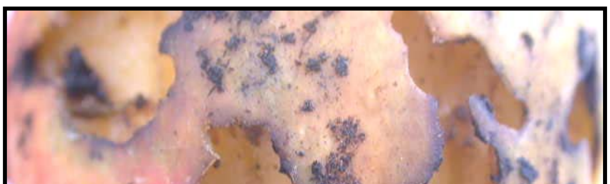


Fig. 6.	Excessive mango seed weevil feeding damage on mango flushes (left) and mango fruit (right).

However, despite noting more adult weevils, finding a number of eggs on fruit surfaces and noting prominent feeding damage, the majority of adult weevils were still found clustered and inactive on the soil surface. Although the majority of these inactive weevils were seeking shelter underneath the foliage, some adult weevils were found feeding on the underside of the mango fruit, thereby feeding whilst being sheltered.

Although the trigger responsible for terminating diapause is still unknown, it is generally believed to be connected to photo-period (Balock & Kozuma, 1964; Schotman, 1989). Mating started within a day or two after diapause termination and occurred throughout the season (September to January), but the bulk of mating activity seemed to have occurred from October to the end of November, with only few mating pairs found after this time. From December, up to January, mating was negligible, but did occur sporadically.

During the four years that behaviour and activity of adult weevils in captivity was monitored, the onset of oviposition for mango seed weevil adults in captivity was consistently between the middle and the end of September. Coinciding with increased mating, the majority of eggs were laid during October and November, with oviposition reaching a peak around the end of October / beginning of November. After November, egg laying declined steadily. From the end of December, up to the end of January / beginning of February, when no more eggs were noted, the number of eggs found on fruit placed in the breeding boxes was negligible when compared to egg laying during peak season (See graphic representation of natural MSW oviposition; Chapter 4: Oviposition in the field).

Overall activity levels during the day, even during peak season (October to November), were low, with the majority of weevils inactive and clustered within rolled leaves or on the soil surface. This information supports the findings of Joubert and Pasques (1994), namely that the mango seed weevil is extremely inactive and tends to remain in the same spot for several hours if undisturbed.

The peak of weevil activity, irrespective of the time of the day or the season, when most of the adult weevils were seen moving about, were directly after changing old flushes and spoiled fruit with fresh foliage and freshly collected fruit, i.e. feeding the MSW adults kept in captivity. Activity seemed to increase more specifically when freshly collected flushes and fruit were washed with water before placement, or when water was sprinkled over the flushes and fruit to increase moisture levels in the breeding boxes.

As part of the process of studying the activity patterns of adult seed weevils in captivity, emerging or emerged adult weevils were placed in a separate breeding box to monitor behaviour and activity after emergence. These adults were obtained from within infested fruit at the same time that natural adult eclosion was noted in the orchards (middle of January to March), as well as from eclosion studies.

Contrary to the expectation that these adults would immediately go into diapause, some activity and feeding was noted. By the end of January mating was observed, with oviposition found from the end of February through to the middle of March (Fig. 7). Both mating and oviposition, however, was found to be negligible when the number of emerging / emerged adults present in the breeding box at this time was taken into consideration.

Fig. 7. Seed weevil oviposition from adult females that have eclosed or were removed from infested mango fruit and seeds at the end of the season (January to March).

Initially, egg laying did seem fairly high (Fig. 8) when compared to the number of adults seen mating and moving about, since the majority of the weevils were found clustered and inactive at the bottom of the breeding box, sheltering under the foliage. A closer inspection of these eggs, however, showed that only a few eggs were present on the fruit skin, and that the majority of the egg laying sites contained no eggs (Fig. 9).

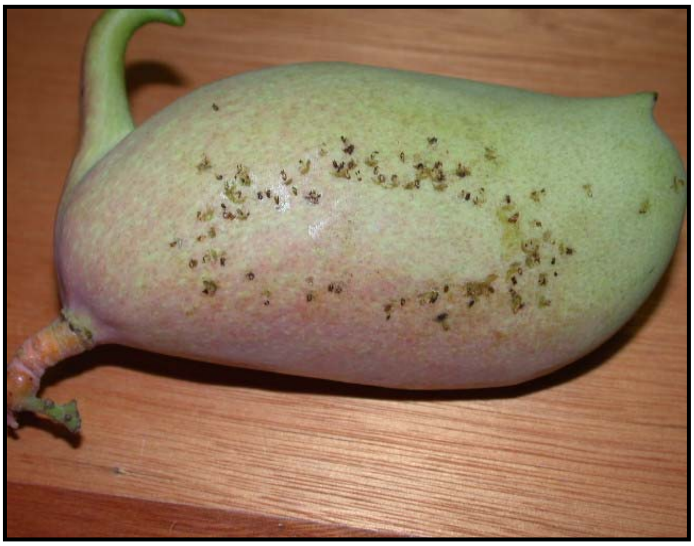


Fig. 8. Mango seed weevil oviposition from captive females that have eclosed, or were removed from infested seeds in the same time period that natural eclosion took place.

Fig. 9. Close-up of mango seed weevil eggs that were laid by adult females at the end of the mango growing season (February to March, 2006).

In order to investigate the viability of these eggs, a piece of the mango peel containing intact eggs was removed with a scalpel and placed under a stereo microscope. The latex covering the eggs was carefully removed to reveal the eggs. The majority of the eggs that were studied appeared to have been intact (Fig. 10).

Fig. 10. Mango seed weevil eggs laid during February / March, with the latex cover (left) removed to reveal seemingly viable eggs underneath (right).

However, even though it did appear as if the majority of the eggs that were laid by eclosed females at the end of the growing season did have the potential to produce viable offspring, the chances of successful development could not be determined. At this late stage in the season the majority of the mango fruit that were placed inside the breeding boxes were already physiologically mature, ripening and rotting too fast to monitor for the time span required by larvae to develop into adults. Although these findings are contradictory to the observations made by Hansen (1991), who found that eclosed females had undeveloped ovaries, it does support the findings of Balock and Kozuma (1964), who found that MSW adults, collected from the field after harvest or fruit fall, required 11 to 40 days before laying eggs. Adults that were excised during the same period from infested seeds required 56 days to complete the pre-oviposition period.

Activity declined steadily from the end of March and, by the middle of April, the majority of adults were found, at any given time, at the bottom of the breeding box. The weevils were either clustered on the soil surface under leaves, or sheltered within rolled or folded leaves, corresponding to literature references mentioning this clustering behaviour of over-wintering adults (Hansen, 1991). Although the majority of weevils remained inactive at this stage, some weevils did become active as a result of disturbances, e.g. handling when replacing flushes upon which they moved away in order to seek alternative shelter. During diapause very little feeding was observed, although some feeding scars were seen on flushes (foliage and stems) throughout the over-wintering period. Feeding seemed to have occurred more readily when replacing older foliage with fresh, young flushes and, more specifically, when moisture levels were increased at the same time (e.g. washing or sprinkling), although overall activity remained negligible.

Throughout the season, but mainly during November, many adult weevils were found dead on the soil layer that covered the bottom of the breeding boxes. This phenomenon occurred each year, supporting literature references stating that the majority of weevils have a life span of 140 to 300 days (Schotman, 1989; De Villiers, 1989), although they may live for two years if provided food and water (Balock & Kozuma, 1964).

2.3.1.2. Daily activity patterns of the mango seed weevil

Corresponding to literature references (Schotman, 1989; CABI & EPPO, 2005), adult weevils appeared to be nocturnal. Mating, however, was found to occur mainly during the day (inactivity period), with mating pairs staying together for long periods in the same spot if undisturbed. Although these findings are contradictory to some literature references claiming feeding, mating and egg laying to occur at dusk (CABI & EPPO, 2005), it does support the findings of Balock and Kozuma (1964), who also observed adult weevils mating during the day. While some mating was noted at night, the majority of weevils were found to be single from dusk to the early hours of the morning.

At night the majority of adult weevils were found in the top half of the breeding box, moving singularly among the flushes and along the bottom on the glass covering the breeding box. Overall mobility also increased, with weevils not remaining in the same spot for long periods. Although adult weevils were found feeding during the day, feeding did appear to occur more frequently at night, with greater numbers of weevils found among the flushes. More adult weevils were also found feeding singularly all over fruit surfaces, contrary to sheltered feeding during the day that occurred mainly in clusters on the underside of the fruit and at the junction of the fruit and soil surface.

During the early hours of the morning activity steadily declined, with fewer weevils actively moving about in the breeding box, and numbers on the glass cover declining visibly. At dawn, only few weevils were found in the top of the breeding box, with the majority found in the bottom half of the breeding box, sheltering among the flushes or under fruit. The few individuals visible at the top of the breeding box were, at this stage, also found to be more inactive, clustering at the interface of the glass cover and the side of the breeding box, rather than remaining single and moving about. Balock and Kozuma (1964) also recorded that, during the day, adult weevils crowded together in clusters, or concealed themselves in crevices or cavities.

2.3.2. Activity and behaviour of adult seed weevils under natural conditions

No adult weevils were found, either in the mango trees, or on the soil surface, during the first visit to the farm Jonkmanspruit on 23 September 2004. During the subsequent visit on 13 October 2004, four adult weevils were found in a time span of 2 hours, three in the crevices of a tree crotch, and the other one walking along a tree branch. On 15 October 2004, twenty five adult weevils were found within 3 hours. Four of these weevils were found along branches and on fruit, with the remaining number dislodged when shaking and / or beating the tree branches.

The weevils found by inspecting the tree branches, foliage and tree trunks were either already in an inactive state (Fig. 11), or feigned death when handled, retracting their legs and proboscises tightly against their bodies. They remained in this condition for a considerable period of time, corresponding to observations made by De Villiers (1984).

Fig. 11. Inactive adult mango seed weevils, with the proboscis and legs retracted (left) and an active weevil (right) moving about on a mango fruit.

More adult weevils were dislodged by shaking the tree branches and / or beating the trees than were found inspecting the branches, foliage and tree crotches, stressing the fact that these small insects are well camouflaged and difficult to find within the mango trees. As was reported by Schoeman (1987b), the total number of adult weevils found in the mango trees did not correlate to infestation levels as indicated by the number of fruit with eggs on the fruit skin. The reason for this could be that the adults were hiding lower down on well established tree trunks or in the sturdy tree crotches, making it difficult to dislodge them. All the adults that did fall onto the sheet were inactive, feigning death with their legs and proboscises pulled in tightly against their bodies. They remained in this condition long after falling out of the trees.

Only a few adult weevils were found when sifting through the soil and debris samples collected from beneath weevil infested mango trees. All the individuals were dead, some specimens already in the process of breaking apart, sometimes with only pieces of the exoskeleton remaining (Fig. 12). These observations support the findings of Schoeman (1987b) and Joubert and Pasques (1994), who reported that adult mango seed weevils do not hibernate in the soil or among debris on the soil surface.

Fig. 12. A dead mango seed weevil found among the debris underneath an infested mango tree (left). Some of the weevils found in the soil and debris samples were already breaking apart, with only pieces of the exoskeleton remaining (right).

On the farm Murlebrook, during the 2005 / 2006 mango growing season, more adult weevils were dislodged from weevil infested mango trees than the previous season on the farm Jonkmanspruit, despite the fact that some of these trees were large with well developed, sturdy trunks. The adults that were dislodged by shaking and / or beating the tree branches were also, contrary to the previous season, quite active. Although the majority of the weevils feigned death upon landing on the sheet, they became active within a minute or two, seeking alternative shelter. Some weevils took to flight upon landing on the sheet, flying back into the same tree or flying the short distance to adjacent trees.

The reason that more weevils were dislodged during the 2005 / 2006 season could be due to the fact that more adult weevils were active and moving along the tree branches later in the season (sampling on 25 October & 2 November 2005 vs. 13 and 15 October in the previous season), or it could have been that infestation levels were higher at Murlebrook than at Jonkmanspruit (comparative studies regarding fruit infestation levels were not done). On 25 October, 165 adult weevils were collected from 7 separate and isolated trees between 08h00 and 11h30, with 178 adults collected from the same trees on 2 November between 12h00 and 17h00.

Since more promising results were obtained in the 2005 / 2006 mango growing season when using this method of shaking and / or beating tree branches to dislodge adult weevils from infested trees, the same procedure was repeated in Hoedspruit the following season. For the 2006 / 2007 mango growing season, the number of adult weevils present within an area or orchard, as determined by shaking and / or beating mango trees, was correlated to egg laying.

Monitoring the incidence of adult weevils commenced with the onset of the mango growing season, with the mango inflorescences in full flower and with the first fruit just setting (1 August 2006). Monitoring adult weevils continued only until the fruit reached full size (3 December 2006), since too many non-data fruit were dislodged during the process of shaking and / or beating the mango branches, especially as the fruit became physiologically mature, effectively reducing the yield with each sampling session. Fruit sampling to determine the presence of weevil eggs on the fruit surface could only commence with the onset of oviposition, after the fruit more or less reached golf ball size (10 October 2007). The process of fruit sampling continued up to the time of the commercial harvest for the cultivar (1 January 2008).

Table 1 summarizes the total number of adult weevils dislodged from 8 trees (8 replications), with table 2 summarizing the total number of fruit out of the 240 fruit sampled (3 fruits from 10 trees, 8 replications), with weevil eggs on the fruit skin, from Block B41, Moriah. Tables 3 summarizes the total number of adult weevils dislodged from 8 trees, while table 4 summarizes total number of fruit with weevil eggs on the fruit skin, obtained from Block GD7, Bavaria Fruit Estates. Tables 5 and 6 summarize the average number of eggs per egg infested fruit obtained for each of the assessment dates.

Figures 13 and 14 graphically depicts the relationship between the number of weevils present in an area, and the number of egg infested fruit from that same area, as the season progressed, for Blocks B41 (Moriah) and GD7 (Bavaria Fruit Estates) respectively.

Table 1. The total number of adult seed weevils collected by shaking and / or beating 8 mango trees, cv. 'Tommy Atkins', in Block B41, Moriah, during the 2006 / 2007 mango growing season.

Date / Rep.	01.08	16.08	28.08	12.09	26.09	10.10	24.10	07.11	20.11[1]	06.12[1]	19.12[2]	03.01[2]
1	0	0	0	0	0	0	2	0	0	0		
2	0	0	2	1	0	1	0	0	1	0		
3	0	0	0	1	0	1	0	0	0	0		
4	1	0	0	0	0	0	0	0	2	0		
5	0	0	0	0	0	0	0	1	0	0		
6	0	0	0	0	0	0	0	0	0	0		
7	0	0	0	0	0	0	0	0	1	0		
8	0	0	0	0	0	0	0	1	0	0		
Total	**1**	**0**	**2**	**2**	**0**	**2**	**2**	**2**	**4**	**0**		

[1]Fruit full size and starting to mature with many non-data fruit dropping when sampling for adult weevils

[2]No sampling for adult weevils due to influence of fruit-drop on yield

Table 2. The total number of fruit with weevil eggs on the fruit skin from Block B41, Moriah, expressed as a percentage of the total

number of fruit sampled, cv. 'Tommy Atkins'. A total of 240 fruit (3 fruit from 10 trees, 8 replications) were sampled fortnightly from the time that the first weevil eggs were noticed, up to the commercial harvest of the cultivar.

Date / Rep.	**01.08[1]**	**16.08[1]**	**28.08[1]**	**12.09[1]**	**26.09[1]**	**10.10**	**24.10**	**07.11**	**20.11**	**06.12**	**19.12**	**03.01**
1						1	15	18	20	9	16	6
2						3	11	15	4	10	12	7
3						4	7	9	15	10	11	1
4						5	11	17	14	18	12	10
5						1	5	8	3	9	6	1
6						3	1	13	2	12	4	0
7						2	5	7	7	4	1	4
8						11	0	0	3	1	3	1
Tot.						**30**	**55**	**87**	**68**	**73**	**65**	**30**
% egg infested fruit						**12.5**	**22.92**	**36.25**	**28.33**	**30.42**	**27.08**	**12.5**

[1] Early fruit-season with fruit smaller than golf boll size and no oviposition

Table 3. The total number of adult seed weevils collected by shaking and / or beating 8 mango trees, cv. 'Tommy Atkins', in Block GD7, Bavaria Fruit Estates, during the 2006 / 2007 mango growing season.

Date / Rep.	01.08	16.08	28.08	12.09	26.09	10.10	24.10	07.11	20.11[1]	06.12[1]	19.12[2]	03.01[2]
1	0	0	0	0	2	2	1	0	0	0		
2	0	0	0	0	0	1	3	0	1	0		
3	0	0	0	0	0	0	0	1	0	0		
4	0	0	0	0	0	0	0	0	0	0		
5	0	0	0	0	0	0	0	2	0	0		
6	0	0	0	0	1	0	0	0	0	0		
7	0	0	0	0	0	0	0	0	0	0		
8	0	0	0	0	0	0	0	0	1	0		
Total	**0**	**0**	**0**	**0**	**3**	**3**	**4**	**3**	**2**	**0**		

[1] Fruit full size and starting to mature with many non-data fruit dropping while sampling for adult weevils

[2] No sampling for adult weevils due to influence of fruit drop on yield

Table 4. The total number of fruit with weevil eggs on the fruit skin from Block GD7, Bavaria Fruit Estates, expressed as a percentage of the total number of fruit sampled, cv. 'Tommy Atkins'. A total of 240 fruit (3 fruit from 10 trees, 8 replications) were sampled fortnightly from the time that the first weevil eggs were noticed, up to the commercial harvest of the cultivar.

Date / Rep.	01.08[1]	16.08[1]	28.08[1]	12.09[1]	26.09[1]	10.10	24.10	07.11	20.11	06.12	19.12	03.01
1						4	21	24	22	28	27	14
2						3	13	23	25	24	24	21
3						2	9	19	19	20	12	7
4						4	16	29	26	26	24	14
5						0	6	6	0	2	6	1
6						5	11	21	5	16	21	4
7						2	11	19	20	20	19	15
8						3	7	23	24	15	18	11
Tot.						23	94	164	141	151	151	87
% egg infested fruit						9.58	39.17	68.33	58.75	62.92	62.92	36.25

[1]Early fruit season with fruit smaller than golf ball size and no oviposition

Table 5. The average number of seed weevil eggs per egg infested fruit, from Block B41, Moriah.

Date / Rep.	01.08[1]	16.08[1]	28.08[1]	12.09[1]	26.09[1]	10.10	24.10	07.11	20.11	06.12	19.12	03.01

1						2.67	1.53	1.83	2.15	2.22	1.69	2.00
2						0.00	1.45	2.20	2.75	2.90	1.92	1.86
3						1.00	1.14	1.44	2.27	1.30	1.45	1.00
4						1.67	1.55	4.00	1.93	1.94	2.42	2.20
5						1.75	1.40	1.13	1.33	1.56	1.17	2.00
6						0.00	1.00	1.92	1.00	2.33	1.50	0.00
7						1.50	1.20	1.86	1.00	2.50	1.00	1.00
8						1.00	0.00	0.00	1.33	1.00	1.33	1.00
Ave.						**1.40**	**1.42**	**2.23**	**1.94**	**2.05**	**1.74**	**1.83**

[1]Early fruit season with fruit smaller than golf ball size and no oviposition

Table 6. The average number of seed weevil eggs per egg infested fruit, from Block GD7, Bavaria Fruit Estates.

Date / Rep.	**01.08[1]**	**16.08[1]**	**28.08[1]**	**12.09[1]**	**26.09[1]**	**10.10**	**24.10**	**07.11**	**20.11**	**06.12**	**19.12**	**03.01**

1						1.25	1.95	3.58	4.50	3.71	2.96	2.21
2						1.67	1.92	3.22	4.76	2.58	3.38	2.57
3						1.00	1.44	2.21	2.53	1.95	1.58	3.71
4						1.25	1.56	2.79	3.58	3.38	2.17	3.00
5						0.00	1.17	1.50	0.00	1.50	1.33	1.00
6						1.00	1.82	3.05	1.60	3.13	2.29	1.75
7						1.00	1.55	2.68	2.05	5.20	2.74	2.67
8						1.33	1.43	3.61	3.00	3.47	2.33	2.27
Ave.						**1.22**	**1.68**	**2.99**	**3.40**	**3.32**	**2.53**	**2.60**

[1]Early fruit season with fruit smaller than golf ball size and no oviposition

The number of egg infested fruit, as well as the average number of eggs per fruit, increased as the season progressed, up to a point where minimal additional egg laying occurred, with oviposition declining at the end of the season. The number of adult weevils did not increase as the season progressed (Figs. 13 – 14), and remained low up to the last assessment.

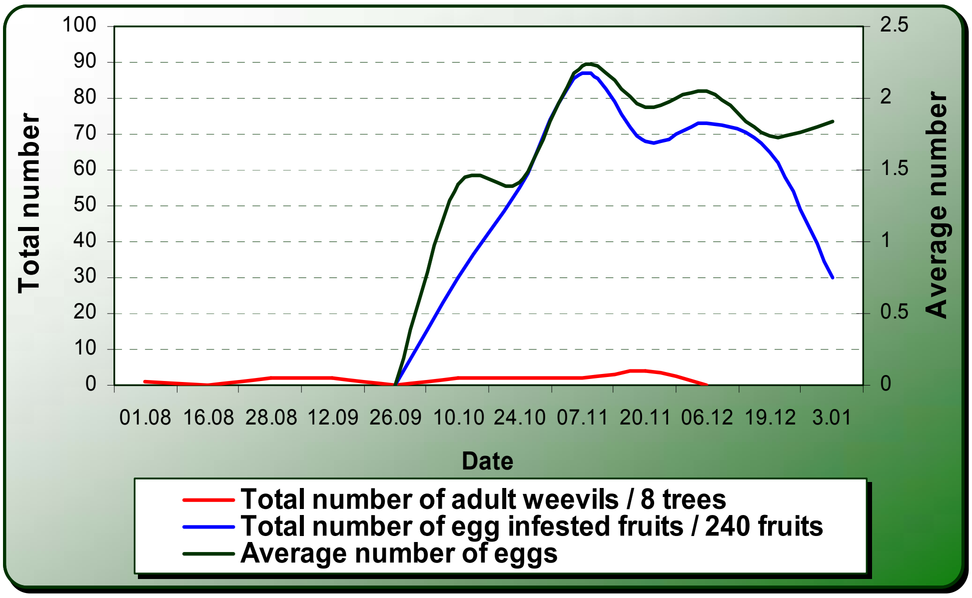


Fig. 13. The number of mango seed weevils per assessment, compared to the number of egg infested fruit (cv. 'Tommy Atkins', Block B41, Moriah), 2006 / 2007.

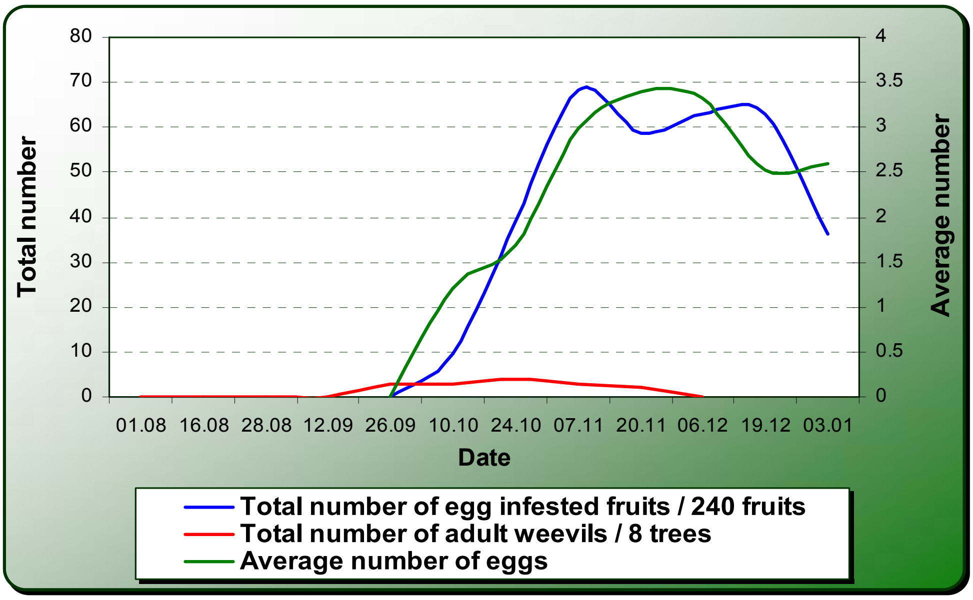


Fig. 14. The number of mango seed weevils per assessment, compared to the number of egg infested fruit (cv. 'Tommy Atkins', Block GD7, Bavaria Fruit Estate), 2006 / 2007.

The reason for the low incidence of adult weevils, compared to the considerably higher incidences of fruit infestations, could possibly be attributed to any of the following:

1) A single female can lay between 175 (De Villiers, 1987) and 300 (Balock & Kozuma, 1964) eggs in a season, resulting in a 1:175 – 300 ratio between the number of females and the number of eggs present within a specific area during peak season.
2) All of the experiments were conducted during the day, coinciding with the inactivity period of adult weevils, with the majority of adults hiding away in crevices and other places from which they couldn't easily be dislodged.
3) Adult weevils may hide in places other than on the mango tree, i.e. in cracks and crevices of board or stone walls surrounding orchards (Hansen, 1991), although they do not seem to hide in the soil or among debris on the soil surface. Also, the fact that some adult weevils were dislodged from mango trees at the onset and during the season, indicates their presence within mango trees. During the 2007 / 2008 season, for the first time, active adult weevils, as well as feeding damage, was seen in mango orchards, supporting the notion that adult weevils do reside in the mango trees during the season. Since these weevils were noted between 07h00 and 18h00, it supports the notion that some weevils do feed (Fig. 15) and that they do mate (Fig. 16) during the day.

Fig. 15. An adult mango seed weevil feeding on a developing mango fruit.

Fig. 16. Adult mango seed weevils mating (left), and moving about on a mango fruit (right), during the day.

2.4. Conclusion

Although the investigation into activity patterns, mating behaviour, and oviposition of, MSW adults in captivity cannot constitute a true representation of MSW activity and propagation under natural conditions, observations made during this early part of the study did provide general information on these aspects of MSW biology. During the latter part of the study, i.e. oviposition in the field (Chapter 4), aspects regarding the onset and duration of oviposition under natural conditions were found to have compared well to what was observed from adult weevils in captivity. These observations also corresponded well to observations made by various authors.

Although some captive adult weevils were already active by late August, the majority of mango seed weevils consistently terminated diapause between the middle and the end of September. Mating and oviposition commenced soon after and peaked between the latter part of October and the beginning of November. By the end of November activity declined noticeably, with mating and egg laying negligible from December up to January, although occurring sporadically.

During the latter part of the mango growing season, emerging and emerged adults did not immediately went into diapause, but were found feeding and mating, with some oviposition occurring in February and March, although negligible. These eggs appeared intact and viable, but the chances of successful development could not be determined as all the fruit at this stage were physiologically mature and tended to ripen and deteriorate too fast. With the majority of mango fruit already harvested at this stage, and with weevil development taking between five to eight weeks from egg to adult (Woodruff & Fasulo, 2006), chances of larvae developing into adult weevils appear to be slim. The presence of any developmental stage within the fruit, however, constitutes weevil infestation of the fruit and could constitute a potential phytosanitary risk. It is therefore imperative to investigate this phenomenon, should one wish mango fruit to be exported to countries requiring a guarantee that no mango seed weevil is present in fruit destined for their markets.

By April, the majority of weevils were hibernating, although some feeding and activity were observed throughout the diapause period, more specifically when moisture levels in the breeding boxes were increased. Adult seed weevils were found to be, for the most part, inactive during the day, with activity increasing from dusk through to dawn, confirming that adult weevils are indeed nocturnal.

From studies in the field it appeared as if the phenomenon, where adult weevils feign death when disturbed, were more prominent early in the season. Weevils taking flight when disturbed, e.g. when dislodged from tree branches, were noted later in the season, with the adults flying short distances to nearby trees or back into the same tree from where they were dislodged. Only a few dead specimens were found in soil and debris samples taken from beneath infested trees, confirming that adult weevils do not hibernate in the soil.

The sampling method to dislodge adult seed weevils by shaking and / or beating mango trees proved to be very destructive and ineffective in reflecting either fruit infestation levels or the whereabouts of adult seed weevils during the day and during the season. The fact that adult weevils were dislodged from mango trees, that adult weevils were seen during the day in mango trees during the 2007 / 2008 season, and that no adult weevils were found in soil and debris samples, however, do indicate that the adults do reside within mango trees during the season.

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CHAPTER 3

Feeding behaviour and preferences of the mango seed weevil

3.1. Introduction

The mango seed weevil (MSW) is a monophagous pest (Follett and Gabbard, 2000) with mango the only known host (Hansen & Armstrong, 1990; Follet, 2002). Although oviposition in the laboratory has been observed on potatoes, peach, litchi, plum, string beans and several varieties of apple, the larvae did not develop successfully in any of these products (Woodruff & Fasulo, 2006).

Mango seed weevils feed and develop mainly within the seeds (De Villiers, 1989), although some instances of pulp development have been reported (Balock & Kozuma, 1964). The mango seed or stone weevil is sometimes mistaken for two closely related species that also attack mangoes, i.e. the mango pulp weevil, *Sternochetus frigidus*, and the mango nut weevil from India (Javanese mango weevil), *Sternochetus gravis* (Hansen, 1991). This has resulted in varying opinions in the literature regarding pulp damage of the fruit (Follet & Gabbard, 2000) and the development cycle of the mango seed weevil (Schotman, 1989; Woodruff & Fasulo, 2006). *Sternochetus frigidus*, the mango pulp weevil, is prevalent in Malaysia, the Philippines and parts of Indonesia. It has also been recorded in Northern Australia (Anonymous, 2008), but not in South Africa. These weevils are similar in appearance to the mango seed weevil, but shouldn't be mistaken for the mango seed weevil, or be confused with the other generic names allocated to the MSW.

The scientific name for the MSW, initially described by Fabricius and accepted by the Entomological Society of America, was *Cryptorhynchus mangiferae* (Hansen, 1991). This generic name is commonly found in older literature references (Woodruff & Fasulo, 2006). The generic name, *Sternochetus*, has later been allocated (Hansen, 1991) and is therefore more commonly found in recent literature, especially those originating from India, Asia and Africa. Other generic names that were previously used are *Acryptorhynchus* and *Paracryptorhynchus* (Hansen, 1991).

The economic importance of the MSW lies not necessarily in the feeding damage caused by the adult weevil, but more in the fact that they are considered to be a phytosanitary pest, with their mere presence in mango seeds resulting in restrictions on the export of mango fruit to certain existing, and potentially new, overseas markets (Schoeman, 1987; Hansen, 1991; Joubert & Pasques, 1994; Follet & Gabbard, 2000; Woodruff & Fasulo, 2006). The economic loss (damage) resulting from MSW infestations can be attributed to larval feeding and development, mainly within the mango seed (De Villiers, 1987).

Many ambiguous and often contradictory statements are found in the literature on the importance of seed damage (Schotman, 1989). Some authors described larval feeding in the seed only as being detrimental (De Villiers, 1984), while other authors claim it to be a constraint on production, since weevil infested fruit drop prematurely (Verghese, 2000). Follet and Gabbard (2000) investigated the effect of larval development and feeding on (1) pulp damage; (2) the seed germination potential of infested seeds; and (3) premature fruit drop. They concluded that: (1) since the initial tunnels made by the larvae completely disappear with time, no secondary infections develop due to tunneling and because pulp development is extremely rare, mango seed weevil attack usually goes unnoticed and does not reduce fruit marketability; (2) since no significant differences could be found between the germination of infested and non-infested seeds, mango seeds withstood substantial damage and still germinated successfully; and (3) that since no significant differences could be found regarding infestation levels between dropped and tree-picked fruit, no clear evidence exists to suggest that fruit drop is caused by seed weevil infestations. In a follow-up study, however, Follet (2002) did find dropped fruit to have had significantly more weevils developing in the seed than in fruit of the same size sampled directly from the trees.

Although the majority of the literature refers only to fruit damage due to larval feeding and development, mention of adult seed weevil feeding is only found in one article (CABI & EPPO, 2005), where the adult seed weevil feeds on leaves and tender shoots. No references could be found that describe either adult feeding damage, or the economic impact of adult feeding. Since producers frequently enquire about: (1) the economic impact of adult feeding; (2) whether it would be possible to predict infestation levels on the basis of feeding damage; and (3) whether potential traps or lures could be developed to control adult weevils, Westfalia Technological Services (WTS) investigated adult seed weevil feeding preferences.

3.2. Materials and Methods

3.2.1. Adult seed weevil feeding preferences for mango

Feeding preferences of adult seed weevils for various mango substances and extracts was determined during the 2005 / 2006 mango growing season. Thirty adult mango seed weevils were placed in a container with a glass lid (breeding box) in an office at ambient temperatures and under artificial (electrical) lights. Feeding preferences for the following mango substances were investigated (Fig. 1):

- young mango flushes (leaves)
- older, hardened mango flushes
- green mango fruit (cut in half to expose the pulp)
- sap extracted from young mango leaves[1]
- sap extracted from young petioles and stems[1]
- sap extracted from a young mango fruit[1].

[1]extraction with a garlic press and drenching a cotton wool disc placed in a petri dish up to the point of saturation

Fig. 1. A breeding box containing various mango substances (fresh plant material and extracted plant sap from various plant parts) to investigate adult mango seed weevil feeding preferences.

Monitoring occurred sporadically during the day, noting the number of adult weevils present at that stage on any of the substrates provided, from 10 to 19 October 2005. Substances were replaced every second day. During the course of the study, the feeding behaviour of the larger colonies of captive adult weevils (200 to 300 individuals in a single breeding box) were also monitored, noting especially the feeding on physiologically mature or ripe mangoes (whole and cut in sections) compared to green fruit, and feeding preferences between soft, young mango flushes and older, more mature flushes.

A second study was also undertaken to investigate adult weevil preferences for various mango cultivars. As in the first study, thirty adult weevils were placed in a breeding box, noting the number of adults visiting any of the specific substrates. The breeding box was kept in an office at ambient temperature and artificial (electrical) lights. Substances were replaced every second day. Fruit were cut in halves to monitor feeding on the exposed inner pulp, while oviposition was monitored on the intact, bottom halves of the fruit.

The cultivars tested, and the monitoring periods, were:

- 'Heidi'[3], 'Long Green'[2] and 'Kent'[3], monitored over a period of 19 days from 20 October to 7 November 2005
- 'Keitt'[4], 'Tommy Atkins'[1] and 'Sensation'[4], monitored over a period of 11 days from 7 November to 17 November 2005.

[1] early season cultivar
[2] mid season cultivar
[3] mid to late season cultivar
[4] late season cultivar

The number of weevils visiting or feeding on any given substance was noted sporadically, totaling the number of weevils visiting a substrate over the course of the study and then calculating the average number of adult seed weevils per substrate per assessment. The number of eggs on the bottom halves of the placed fruit was counted with each assessment and the averages were calculated. The data obtained was processed and statistically analyzed using a one way analysis of variance with Tukey's HSD test at 95% confidence levels (Statistica Version 6).

3.2.2. Alternative substances for use as field lures

Studies into alternative substrates were conducted in the 2004 / 2005 and 2005 / 2006 mango growing seasons to investigate the potential of these substances to attract adult seed weevils. This was done in order to determine the probability of using these substances in the field as adult weevil lures.

The reasoning behind this study was that successes had been obtained (1) in the field with adult fruit flies (*Ceratitis* spp) attracted by protein containing lures (adult females need to feed on a protein based substance before oviposition can commence) and (2) at the local insectarium where predacious beetles, *Cybocephalus binotatus* (Grouvelle) (Coleoptera; Coccinellidae) and *Rhizobius* spp., were reared and maintained on sugar water solutions in addition to their natural food sources, i.e. mango scale (*Aulacaspis tubercularis)* and mealybug (various species).

In the 2004 / 2005 mango growing season, adult feeding preferences to the following substances were investigated (Fig. 2):

- water[1]
- salt water[1]
- protein[2]
- sugar[3]
- mango pulp
- re-hydrated dried mango
- immature mango fruit (wedged to expose inner pulp)
- mature mango leaves
- young mango flushes (leaves) .

[1] saturated tissue paper in a petri dish
[2] Marmite®
[3] honey

Thirty adult weevils in an equal sex ratio were placed in the breeding box amid the various substances. The breeding box was placed in an office at ambient temperature and under artificial (electrical) lights. Monitoring was done sporadically during the day from 19 November to 21November 2004. Substances were replaced daily. Weevil preferences were noted as the number of weevils present at, or on, any specific substrate at the time of the assessment.

Fig. 2. A breeding box containing various potential food sources to investigate the probability of using these substances in the field as mango seed weevil lure.

During the 2005 / 2006 mango growing season, feeding preferences to alternative substances were again investigated. Thirty adult weevils in an equal sex ratio of male: female were placed inside a breeding box, sporadically monitoring the number of weevils present at, or on, any of the substrates. The breeding box was kept in an office at ambient temperature and under electrical (artificial) lights. The substances investigated were:

- young and soft mango flushes
- old(er) flushes
- half a mango fruit
- a whole mango
- a petri dish containing a protein solution (Marmite® dissolved in water)
- a petri dish containing a sugar based substance (sugar dissolved in water)
- Texas Volatile® (a plant pheromone) (Fig. 3).

This study commenced on 10 October 2005, and continued up to 19 October 2005. Materials were replaced twice weekly.

Fig. 3. A capsule containing the plant pheromone, Texas Volatile®, of Insect Science (Pty) Ltd.

3.3. Results, Discussion & General observations

3.3.1. Adult seed weevil feeding preferences for mango

Whilst investigating adult weevil preferences to various mango substrates, it was found that the adult seed weevils visited all the fresh mango plant materials (Table 1). No adult weevils were found on the cotton disks saturated with plant sap extracted from the stems of flushes or from mango fruit, while a single weevil was found on the petri dish containing the plant sap extracted from young leaves.

Although adult weevils visited all the fresh mango substances, feeding did not occur on all of them. Adult weevils did not feed on old, mature leaves, but used these flushes and individual leaves mostly for aggregation sites and as shelter. Adult weevils were also found, in greater numbers, to seek shelter among the young mango flushes, usually clustering in protective folds. The weevils preferred to feed on very young, soft flushes, feeding both on the lamina, consuming parts of the leaf surface (Fig. 4) and on the leaf vein (petiole) of single leaves (Fig. 5). The same preferences were seen in the breeding boxes containing the bulk of the weevil colony, where the adults fed mainly on young mango flushes.

Table 1. A summary of adult mango seed weevil visitations, expressed as the number of weevils present at, or on, a specific mango substrate.

Date	Time	½ Fruit (immature)	Young flush	Mature leaves	Extract Leaves	Extract Stems	Extract Fruit	Bottom of box	Glass surface
10.10	12h00	9	8	2	1			7	3
11.10	10h00	5	9	4				8	4
12.10	08h00	6	12	4				2	6
	09h30	4	8	2				9	7
	11h00	8	8	2				9	3
	14h00	3	14	4				8	1
13.10	08h00	11	4	3				3	9
14.10	08h00	12	3	2				6	7
	12h00	9	6	6				6	3
	16h00	3	9					13	5
17.10	09h00	7	11					2	10
	10h30	4	13	3				6	4
	13h30	8	12	5				4	1
18.10	10h00	6	14	3				5	2
	14h30	7	8	6				6	3
19.10	08h30	9	5	1				3	12
	10h00	5	8	2				12	3
	12h00	7	13	4				3	3
Total		123	165	53	1	0	0	112	86
Ave.		6.83	9.17	2.94	0.06	0.00	0.00	6.22	4.78

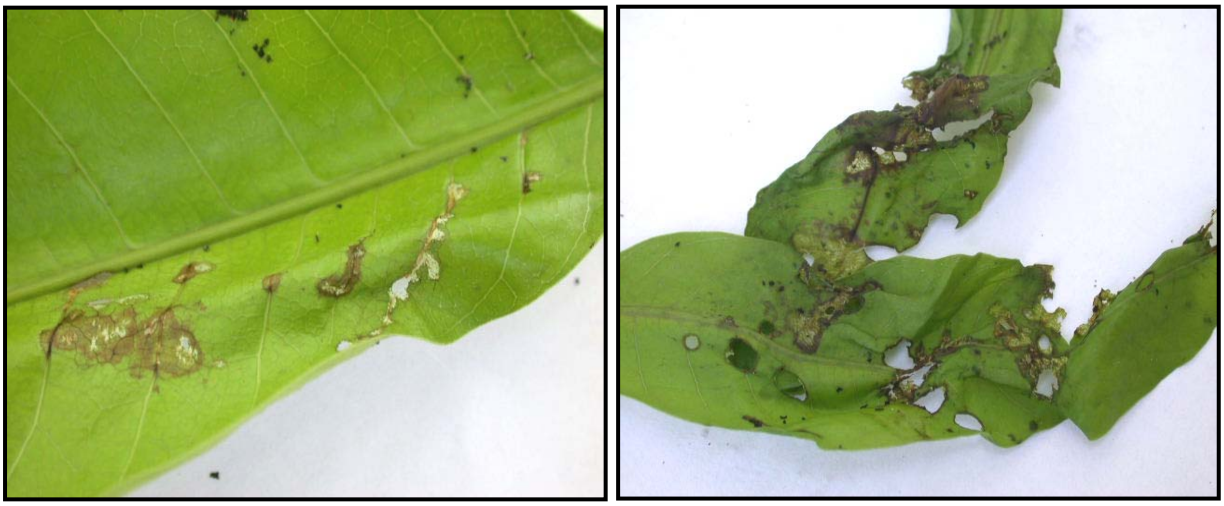

Fig. 4. Adult mango seed weevil feeding damage on the lamina of a young mango leaf (left), with the damage more prominent when a large number of weevils were maintained in a single breeding box (right).

Fig. 5. Adult mango seed weevil feeding damage on the petiole of a young mango leaf (left), with the damage more prominent when a large number of weevils were maintained in a single breeding box (right).

When slightly older flushes (a group of individual leaves or leaflets) were placed in the breeding box, feeding occurred mainly on and along the main stem of the flushes (Fig. 6). This was also seen in the breeding box containing the bulk of the weevil colony. Mango fruit served both as a food source (Fig. 7) and an oviposition site (Fig. 8). Although the adult seed weevils fed readily on whole green, immature fruit, areas where the fruit pulp was exposed, was preferred (observations from colony kept in captivity) (Fig. 9).

Fig. 6. Adult mango seed weevil feeding damage on a mature mango flush (left), with the damage increasingly prominent as the number of weevils increase (right).

Fig. 7. Adult mango seed weevil feeding on an immature, green fruit.

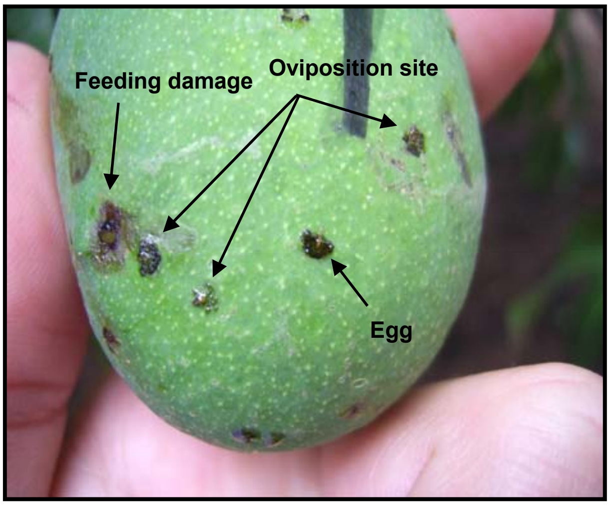

Fig. 8. Mango seed weevil feeding damage and oviposition sites on an immature mango fruit. The fruit was removed from a breeding box containing 200 to 300 individuals, a few hours after placement.

Fig. 9. Adult mango seed weevils feeding on an immature mango fruit (red variety) of which a wedge was cut out.

By monitoring feeding activity of the bulk of the weevil colony, it seemed that adult weevils preferred physiologically mature (ripening or ripe mango fruit) to immature fruit, with feeding occurring on all parts of the fruit surface and not only on cut surfaces exposing the mango pulp (Fig. 10). Some individuals were even found embedded into the flesh, feeding on the softer inner pulp of the mature fruit.

Fig. 10. Adult mango seed weevil feeding damage on the exposed pulp (left) and fruit surface (right) of a mature mango fruit. Fruit were placed in a breeding box containing the bulk of the weevil colony (200 to 300 individuals) and removed after 2 days.

Results from the study investigating possible feeding preferences between different cultivars, are summarized in table 2. The table indicates the two assessment periods (separated by the grey dotted line), with the feeding and oviposition preferences between 3 cultivars investigated simultaneously with each assessment.

For each assessment the majority of the adult weevils that were placed inside the breeding box containing the various substances (foliage, half a fruit with the pulp exposed and a whole fruit) from each of three cultivars were found either in clusters on the soil surface, or singularly seeking shelter under individual leaves. For this reason only the number of adult weevils present at, or on the different substrates placed were noted.

Except for the weevil count on the flushes where statistical differences occurred, no visible preferences to any specific cultivar could be found. The statistical differences that were found between cultivars regarding the average number of weevils found on the various flushes may have been influenced by the age of the flushes, since not all the flushes that were collected were of the same age.

Depending on the cultivar, some flushes were slightly more mature with the leaves already hardening, while other flushes were younger with soft and succulent leaves, since not all cultivars produce new flushes or new growth at the same time. With the previous study it was established that adult weevils preferred to feed on young, succulent flushes.

The slight variations that were found between the average number of eggs laid on fruit that were placed and evaluated between 20 October and 7 November 2005 (‘Heidi’, ‘Long Green’ and ‘Kent’), compared to fruit placed and evaluated between 07 November and 17 November 2005 (‘Keitt’, ‘Tommy Atkins’ and ‘Sensation’), could probably be attributed to seasonal variations in either oviposition (timing effect), or environmental conditions.

Table 2. The average number of mango seed weevils present at or on each of the substrates provided. Thirty individuals were placed in a breeding box and monitored for possible feeding preferences to specific cultivars.

	½ Fruit	Whole fruit	Flush	Egg laying
Heidi *	1.33 **a**	0.60 **a**	0.47 **a**	2.10 **a**
Long Green *	1.87 **a**	0.77 **a**	0.40 **a**	3.37 **a**
Kent *	1.73 **a**	0.77 **a**	1.10 **ab**	3.53 **a**
Keitt **	1.20 **a**	0.50 **a**	1.85 **b**	1.30 **a**
Tommy Atkins **	1.70 **a**	0.65 **a**	1.55 **ab**	1.55 **a**
Sensation**	0.95 **a**	0.45 **a**	1.55 **ab**	0.90 **a**
F (5,144)	0.669	0.303	4.643	1.977
p	0.648	0.911	0.001	0.086
MS	3.03	0.425	9.151	30.28

* Observation period from 20 October to 07 November 2005

** Observation period from 07 November to 17 November 2005

Statistical analysis done with a One-Way Anova at 95% confidence levels. Values with the same denomination did not differ statistically (Tukey's HSD test)

3.3.2. Alternative substances for use as field lures

The results obtained during the 2004 / 2005 mango growing season are summarized in Table 3 (courtesy of Dr. Danielle LeLagadec, Senior Researcher - Mangoes, WTS, Mariepskop Estate, Hoedspruit). The total number of weevils present at, or on a specific substance was calculated for the duration of the observation period. Averages were calculated as the total number of individuals per substance, for the whole of the observation period, divided by the total number of assessments made.

The majority of the adult weevils, for the duration of the observation period, were found among the young, soft mango flushes, with these flushes showing visible feeding damage. Although some were active, feeding on the flushes, most were inactive (typically with the proboscis and legs retracted tightly against the body) and found in clusters underneath the foliage, seeking shelter. Some weevils were found on the mango fruit, feeding on the underside of the fruit where the fruit touches the soil, indicating that, during the day, the adults preferred to feed while being sheltered. Only a couple of adults were found hiding singularly under mature (old) leaves. All the weevils that were found under the mature leaves were inactive, seeking shelter. An insignificant number of adult weevils were found on / at containers with water, salt water, marmite, honey or the processed mango pulp, indicating that MSW adults were generally not attracted to any of these substances.

For the study conducted in the 2005 / 2006 mango growing season, sugar water and a plant kairomone (Texas Volatile®) was included, with the processed mango substances, the water and the salt water being excluded. The same procedures were followed and the results are portrayed in Table 4.

Adult weevils visited only the mango substrates, again preferring very young mango flushes to feed on and as shelter. Immature (green) fruit also served as a feeding source, with more adults feeding on fruit that was cut to expose the inner mango pulp. Eggs were laid equally on the surfaces of the whole mango fruit and on the fruit skin of the cut fruit (data not shown). Negligible numbers visited the alternative substances. Again the majority of the weevils were inactive, either singularly or in clusters, on the soil surface during the day (observation period).

Table 3. Outcome of feeding preferences of adult mango seed weevils to various substances in the 2004 / 2005 mango growing season. The number of adult seed weevils present at, or on a specific substance was noted, with the totals for the observation period, and averages (total number of individuals per assessment divided by the total number of assessments) indicated.

Time	Water	Salt water	Mango pulp	Mango slices	Mango fruit	Mature leaves	Young flush	Marmite®	Honey	Other*
Day 1: 19 November 2004										
12h25					1	3	22			4
12h30						3	23			4
13h30			1		2	3	21			3
16h00			1			2	22			5
Day 2: 20 November 2004										
06h35			1				12	1	1	14
08h00				1	12	6	9			2
09h30			1	1	2		18			8
12h00	1				6		21			2
Day 3: 21 November 2004										
06h45					5		20			5
09h10					6	1	15			8
17h00							1			29
Total	1	0	4	2	34	18	184	1	1	84
Ave.	0.09	0.00	0.36	0.18	3.09	1.64	16.73	0.09	0.09	7.64

*'Others' denote weevils found on the side of the breeding box / on the glass lid / on the soil surface

Table 4. Outcome of feeding preferences of adult mango seed weevils to various substances in the 2005 / 2006 mango growing season. The number of adult seed weevils present at, or on a specific substance was noted, with totals for the observation period, and averages (total number of individuals per assessment divided by the total number of assessments) indicated.

Date	Time	½ Fruit	Whole fruit	Young flush	Old flush	Marmite solution	Sugar water	Texas volatile	Soil (inactive)	Glass
10.10	12h00	4	2	12	3		1		2	6
11.10	10h00	2		2	3				8	15
12.10	08h00	1	1	14	2				5	7
	09h30	1	1	1					20	7
	11h00	1		3					14	12
	14h00	1							19	10
13.10	08h00		1	10	5	1	1		5	7
14.10	08h00			20					6	4
	12h00	1		14					15	
	16h00	2	2						22	4
17.10	09h00			5	2				13	10
	10h30	1	1						28	
	13h30								28	2
18.10	10h00	2		6		1			16	5
	14h30		2	1					24	3
19.10	08h30	2	2	5					19	2
	10h00	2							25	3
	12h00								26	4

Total	**20**	**12**	**93**	**15**	**2**	**2**	**0**	**295**	**101**
Ave.	1.05	0.63	4.89	0.79	0.11	0.11	0	15.53	5.32

3.4. Conclusion

Adult mango seed weevils preferred mango, and more specifically young, succulent flushes, consuming portions of the lamina of individual leaflets or feeding along the veins (petioles) of the leaves. With more mature flushes, feeding occurred mostly on the main stem. No feeding occurred on very old leaves. In all instances foliage provided a place for shelter.

Mango fruit served as both a food source and as a site for oviposition. Adult weevils preferred to feed on the exposed inner pulp of immature fruit. With physiologically mature (ripe) fruit, feeding occurred all over the fruit surface, with individual weevils sometimes seen burrowing into the fruit to reach the soft inner pulp.

Severe feeding damage was found on both the foliage and mango fruit placed inside breeding boxes containing 200 to 300 individuals, but this was expected since a large number of adult weevils were kept in a small enclosed area in captivity, feeding on a limited food supply. Considering the abundance of new growth (flushes) and fruit produced by a mango tree during the growing season, and the small number of adult weevils dislodged from infested mango trees (Chapter 2), chances of seeing adult seed weevil feeding damage in the field appear to be slim. Assuming this to be the case, it would explain why no adult seed weevil feeding damage was seen in the field up to the 2007 / 2008 mango growing season, even though fruit infestation levels indicated that various orchards were quite heavily infested.

During the 2007 / 2008 mango growing season, however, adult seed weevils were seen for the first time during the day in mango orchards. Adult weevils in the field were noted for the first time at the end of October 2007, with these weevils active and moving about on the mango fruit (Fig. 11) and fruit panicles. A couple of mating adults, as well as weevils feeding on fruit, were also seen. Adult weevils were seen frequently during November, sometimes more than one weevil on a single fruit (Fig. 12). By the end of November 2007, fewer weevils were found in the orchards, with the last weevils observed on 13 December 2007.

Fig. 11. An adult mango seed weevil observed on an immature mango fruit (cv. 'Kent'), 25 October 2007.

Fig. 12. Adult mango seed weevils seen on an immature mango fruit (cv. 'Kent'), 08 November 2007.

During the 2007 / 2008 mango growing season, adult seed weevil feeding damage was also observed for the first in the field on tree-hanging, immature mango fruit (Fig. 13). No feeding damage to foliage was observed, probably since the majority of the fruit bearing trees, at this stage, did not produce vegetative growth in the form of mango flushes. The reason for the increase in activity during the day in the 2007 / 2008 season could probably be attributed to environmental conditions, since infestation levels did not increase significantly from the 2006 / 2007 to the 2007 / 2008 mango growing season (Chapter 4: 4.4.2 - Oviposition in the field). The 2007 / 2008 mango growing season was characterized by cool, humid conditions prevailing for most of the season.

Fig. 13. Adult mango seed weevil damage observed on an immature mango fruit (cv. 'Kent'), 08 November 2007.

Adult seed weevils appeared not to have any preferences towards any of the cultivars tested. Some authors did report significant differences between cultivars regarding fruit drop (Verghese *et al.*, 2005) and fruit infestations (Singh, 1985), but none of these cultivars are currently under commercial production in South Africa. Dieckmann (1982) reported noticeable differences between the number of eggs laid on early-season, fibrous cultivars and late-season, fibreless cultivars, with fewer eggs laid on the latter. She concluded that mango seed weevils may prefer fibrous to fibreless mangoes for oviposition, although it most probably was only due to seasonal variations, i.e. the fact that more eggs are laid early in the season, manifesting as cultivar preferences. Hansen *et al.* (1989) reported no significant differences in the infestation rates among 20 Hawaiian cultivars.

Mango seed weevil adults preferred mango to any other substance used during the various studies. A greater variety of food sources could be used to investigate the possibility of using alternative food sources as possible attractants or lures in the field. But, considering the fact that the adult seed weevil is a monophagous pest, chances of finding such a substrate seem slim.

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CHAPTER 4

Oviposition of the mango seed weevil

4.1. Introduction

Since no known natural enemies of the mango seed weevil (MSW) is known (Schoeman, 1987a), with no parasitoids of MSW eggs recorded up to date (Hansen *et al.*, 1989; Joubert & Labuschagne, 1995), and with sanitation practices that are labour intensive (Joubert & Pasques, 1994), chemical control is often the only management measure remaining. However, since the adult MSW is extremely inactive (Joubert & Pasques, 1994) and nocturnal (CABI & EPPO, 2005), with a tendency to hide in crevices and other sheltered places (De Villiers, 1984; De Villiers, 1989), control of this elusive insect with contact and semi-penetrant insecticides necessitates an in-depth knowledge regarding activity patterns and reproduction.

To ensure effective chemical control with contact and semi-penetrant insecticides aimed at controlling the miniscule larvae, either when leaving the egg to penetrate the fruit pulp, or while still developing inside the egg, it is important to apply the insecticides with the onset of oviposition (Joubert & Pasques, 1994; Joubert & Labuschagne, 1995; De Villiers, 1989). This, however, would require frequent fruit inspections (scouting) to determine the onset of oviposition, as well as the ability to identify seed weevil eggs. Verghese (2000) also found the timing of the first spray to be of the utmost importance. He concluded from his study that, once the larva (grub) penetrates the protective husk of the seed, chemical control becomes ineffective.

On the contrary, Schoeman (1988) stated that chemical control should be applied during the peak of weevil activity. This, however, may result in some larvae having already reached and penetrated the mango seed if the time interval from onset to peak oviposition is too extended, reducing the effectiveness of chemical applications (personal observations, 2006 – 2007). In order to effectively control mango seed weevil with contact and semi-penetrant insecticides, an extensive knowledge regarding seasonal activity and the onset and duration of MSW oviposition are therefore a prerequisite. In order to better understand MSW oviposition to enhance control measures, various aspects of MSW oviposition were investigated.

4.1.1. Oviposition and fruit size

Varying opinions are found in the literature regarding MSW oviposition and fruit size. Follet and Gabbard (2000) found oviposition to have occurred on very small, green or immature fruit that are 1.9cm in diameter or larger (marble size). Other authors that describe oviposition to have occurred on young, immature or developing fruit were De Villiers (1984), Schoeman (1987b), Hansen *et al.* (1989) and Hansen and Armstrong (1990).

Balock and Kozuma (1964) found oviposition to have occurred on marble sized to three-quarters grown fruit (tennis ball size) and even sometimes on the fruit stem (panicle). Joubert and Pasques (1994) also found the majority of oviposition to have occurred when the average fruit length ranged between 14mm (marble size) and 56mm (golf ball size), although some oviposition did occur on fruit exceeding an average length of 80mm (tennis ball size). Schotman (1989) and Woodruff and Fasulo (2006), however, reported oviposition to have occurred on immature (green) to ripe (full size) mango fruit.

4.1.2. Oviposition and fruit / tree position

Schotman (1989) and Hansen (1991) stated that it appeared as if adult females selected fruit at random, with eggs laid singly on any part of the fruit skin. Hansen *et al.* (1989) investigated oviposition on fruit collected from three vertical zones (top, middle and bottom of the tree) and four directional quadrants (north, east, south and west). They found no noticeable differences and concluded that oviposition appeared to be random.

4.1.3. Oviposition of adult females in captivity

Balock and Kozuma (1964) reported that a single female was able to lay 15 eggs per day, with a maximum of 300 eggs in a 3-month period. On average, between 2.2 and 3.7 eggs were laid per day, but with only 40% to 68% of all eggs deposited hatching. De Villiers (1987) reported that a single female had the potential to lay 175 eggs.

4.1.4. Oviposition in the field

Varying opinions regarding the duration of MSW oviposition are also found in the literature. De Villiers (1984, 1987) found the period of peak MSW activity and oviposition in South Africa to be between October and November, with egg laying extending over a 3 – 5 week period. Schoeman (1988) investigated seasonal activity of the seed weevil in South Africa by investigating infestation levels of fruit exposed for natural egg laying at various times in the season. He found the bulk of oviposition on infested fruit to have occurred during November, with the number of egg infested fruit showing a definite peak, after which oviposition declined. The number of egg infested fruit increased again slightly at the beginning of December, before oviposition, and therefore the percentage of infested fruit, declined steadily up to the end of the season. Egg laying was found to have occurred between the latter part of October and the middle of December (nearly 60 days).

In 1994, Joubert and Pasques investigated the onset, rate and duration of mango seed weevil egg production of adult weevils in captivity. Some weevils were found to be active by the middle of August, although the bulk of MSW activity started in September when mating was observed. The first eggs were laid during the week of 01 to 08 October 1993, with egg laying peaking 3 weeks later at the end of October 1993. Oviposition extended over a period of 60 days, with the majority of eggs being deposited during October. The following year the same procedures were repeated, but in the field (Joubert & Labuschagne, 1995). Contrary to the previous season, egg laying on enclosed data fruit commenced late October and ended three weeks after onset (mid November). Natural egg laying in the rest of the orchard, however, continued up to the first week in January 1995.

Hansen *et al.* (1989) found oviposition on Kalapama, a Hawaiian island, to conclude within a month, while Balock and Kozuma (1964) recorded oviposition in the laboratory to be about 90 days. By studying adult seed weevils in captivity, Louw and Mukhethoni (2006) found, over a two-year period, that oviposition commenced around the middle of September and continued up to January, extending over four months (120 days). The majority of eggs were laid between October and November.

4.2. Materials and Methods

4.2.1. Oviposition and fruit size

In order to investigate correlations between MSW oviposition and fruit size, a field study was undertaken by Westfalia Technological Services (WTS) in the 2004 / 2005 mango season on the farm Grovedale (latitude 24°24'S, longitude 30°51'E) in the Hoedspruit magisterial district of the Limpopo Province. The study was conducted in Block G81, since no natural MSW infestations were recorded for this specific orchard prior to the study, and since data fruit of various sizes could be obtained from the mid-to-late season cultivar, 'Keitt', for the duration that MSW oviposition occurred (mid September to end January).

Since no incidence of MSW was previously recorded in this specific orchard, oviposition was artificially induced by enclosing chemically untreated (no insecticides) fruit in bags containing 6 adult seed weevils of an equal sex ratio. The material from which the bags were made was such that the adult weevils could not escape from the bags ('insect proof'). Thirty eight (38) bags were used. The bags were removed after 3 to 5 days (longer enclosure periods were implemented during December since oviposition declined visibly at this stage) to ensure sufficient egg laying and to guarantee infestation. Each bag contained a mango flush (foliage) for shelter, and half a mango fruit for the weevils to feed on (Fig. 1).

Fig. 1. A gauze bag containing 6 adult mango seed weevils, mango flushes (shelter) and half a mango fruit (feeding substrate).

Prior to bagging (enclosure), fruit length was measured from stem to tip using a caliper (Fig. 2). This was conducted for 38 fruit clusters (two or more fruit borne on the same / adjacent fruit panicles) per assessment (bagging date). After marking each fruit with a number depicting the date of enclosure, followed by a number depicting the size category, fruit clusters containing fruit from 2 to 4 different size categories were enclosed together in one bag.

Fruit sizes were categorized as follows:

- category 1 = 66 – 75mm
- category 2 = 76 – 85mm
- category 3 = 86 – 95mm
- category 4 = 96 – 105mm
- category 5 = 106 – 115mm
- category 6 = 116 – 125mm
- category 7 = 126 – 135mm
- category 8 = 136 – 145mm
- category 9 = 146 – 155mm.

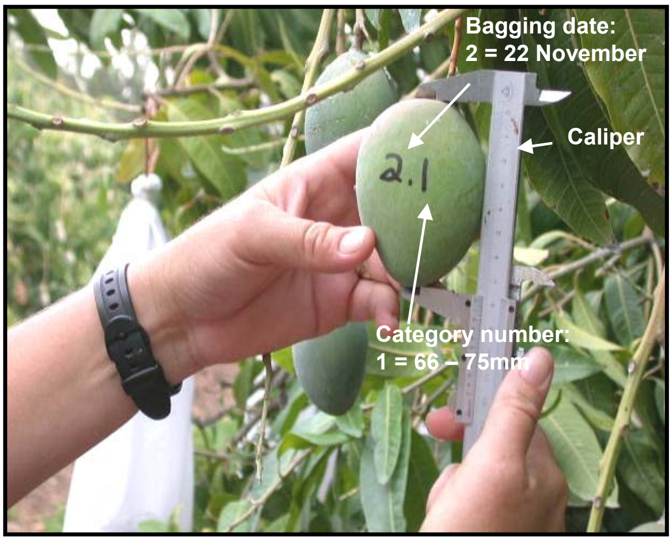

Fig. 2. Measuring and marking 'Keitt' fruit to investigate the correlation between oviposition and fruit size. The first number indicates the date of enclosure, while the second number depicts the fruit size category.

After removing a bag from a set of data fruit, the number of weevil eggs present on the fruit skin was noted, after which the fruit were tagged with brightly colored flagging tape for easy identification. The bags were then moved to the next set of fruit, following the same procedure. The study commenced on 17 November 2004, with the last fruit bagged on 3 January 2005. The data fruit were sampled at the same time as the commercial harvest for the cultivar, on 16 February 2005.

The number of fruit that were retained with sampling was noted for every fruit size category and for every period that bagging occurred. All data fruit were then cut open to determine the number of weevils developing in the fruit, distinguishing between larvae, pupae and adults. From this data collected, for each fruit size category, the number of eggs was correlated to the number of weevils developing in the seed. Some weevils (larvae, pupae and adults) were found developing inside the fruit pulp (Fig. 3), while in other instances pulp - and seed development was noted in the same fruit (Fig. 4). Since oviposition occurred only 3 to 5 days apart, the seed husk did not harden sufficiently to allow some larvae, while preventing others, from penetrating through the seed husk into the seed. There is no clear explanation why, in instances where penetration into the seed did occur, development also occurred in the pulp. A small percentage of data fruit also showed emergence holes (Fig. 5), indicating that adult weevils had already eclosed and vacated the seed. These incidences were noted.

The data was analyzed statistically with a one way analysis of variance. Tukey's HSD test at 95% confidence levels (Statistica version 6) was used.

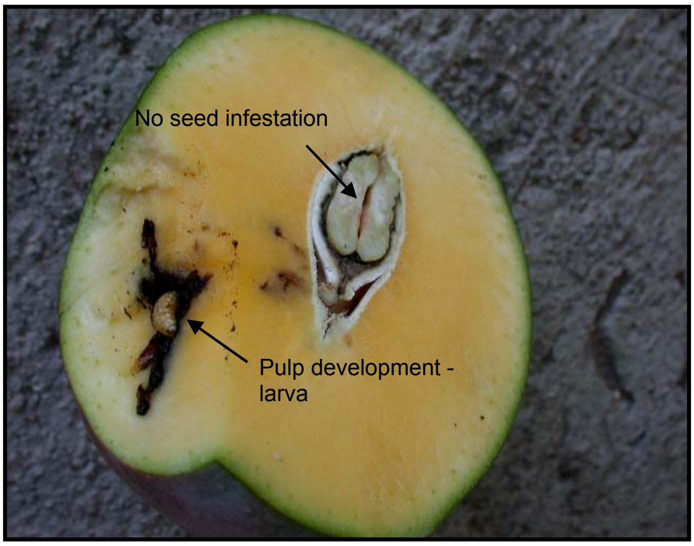

Fig. 3. A mango seed weevil larva found developing inside the mango fruit pulp. This specific fruit had no weevils developing inside the mango seed.

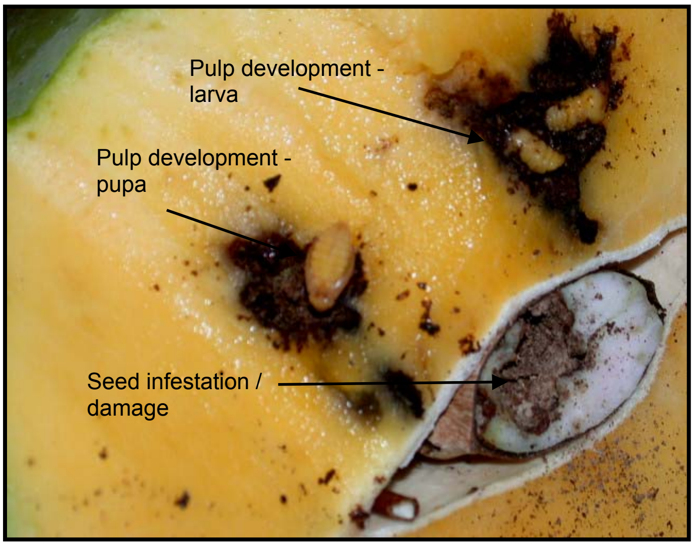

Fig. 4. Mango seed weevil larvae and pupae developing inside the mango fruit seed and pulp.

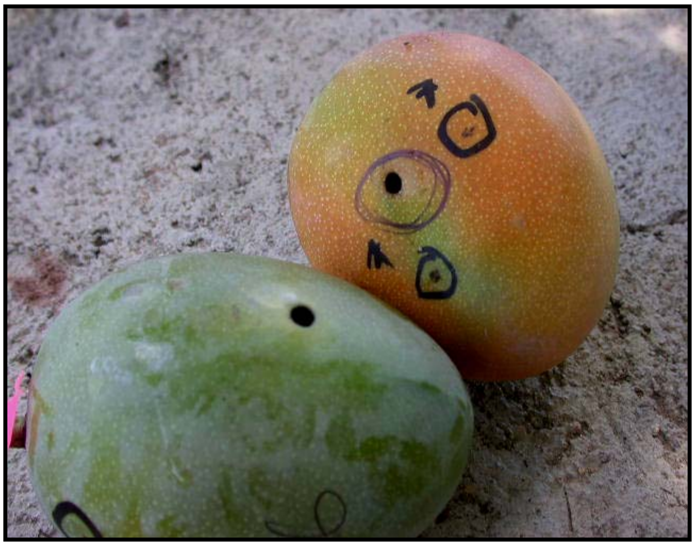

Fig. 5. Emergence holes of adult mango seed weevils that vacated the fruit.

4.2.2. Oviposition and fruit / tree position

In the 2004 / 2005 mango growing season, a study was also undertaken to investigate whether adult female weevils had any oviposition site preferences regarding fruit position in a tree, and tree position in an orchard. The study was conducted on the organic farm, Moriah (latitude 24^{o}25'S, longitude 30^{o}51'E), in the Hoedspruit magisterial district, using the early season cultivar 'Tommy Atkins'. Two adjacent orchards with known high levels of weevil infestation were used.

In Blocks B41 and B46 the three most eastern rows, situated adjacent to an open field and with the main dirt road running alongside the orchards between the orchards and the field, were used for the study. The trees were planted in rows facing north to south. All the fruit within reach, on all the trees in each data row, were examined for MSW eggs. Fruit with eggs on the fruit skin were tagged with coloured flagging tape and the eggs were encircled with a permanent marker. All the fruit investigated were categorized according to their position in the tree, i.e. east-outer, east-inner, west-inner and west-outer, and marked accordingly.

In Block B41, initial fruit marking was done between the end of October (week 44) and the beginning of November (week 45), with fruit about golf ball size, and again during the latter part of November (week 48 to 49), with fruit about tennis ball size. Fruit in Block B46 were only marked around the middle of November (week 46 to 47), with fruit between golf ball and tennis ball size, with time constraints preventing a follow-up inspection. The fruit were sampled on 15 and 16 December 2004 from Block B46 and Block B41 respectively.

4.2.3. Oviposition of adult females in captivity

During the 2005 / 2006 mango growing season, Westfalia Technological Services (WTS) investigated oviposition by captive mango seed weevil females in order to understand the pest and its impact on mango production. The study was conducted in an office, at ambient temperature and under electrical (artificial) lights. Female weevils were placed in small plastic containers (Fig. 6) containing fresh mango flushes (foliage) and half a mango fruit for feeding. A whole, green or immature mango fruit was placed in the container to monitor oviposition.

In seven of the containers, a single female was placed together with a single male (7 repetitions). But, in order to determine whether oviposition would increase if a female was more prone to encounter a potential mate, five additional containers, each containing a single female and two males (5 repetitions), were included in the study. However, since weevils may, if undisturbed, mate for a considerable length of time (personal observations, 2004 – 2005 mango growing season), it was assumed that gravid females may be capable of producing eggs for an extended period without having to mate repetitively. For this reason five additional containers containing only single mated females (5 repetitions) were included in the study.

Fig. 6. Small plastic containers with insect proof gauze netting inserted into the lids and the sides to facilitate visual monitoring of the inside of the container and to ensure air movement through the containers, as seen from the top (left) and the front (right).

The number of eggs per fruit for each container was counted daily from 28 September to 18 November 2005, at which stage the study was terminated since the majority of the weevils in captivity (colony) had died. After noting the number of eggs per container, the eggs were removed from the skin of egg infested fruit to prevent them from being re-counted during subsequent assessments. Fruit and flushes were replaced three times a week to prevent fungal growth on the cut mango fruit surfaces, wilting of the mango flushes and excessive oviposition scarring inhibiting accurate assessments. The females that were placed singularly inside containers (single mated females) were replaced with gravid females (females in the process of mating) from a breeding box containing the bulk of the weevil colony when no more oviposition occurred for a period of 3 to 4 days. Dead weevils, males and females, were replaced with live weevils from the colony.

4.2.4. Oviposition in the field

In both the 2006 / 2007 and 2007 / 2008 mango seasons, field studies were undertaken in order to investigate natural onset and duration of MSW oviposition. This was done by marking 500 fruit with coloured flagging tape, numbering the fruit from 1 to 500 to ensure that all tagged fruit were inspected with each assessment. The flagging tape used was assumed to influence neither MSW movement (Fig. 7), nor mating (Fig. 8). Data fruit were inspected on a weekly basis for the presence of MSW eggs, up to the time that no more eggs were found. The eggs were, in all instances, readily visible, whether covered with latex or without this protective shield (Fig. 9). After each assessment, the eggs were removed to prevent the eggs from being re-counted with consecutive evaluations.

Fig. 7. An adult mango seed weevil moving onto a mango fruit despite the presence of flagging tape.

Fig. 8. Adult mango seed weevils mating and moving about on a data fruit marked with flagging tape.

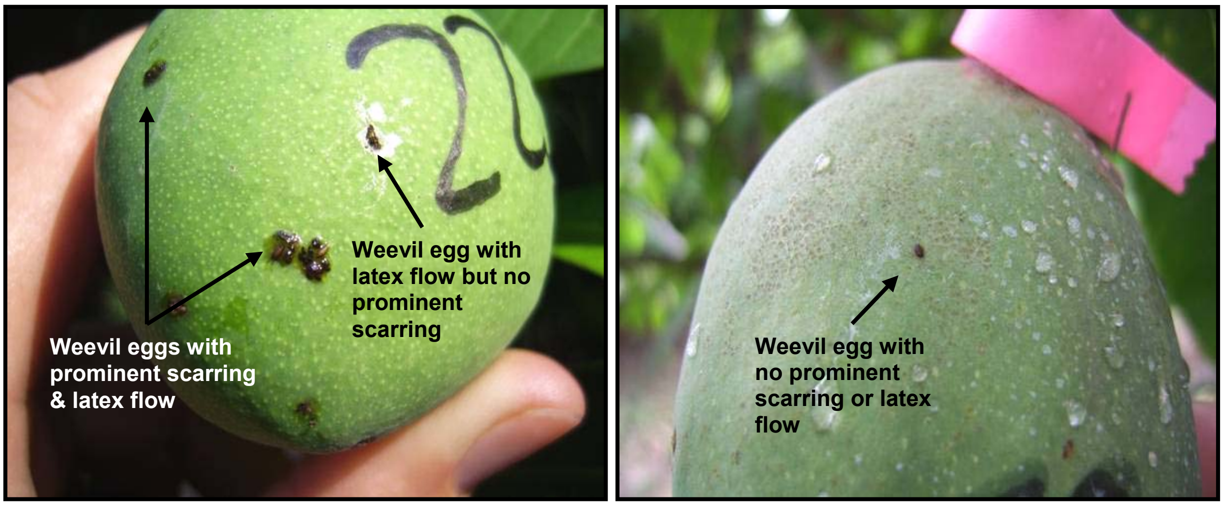

Fig. 9. Mango seed weevil eggs readily visible on the fruit skin of mango fruit, whether the egg is covered with latex and showing prominent scarring or

not (left), or where no latex flow was induced by the ovipositioning female (right).

The onset of weevil oviposition in the field was recorded as the day on which the first mango seed weevil egg was noted, irrespective of the cultivar, by scouts monitoring mango fruit constantly from the beginning of September onwards. In the 2006 / 2007 season, the first MSW eggs were noted on 19 September 2006. In 2007 / 2008, the first eggs were noted on 17 September 2007. Tagging and evaluation of mango fruit, however, only commenced on 4 October 2006 in order to reduce the effect of data fruit-weaning by the trees. For both seasons, Block C14b, cv. 'Kent' (mid-to-late season cultivar), an orchard with a high incidence of MSW on the organic farm, Moriah, was used for evaluations.

One row adjacent to *Cassuarina* trees (windbreak) was used for the study. This was done since it appeared from previous studies that mango seed weevil infestations were highest at the orchard edges, declining as one moved towards the centre of the orchard. In the 2006 / 2007 season, tags around the fruit panicles of weaned fruit (data not shown) were initially removed and the corresponding numbers deleted from the data sheet, but after loosing nearly 50% of the data fruit, previously unmarked fruit were tagged to be used as data fruit for subsequent assessments, removing all existing eggs on the fruit skin.

However, in the 2007 / 2008 season, flagging tape of weaned or fallen fruit was removed from the beginning of the study, tagging previously unmarked fruit after removing existing MSW eggs from the fruit. This was done for the duration of the study, evaluating 500 fruit with each assessment. In order to compare oviposition between cultivars and different areas, an edge row in an orchard on the farm Bavaria Fruit Estates, Block GD8, cv. 'Tommy Atkins' (early season cultivar), was included in the 2007 / 2008 mango growing season. The same procedures were followed in this orchard, with fruit tagging and assessments also commencing on 4 October 2007.

Oviposition incidence was calculated as the percentage of fruit with weevil eggs on the fruit skin, out of the total number of fruit evaluated, with severity or the rate of oviposition calculated as the average number of eggs per egg infested fruit. Duration and seasonal peaks were graphically expressed by plotting these values over time. No statistical analyses were conducted since the aim of the trial was only to establish egg laying patterns and possible seasonal peaks over time.

4.3. Results, Discussion & General observations

4.3.1. Oviposition and fruit size

Since bagging only commenced late in the season (17 November 2004), with fruit already past golf ball size (smallest fruit in category 1 = 66 – 75mm in length), few data fruit were lost during the process of natural fruit weaning. Four hundred and nine (409) fruit were bagged to ensure oviposition, and 360 egg infested fruit were harvested or sampled (12% fruit loss on average) at the time of the commercial harvest for the cultivar. Fruit losses declined as fruit size increased, with 41% fruit losses for category 1, 31% for category 2, 16% for category 3, less than 10% for categories 4 to 7 and 0% fruit loss for categories 8 and 9 (Fig. 10).

Although one might expect weevil infestation to decline as fruit size increased, with the assumption that the miniscule larvae would have been unable to penetrate the hardening seed husk as fruit matured, the infestation success, expressed as the percentage of egg infested fruit with weevils developing in the seed, was highest for the biggest (most mature) fruit (category 9 = 146 to 155mm) (Fig. 11). The reproductive success, expressed as the percentage of all eggs laid on retained fruit that produced viable offspring, was also highest for this category.

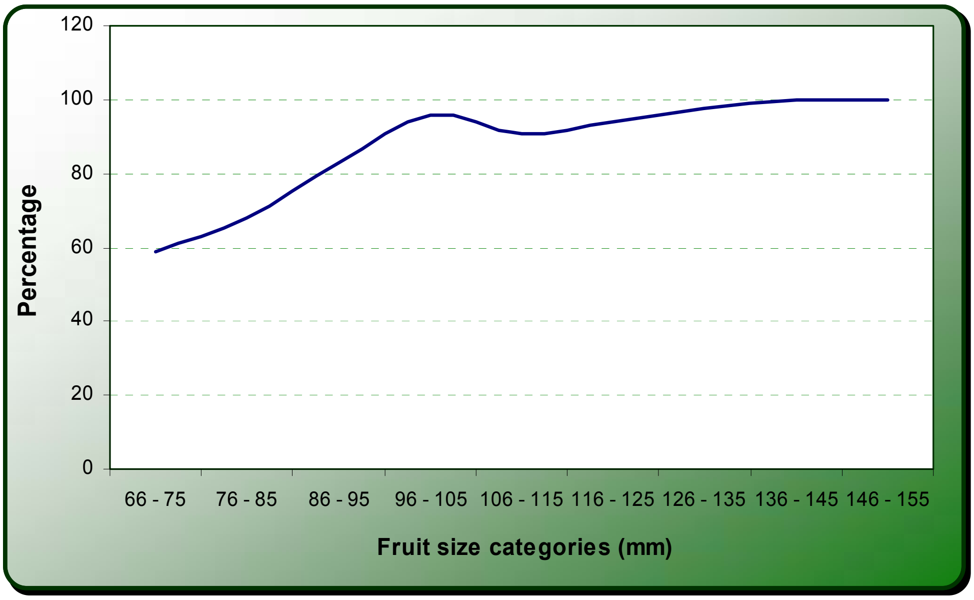

Fig. 10. The percentage of data fruit retained for different fruit size categories at the time of sampling (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

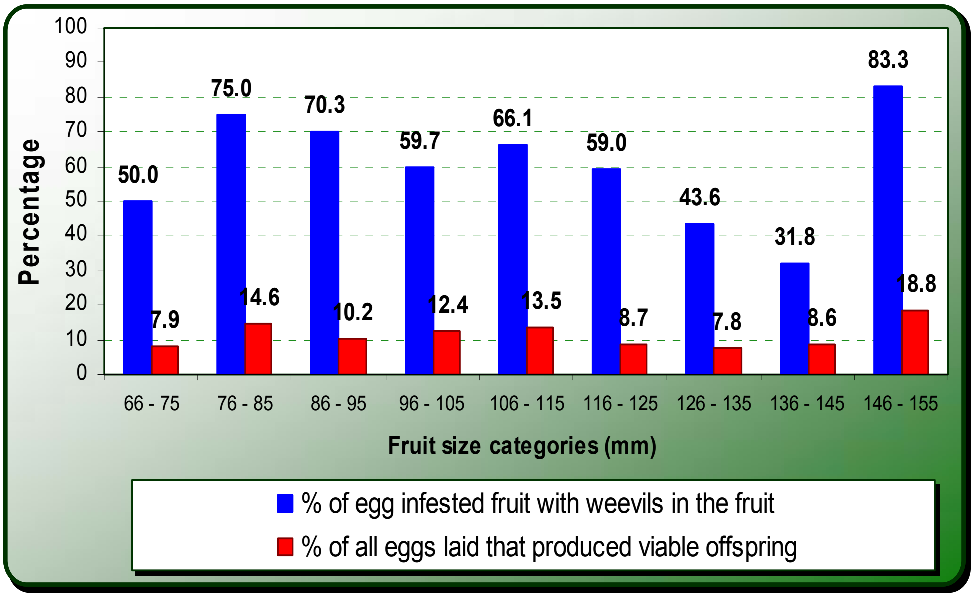

Fig. 11. Infestation success (percentage egg infested fruit with mango seed weevils developing in the seed) and the reproductive success (percentage of eggs producing viable offspring) for different fruit size categories (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

Despite the fact that oviposition was induced, resulting in excessive oviposition (average number of eggs per fruit for the complete study period equaled 10.69), the average number of weevils per fruit (irrespective of the development stage) was only 1.19. The reproductive success (Fig. 11; red bars), averaged for the complete study period, was therefore extremely low at 11.39%. This meant that the majority of eggs found on the fruit surfaces did either not hatch, or that development was inhibited.

The average number of eggs per fruit was fairly constant (Fig. 12), although slightly lower for the two categories containing the biggest fruit. These values, however, did not differ significantly from any of the other categories, with the exception of category 6 (116 to 125mm) (F (8, 81) = 3.2498; p = 0.00294; data not shown). The lower values for the last categories were probably due to oviposition declining as the season progressed, since more big fruit were tagged at the end of the season, with fruit size increasing as the season progresses. The decline in oviposition, as the season progressed, can be seen by the number of fruit tagged and marked for each bagging period (Table 1). When oviposition occurred more readily at the beginning of the season, more egg infested fruit were marked. Fewer egg infested fruit were marked when oviposition occurred less frequently at the end of the season.

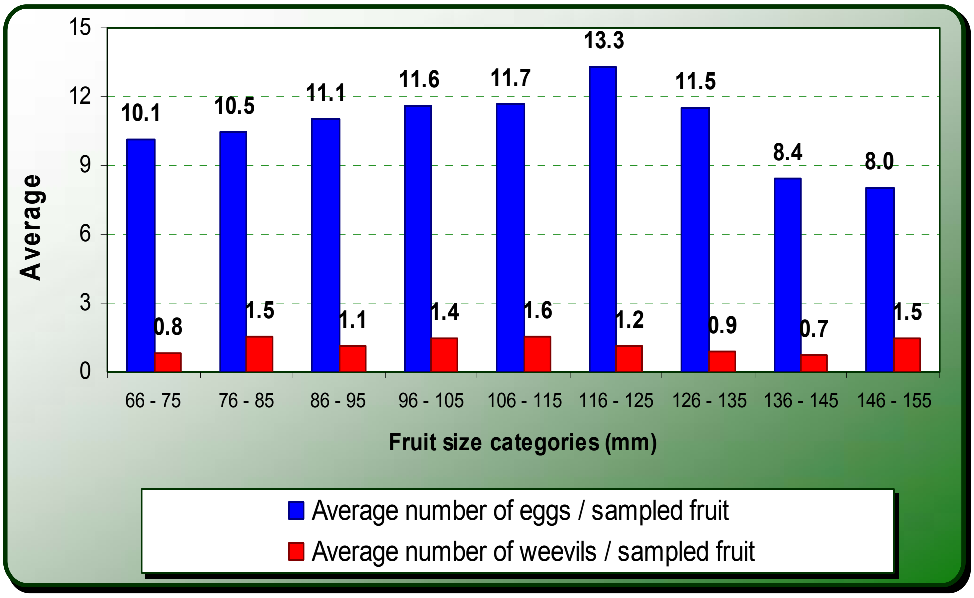

Fig. 12. The average number of eggs and mango seed weevils (larvae, pupae and adults) found on fruit from different size categories (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

No correlation was found between the number of eggs per fruit and the number of successful adult eclosions in that fruit (R^2 = 0.107, F (1,355) = 42.8; data not shown), with no statistical differences present between the different fruit size categories regarding the average number of weevils (larvae, pupae and adults) that were recorded developing inside the fruit (F (8, 81) = 1.3094, p = 0.25066; data not shown).

Table 1. Total number of egg infested fruit obtained with 38 bags, for each of the bagging periods (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

Date:	Number of egg infested fruit obtained with 38 bags
17.11	101
22.11	85
25.11	77
30.11	32
06.12	21
11.12	23
17.12	22
21.12	26
31.12	10

03.01	12
	409

Figure 13 graphically depicts each development stage, calculated as a percentage of the total number of weevils present in the fruit and its seeds, over time. Weevil development, from egg to adult, took less than 47 days (time lapse from oviposition on 31 December 2004 to sampling on 16 February 2005 (33% adults)) to more than 90 days (time lapse from oviposition on 17 November 2004 to sampling on 16 February 2005 (90.5% adults)).

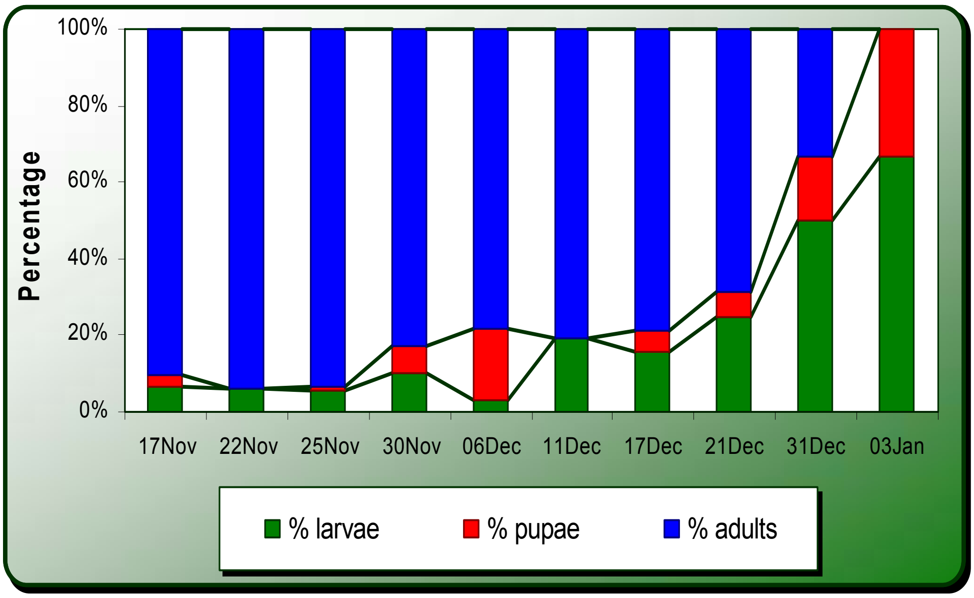

Fig. 13. Distribution of the different development stages recorded in all the fruit from a specific marking period, expressed as percentages (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

General observations:

In this study, while sampling data fruit, some adult emergence tunneling was observed in fruit from the lower categories (category 3 = 86 - 95mm to category 6 = 116 – 125mm). Since the majority of the fruit in these categories were bagged and oviposition occurred between the middle and the end of November 2004, the majority of these weevils were already mature adults prior to sampling on 16 February (Fig. 13). Although the incidence of adult weevil emergence comprised only a very small percentage of all the fruit retained and evaluated (3.6%; data not shown), this phenomenon does hold great significance for producers, since the presence of large, unattractive lesions influences the marketability of fruit. Emerging adult seed weevils from mango fruit, whether marketed on local or overseas markets, will also influence producer-consumer relations negatively.

Incidences of development in the pulp were found more frequently in fruit from the bigger fruit size categories (data not shown). From size category 7 (121 to 135mm), up to category 9 (146 to 155mm), weevils in various stages of development were found in the pulp, suggesting that the hardening of the seed husk, as fruit matured, may have prevented penetration into the seed. However, since the duration of the oviposition period for any specific fruit was only 3 to 5 days (duration of bagging) and, with one specific fruit in category 8 (136 to 145mm) containing 13 weevils developing in the pulp, in addition to 3 weevils that were developing in the seed, there is no plausible explanation why the majority of these weevils developed in the pulp. The number of fruit with weevils developing in the fruit pulp, calculated as a percentage out of the total number of fruit retained for evaluation, comprised only a very small percentage (3.06%) of the total number of fruit evaluated. However, incidences of pulp development may cause the MSW to be mistaken for the mango pulp weevil, *Sternochetus frigidus*, which may in turn cause unnecessary restrictions on mango export to certain foreign countries. Damage caused by pulp feeding will also reduce the marketability of the fruit and influence producer-consumer relationships adversely.

4.3.2. Oviposition and fruit / tree position

Figures 14 and 15 graphically summarizes the distribution of egg infested 'Tommy Atkins' fruit from Blocks B41 and B46 as the percentage of egg infested fruit, out of the total number of egg infested fruit marked, for the different tree positions. The fruit position in the tree, for the rows facing from north to south, were categorized as outer and inner fruit from the eastern and western facing sides of the trees. In Block B41, 1034 egg infested fruit were marked, with 467 egg infested fruit marked in Block B46.

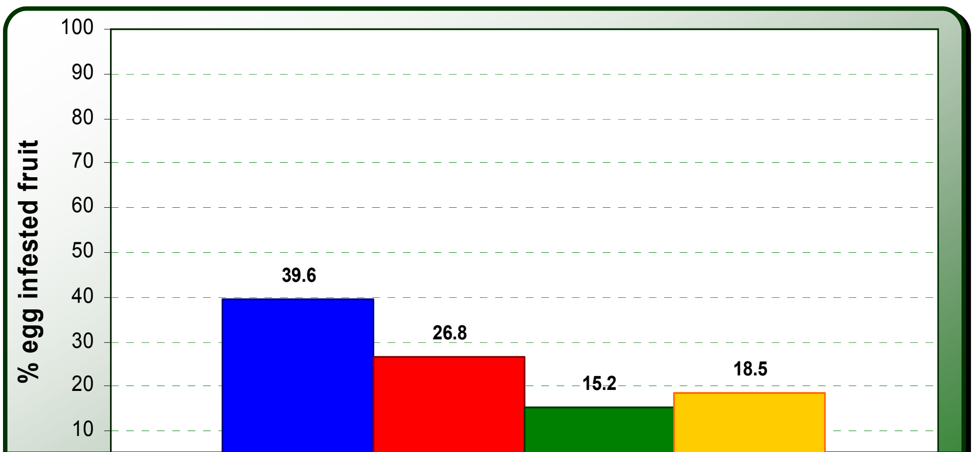

Fig. 14. Mango seed weevil oviposition expressed as the percentage egg infested fruit (cv. 'Tommy Atkins', Block B41, Moriah), 2004 / 2005.

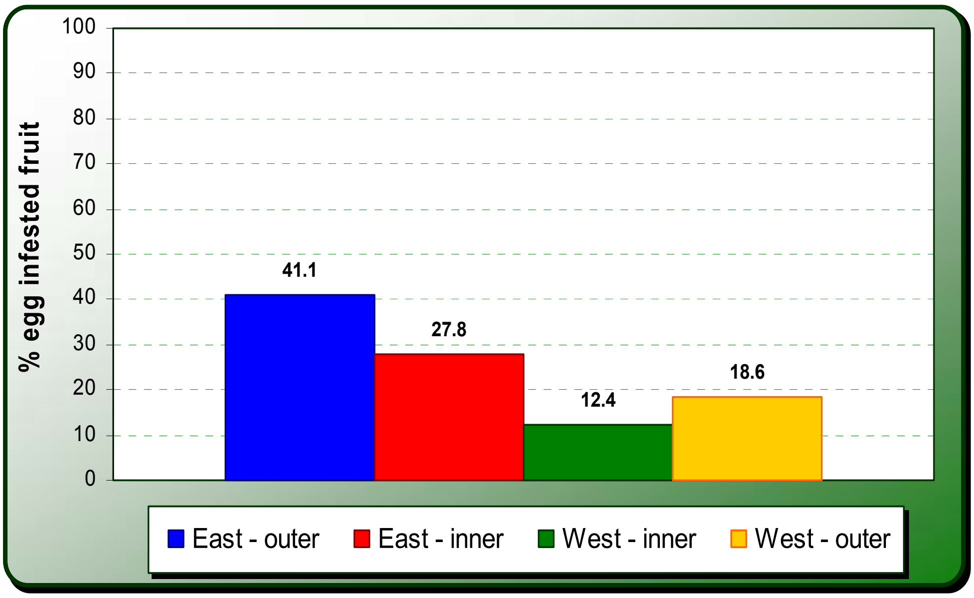

Fig. 15. Mango seed weevil oviposition expressed as the percentage egg infested fruit (cv. 'Tommy Atkins', Block B46, Moriah), 2004 / 2005.

With higher mean percentages of egg infested fruit found for the 'eastern' than 'western' categories, and higher mean percentages found for the 'outer' than 'inner' categories, this suggests that directional orientation may have influenced oviposition. However, since the percentage of egg infested fruit declined from row 1 (most eastern) to row 3 (most western) (Fig. 16[#]), the data suggests that distance from the source of infestation, i.e. the main road (dropped fruit whilst in transit) and the adjacent field (discarded seeds), rather than directional orientation, were the main reason for these differences. The average number of egg infested fruit per tree for each row, statistically analyzed with a One-way Analysis of Variance with Tukey's HSD test at 95% confidence levels (Statistica version 6), indicated that row 1 had significantly more egg infested fruit than row 2 and 3, but that rows 2 and 3 did not differ significantly from one another ($F(2, 362) = 12.532$; $p = 0.00001$) (data not shown). The mean percentage of infested fruit from the western tree sides were, therefore, lower than the eastern sides only due to a decline in population numbers as one moved away from the source of infestation. The fact that the lowest mean percentages of egg infested fruit were found for the inner fruit from both the eastern and western sides of the mango trees, was probably due to the fact that fewer fruit were present on the inside among the foliage than on the outer edges of the trees (personal observations, 2004 – 2005 mango growing season).

Fig. 16. The percentage egg infested fruit for each of the data rows (cv. 'Tommy Atkins', Block B46, Moriah), 2004 / 2005.

Since the first (most eastern) row in block B41 consisted of only 14 trees, compared to 34 trees each in rows 2 and 3, the smaller percentage of egg infested fruit rendered a skew distribution of the data when totaling the percentages per row. For this reason only the results from block B46 were used.

No apparent differences were found regarding oviposition sites on individual fruit, since eggs were found all over the fruit surface (visual observations). Some eggs, although only a few, were found on the fruit panicles and at the panicle-fruit interface.

4.3.3. Oviposition of adult females in captivity

Tables 2 to 4 summarize data pertaining to MSW oviposition in captivity and under artificial conditions. The data were obtained by counting the number of eggs laid by isolated MSW pairs, single mated females (to determine the intensity and duration of egg laying in the absence of a mate), and females placed together with two males (to determine egg laying when the female readily has access to a potential mate) in small containers containing mango flushes and fruit.

Eggs were counted daily in the early morning (07h00), removing the eggs afterwards. In order to prevent excessive oviposition scarring on whole mango fruit and decay of fruit halves, and wilting of flushes, fruit were replaced every second day.

When weevil pairs were isolated in 7 separate containers (7 repetitions) (Table 2), a total number of 554 eggs were oviposited on fruit surfaces, with 79.14 eggs laid, on average (range: 58 - 110), over a 50 day period. This resulted in 1.58 eggs, on average, per day. The maximum number of eggs that were laid by a single female adult per day, not considering eggs that were counted after the weekends where an accumulation of eggs occurred, was 13.

This average cannot be considered to be indicative of the actual number of eggs that a single female in constant contact with a potential mate can lay, since females in some of the containers were often replaced due to mortalities. This average, however, did correspond well to actual values that were obtained for females that were not replaced and that produced eggs for the duration of the study period. In containers 5 and 8, where no mortalities occurred, a total number of 80 (container 5) and 79 (container 8) eggs were laid, resulting in 1.82 (80 eggs / 44 days) and 1.76 (79 eggs / 45 days) eggs that were laid per day, on average, by a single female placed together with a single male weevil in an isolated container.

When females were placed in isolated containers (5 repetitions in 5 containers) with two males to enhance chances of mating in order to investigate oviposition if the female had more readily access to a potential mate (Table 3), a total number of 437 eggs were laid on fruit surfaces. For the duration of the study, 87.4 eggs, on average, were laid, with 1.82 eggs, on average, per day, slightly more than when only a single pair was placed in a container. The maximum number of eggs that were laid by a single female adult, per day, not considering eggs that were counted after the weekends, was 12.

Again, the average obtained is only indicative of potential values, since females were replaced when mortalities occurred. In container 2, where no mortalities occurred and where the same female laid eggs for the duration of the study period, a total number of 134 eggs were laid, resulting in 3.05 eggs, on average, per day (134 eggs

/ 44 days). Contrary to the previous findings, this value was slightly higher than the average obtained when combining the results from all 5 containers, irrespective of whether mortalities occurred.

When single, mated females were placed in containers (5 repetitions in 5 containers) (Table 4), to investigate oviposition in the absence of a potential mate, since weevils may, if undisturbed, mate for long periods, a total number of 252 eggs were laid on fruit surfaces. For the duration of the study, 50.4 eggs, on average, were laid, with 1.58 eggs, on average, laid per day. In container 5, a single mated female laid eggs for a period of 24 days, without having contact with a male. A total number of 82 eggs were laid, with an average of 3.42 eggs per day (82 eggs / 24 days). The maximum number of eggs that were laid by a single, mated female adult, per day, was 8.

It seemed, therefore that, should MSW females more readily have access to a potential mate, that egg laying may increase, although only slightly. Once mated, however, mate availability was not a prerequisite for oviposition. This could possibly explain why, irrespective of the fact that adult weevils are generally inactive, adult weevils mate for long periods if undisturbed. Thereafter females most likely store the male spermatozoa in the spermatheca.

Table 2. Number of eggs counted on a mango fruit from a small container housing one mango seed weevil pair (female plus male). Seven containers (7 replicates) were used.

		Total number of eggs						
Date	**Day**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**	**Rep 6**	**Rep 7**
28.09.05	**1**	3	0	0	1	0	0	0
29.09.05	**2**	7	0	0	4	4	0	0
03.10.05	**5**	3	0	0	3	14	0	0
04.10.05	**6**	7	0	0	5	4	0	6
05.10.05	**7**	6	1	0	5	3	0	1
06.10.05	**8**	10	7	0	3	1	0	3
07.10.05	**9**	4	0	0	4	5	1	3
10.10.05	**12**	0	3	1	3	2	3	1
11.10.05	**13**	1	0	1	2	2	4	2
12.10.05	**14**	1	1	1	5	1	3	2

13.10.05	**15**	2	2	0	4	3	6	1
14.10.05	**16**	13	4	0	3	1	4	2
17.10.05	**19**	1	9	0	4	0	0	5
18.10.05	**20**	1	3	1	1	3	1	10
19.10.05	**21**	0	1	0	0	6	0	2
20.10.05	**22**	3	6	6	0	5	0	7
21.10.05	**23**	0	4	4	0	0	4	2
24.10.05	**26**	0	9	1	0	0	1	0
25.10.05	**27**	3	2	2	1	4	1	3
26.10.05	**28**	0	0	2	1	0	0	0
27.10.05	**29**	0	0	2	3	0	1	0
28.10.05	**30**	3	0	3	4	4	2	2
31.10.05	**33**	0	0	2	0	0	1	0
01.11.05	**34**	2	0	3	0	3	0	0
02.11.05	**35**	3	10	1	0	2	0	6
03.11.05	**36**	1	11	4	0	0	5	4
04.11.05	**37**	2	11	8	0	0	1	3
07.11.05	**40**	0	5	7	0	4	10	1
08.11.05	**41**	1	8	5	0	8	8	6
09.11.05	**42**	1	1	1	0	0	1	2
10.11.05	**43**	5	6	2	1	0	5	3
11.11.05	**44**	3	6	1	0	1	0	1
14.11.05	**47**	0	0	0	12	0	0	1
15.11.05	**48**	0	0	0	6	0	0	0
16.11.05	**49**	0	0	0	2	0	0	0
17.11.05	**50**	0	0	0	2	0	0	0
Total		86	110	58	79	**80**	62	**79**

Areas highlighted in grey indicate a change of weevils when no eggs were laid for long periods, and at the end of the study, due to mortalities.

Numbers between grey dotted lines indicate the days in a week.

Yellow highlights indicate the total number of eggs laid by females, constantly in contact with one male, over a 7 week period.

Table 3. Number of eggs counted on a mango fruit from a small container housing one mango seed weevil female and two males. Five containers (5 replicates) were used.

Date	**Day**	**Total number of eggs**				
		Rep 1	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**
28.09.05	**1**	0	0	0	0	0
29.09.05	**2**	0	0	0	0	0
03.10.05	**6**	0	2	0	0	0
04.10.05	**7**	0	1	0	0	0
05.10.05	**8**	0	1	0	0	0
06.10.05	**9**	0	2	0	0	0
07.10.05	**10**	0	2	0	0	0
10.10.05	**13**	5	6	3	5	8
11.10.05	**14**	1	4	4	2	1
12.10.05	**15**	0	0	2	2	1

13.10.05	**16**	7	4	6	0	9
14.10.05	**17**	3	5	5	3	5
17.10.05	**20**	2	12	6	4	3
18.10.05	**21**	5	7	4	2	5
19.10.05	**22**	6	6	5	0	1
20.10.05	**23**	6	8	1	1	2
21.10.05	**24**	1	4	0	0	1
24.10.05	**27**	1	5	2	0	2
25.10.05	**28**	1	4	4	0	1
26.10.05	**29**	3	3	4	0	3
27.10.05	**30**	5	12	9	0	2
28.10.05	**31**	1	4	10	6	1
31.10.05	**34**	7	7	6	3	2
01.11.05	**35**	1	7	5	3	2
02.11.05	**36**	1	7	3	0	1
03.11.05	**37**	5	3	6	4	2
04.11.05	**38**	1	3	3	4	4
07.11.05	**41**	7	8	3	1	2
08.11.05	**42**	3	1	2	7	3
09.11.05	**43**	1	1	0	2	0
10.11.05	**44**	5	5	0	2	0
11.11.05	**45**	0	0	2	1	0
14.11.05	**48**	0	0	3	3	10
15.11.05	**49**	0	0	0	1	0
16.11.05	**50**	0	0	0	0	0
17.11.05	**51**	0	0	0	0	0
Total		78	**134**	98	56	71

Areas highlighted in grey indicate a change of weevils when no eggs were laid for long periods, and at the end of the study, due to mortalities.

Numbers between grey dotted lines indicate the days in a week.

Yellow highlights indicate the total number of eggs laid by females, constantly in contact with two males, over a 7 week period.

Table 4. Number of eggs counted on a mango fruit from a small container housing one mated mango seed weevil female only. Five containers (5 replicates) were used.

		Total number of eggs				
Date	**Day**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**
17.10.05	**1**	1	6	16	0	7
18.10.05	**2**	1	5	2	4	5
19.10.05	**3**	0	6	0	3	5
20.10.05	**4**	0	7	0	0	5
21.10.05	**5**	0	5	0	0	3
24.10.05	**8**	0	12	0	3	2
25.10.05	**9**	0	6	0	4	3
26.10.05	**10**	1	3	5	1	3
27.10.05	**11**	0	3	1	7	2
28.10.05	**12**	0	3	0	4	1

31.10.05	**15**	0	0	2	2	5
01.11.05	**16**	0	0	0	6	6
02.11.05	**17**	0	0	3	4	3
03.11.05	**18**	5	0	0	0	4
04.11.05	**19**	5	0	0	0	7
07.11.05	**22**	7	0	0	0	13
08.11.05	**23**	0	0	1	0	6
09.11.05	**24**	0	0	1	1	2
10.11.05	**25**	1	2	2	0	0
11.11.05	**26**	0	1	0	0	0
14.11.05	**29**	0	0	0	4	0
15.11.05	**30**	0	0	8	6	0
16.11.05	**31**	0	0	0	0	0
17.11.05	**32**	0	0	0	0	0
Total		21	59	41	49	82

Areas highlighted in grey indicate a change of weevils when no eggs were laid for long periods, and at the end of the study, due to mortalities.

Numbers between grey dotted lines indicate the days in a week.

Yellow highlights indicate the total number of eggs laid by a single mated female over a 5 week period.

4.3.4. Oviposition in the field

Results obtained when monitoring oviposition in the field, for the 2006 / 2007 mango growing season, are graphically expressed in Figure 17. Weevil activity was determined by monitoring oviposition and calculating the percentage of egg infested fruit, out of the total number of fruit evaluated, for each assessment. By plotting these values over time, seasonal occurrence (incidence) and mobility could be determined. To determine the oviposition rate, the average number of eggs per egg infested fruit was calculated (indicated on the second y-axis).

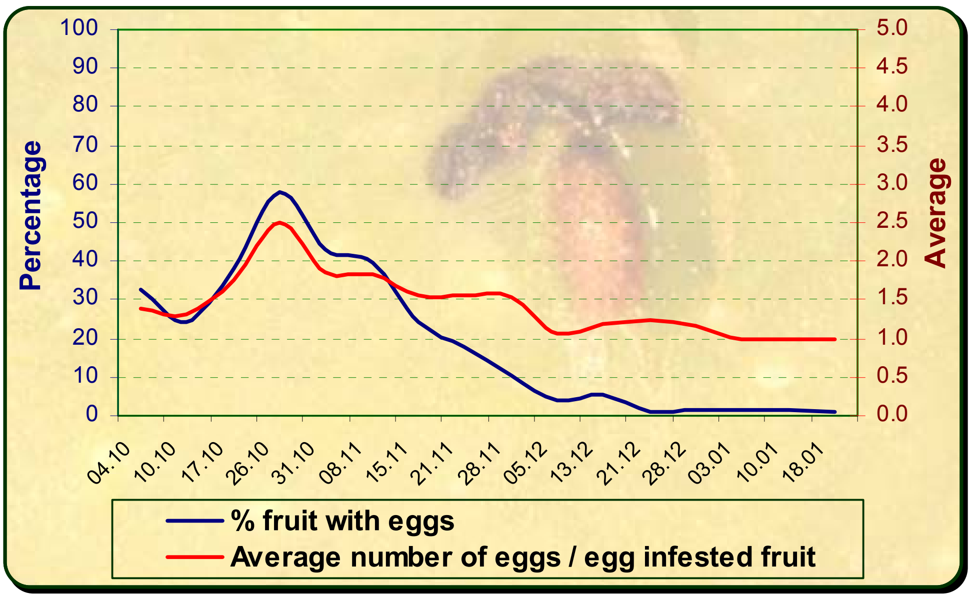

Fig. 17. The incidence and severity of natural mango seed weevil egg laying (cv. ‘Kent’, Block C14b, Moriah), 2006 / 2007.

With the onset of natural oviposition recorded as 19 September 2006, but with evaluations only commencing on 04 October to negate the effect of natural weaning of data fruit, the percentage of egg infested fruit at the beginning of the study was already quite high (32.8%). Weevil activity and movement reached a definite peak at the end of October, with the greatest number of fruit having been visited by female weevils and with 58.0% of the fruit bearing weevil eggs on the fruit skin. After this peak, activity declined steadily as the season progressed, with values for December 2007 fairly low and values for January 2008 negligible. The last MSW eggs were noted on 18 January 2008, indicating that, contrary to literature references, mango seed weevil oviposition in fact extends over four months. The bulk of the weevil eggs were found during October and November, indicating that adult weevils are most active during these two months.

The average number of eggs per egg infested fruit, indicating the rate or severity of attack, followed the same pattern. The majority of eggs were deposited at the end of October (2.51 eggs per fruit) (Fig. 17), with averages declining after this. This means that, not only were the adult weevils more mobile during peak activity, visiting more fruit for oviposition, but egg production also occurred at a higher rate.
Results obtained for the 2007 / 2008 mango growing season, are graphically plotted in Figure 18. Similarly as in the 2006 / 2007 season, weevil activity and mobility was measured by monitoring oviposition and calculating the mean percentage of egg infested fruit per assessment. The severity of attack was determined by calculating the average number of eggs per egg infested fruit. To determine distribution patterns and duration of oviposition, these values were plotted over time.

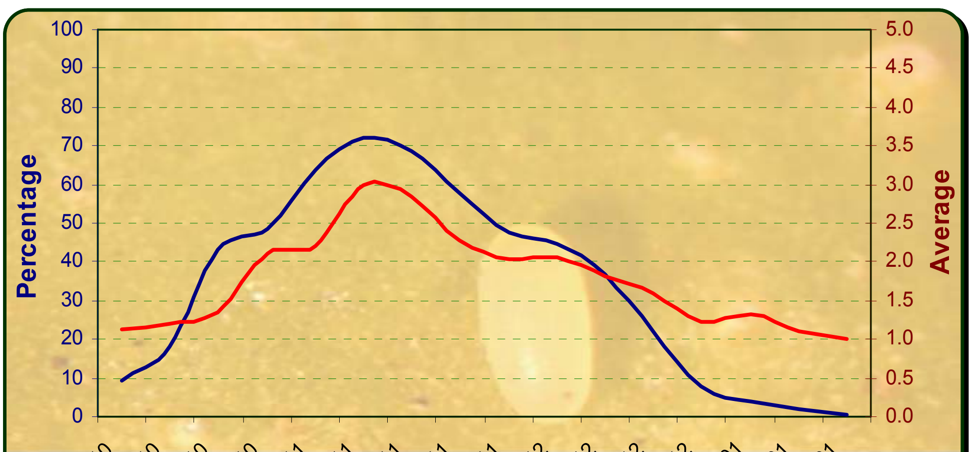

Fig. 18. The incidence and severity of natural mango seed weevil oviposition (cv. ‘Kent’, Block C14b, Moriah), 2007 / 2008.

The onset of natural egg laying in the 2007 / 2008 mango growing season was recorded as 17 September 2007 (isolated garden tree with early fruit set), but the first weevil eggs in a mango orchard was only noted on 26 September 2007, probably due to a delay in fruit set and growth on account of adverse environmental conditions. With evaluations only commencing on 04 October, to negate the effect of natural weaning of data fruit and to have a date sequence comparative to that of the 2006 / 2007 mango growing season, weevil eggs were already present due to this time delay, but on only 9.2% of the data fruit at the time of the first evaluation.

As in the previous season, a definite peak in the percentage of egg infested fruit was found, although this peak showed a lag of about two weeks (middle of November) when compared to the previous season (end October), corresponding to a similar time lag seen in flowering, fruit set and fruit maturation. Also, as in the previous season, the percentage of egg infested fruit decreased steadily after this peak as the season progressed. But, contrary to the previous season, this decrease was not as prominent, with a greater percentage of egg infested fruit found during the latter part of December than in the previous season, again probably due to this lag period and due to environmental conditions conducive to MSW activity and mobility. Despite this shift in the oviposition peak, and despite the fact that higher incidences of egg infested fruit were recorded during December 2007, egg laying was, similarly as in the 2006 / 2007 season, negligible in January. The last eggs were recorded on 17 January 2008. The severity or rate of attack (average number of eggs per egg infested fruit) followed the same trend as the incidence (percentage egg infested fruit), and showed a similar trend as in the 2006 / 2007 season, except for the shift of the distinctive peak from the end of October to the middle of November.

Oviposition for the early season cultivar, 'Tommy Atkins', and for a different geographical area, Block GD8, Bavaria Fruit Estates, showed a similar trend, with both the percentage of egg infested fruit and the average number of eggs per egg infested fruit peaking by the middle of November, declining steadily afterwards as the season progressed (Fig. 19). The decline in the percentage of egg infested fruit, compared to the values obtained from Block C14b at Moriah, however, was more prominent, probably due to the effect of kaolin applied on 20 November 2007.

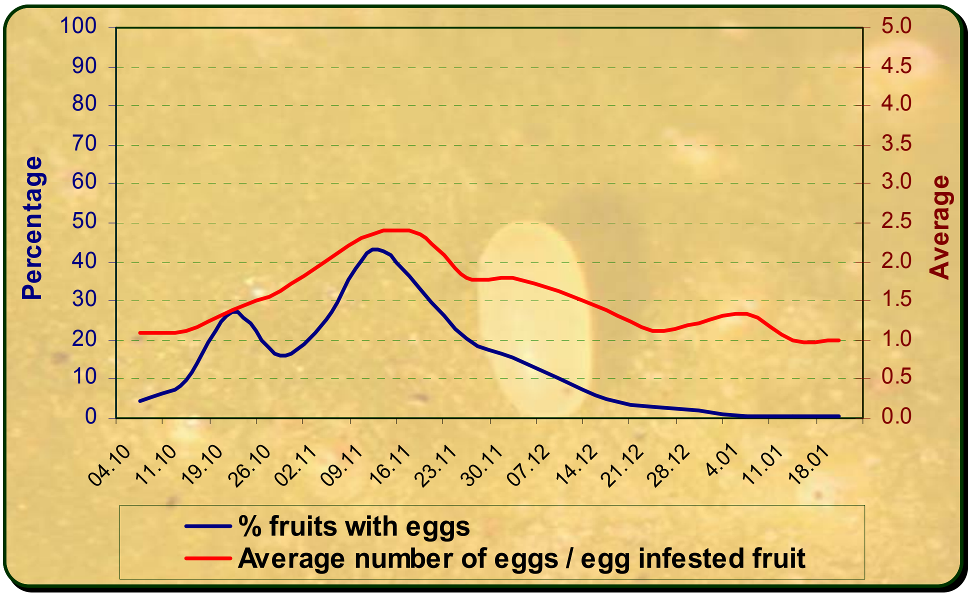

Fig. 19. The incidence and severity of natural mango seed weevil oviposition (cv. 'T. A.', Block GD8, Bavaria Fruit Estates), 2007 / 2008.

In the 2007 / 2008 mango growing season, from the end of October to approximately the end of November, MSW feeding damage (Fig. 20) and adult mango seed weevils (Fig. 21) were frequently, for the first time in mango orchards, observed during the day. In Block C14b, where the majority of weevils were seen, this appearance could have been attributed to infestation levels that were considerably higher than in the previous season (max. 72.3% vs. max. 58.0% egg infested fruit in the 2006 / 2007 season).

Fig. 20. Diurnal feeding by a mango seed weevil feeding on mango fruit (left), often causing severe fruit damage (right) (cv. ‘Kent’, Block C14b, Moriah), 2007 / 2008.

Fig. 21. Diurnal adult mango seed weevil activity on mango fruit recorded as mostly single individuals (left), but sometimes also as mating pairs (right) (cv. ‘Kent’, Block C14b, Moriah), 2007 / 2008.

However, since adult weevils were also observed in other orchards, including Block GD8 (max. 43.3% egg infested fruit), and since these adults were all found to be active, moving about on mango fruit and foliage, environmental conditions may have been the reason for this increase in weevil activity and mobility. During the different mango growing seasons, average temperatures in 2007 / 2008 were lower than in the previous season, with humidity and rainfall overall higher in the 2007 / 2008 than in the 2006 / 2007 season. The different environmental parameters measuring temperature and humidity, for both the 2006 / 2007 and the 2007 / 2008 seasons, are summarized in Table 5.

Table 5. Summary of environmental parameters (temperatures, humidity and rainfall) for months October to December, for both 2006 / 2007 and 2007 / 2008 mango growing seasons.

	2006 / 2007	2007 / 2008

Month	Ave. T (°C)	R_{max} (%)	R_{min} (%)	Rain (mm)	Ave. T (°C)	R_{max} (%)	R_{min} (%)	Rain (mm)
October	24.55	81.29	31.26	7	22.06	83.55	41.74	33.3
November	24.87	68.00	30.07	88.8	23.82	89.03	38.33	125.3
December	27.18	84.52	33.55	159.4	23.61	91.00	42.00	197.0

4.4. Conclusion

Contrary to popular beliefs that MSW females lay their eggs on green, developing mango fruit, it was found, during a study designed to investigate the correlation between MSW oviposition and fruit size, that both infestation success (percentage of egg infested fruit with weevils developing in the seed) and reproduction success (percentage of weevils that developed from all the eggs that were induced for a specific fruit size category) was highest for the biggest fruit. Furthermore, both the average number of eggs per fruit, and the average number of weevils found developing inside the seeds, was found to be relatively constant over the various fruit size categories.

Despite excessive egg laying that was obtained by the artificial introduction of MSW to induce oviposition, the average number of weevils per fruit remained relatively low. The reason for this is probably that a mango fruit, being the only available food source and site for weevil development, can only sustain a certain number of weevils. Incidences of pulp development and adult weevil emergence from tree-hanging fruit, although not common, did occur. This will ultimately influence producer-consumer relationships adversely and reduce marketability. Weevils encountered in the fruit pulp were positively identified as *Sternochetus mangiferae* by the Department of Agronomy, Plant Protection Institute, Agricultural Research Council in Pretoria. Incidences of pulp development may lead, however, to the incorrect assumption that the mango pulp weevil, *Sternochetus frigidus*, are found in mangoes produced in South Africa, putting unnecessary strain on access to certain foreign markets, but it can be categorically stated that this species does not occur in South Africa.

No apparent differences were found regarding oviposition and the position of mango fruit within a tree, or different tree positions within an orchard. In accordance to literature references (Schotman, 1989; Hansen, 1991; Hansen *et al.,* 1989), adult mango seed weevil oviposition seemed to have occurred at random, with eggs laid on any part of the fruit surface. It did seem, however, that infestation levels were highest closer to the source of infestation, and declined the further away the source.

The total number of eggs laid by a MSW female in a single season could not be established, since the majority of the captive weevil died in November. However, from the results it did seem as if egg laying increased slightly as mate availability increased, although differences were small. Single mated females were able to, on average, produce eggs that were comparative in number to females in constant contact with one male. This is probably the reason why adult weevils mate, if undisturbed, for long periods, with the females able to store the male spermatozoa in the spermatheca, fertilizing the eggs as they are laid. The total number of eggs that were laid in a single day by an adult female, i.e. 13 (female with single male), 12 (female with two males) and 8 (single mated female in isolation), corresponded to observations by Balock and Kozuma (1964), namely that one female may lay up to 15 eggs per day.

Mango seed weevils do seem to be active, and lay their eggs, over a more extended period than previously stated in the literature. The onset and duration of oviposition by adult weevils in the field, over two seasons, was comparative and remained constant. Oviposition in the field commenced at more or less the middle of September and continued up to mid January, although fruit size seemed to have had an influence on the onset of oviposition in mango orchards (no weevil eggs were recorded on fruit smaller than golf ball size), with environmental conditions the most probable cause for deviations.

The bulk of MSW weevil activity and oviposition were found to have occurred through October and November. A definite peak in egg laying indicated a peak in weevil activity (mobility and egg laying), although seasonal variations in the onset of flowering, fruit set and fruit maturation on trees resulted in a slight shift of this peak.

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CHAPTER 5

Development, eclosion and emergence of the mango seed weevil

5.1. Introduction

5.1.1. Weevil development

In order to effectively control (biologically, mechanically or chemically) any insect pest, it is imperative to understand its biology and dispersal patterns. For the mango seed weevil (MSW), it is not only important to know the onset and duration of oviposition to determine the best time for chemical intervention, it is also imperative to know the development cycle of the insect in order to know at which time intervention with contact and trans-laminar products would be critical. Chemical control with contact and trans-laminar products, aimed at controlling the miniscule larvae as it hatches from the egg and penetrates the fruit pulp, needs to be applied before the larvae reach the safety of the seed. Joubert and Pasques (1994) reported that the timing of especially single applications of these products is of crucial importance, while Verghese (2000), in turn, reported that, once the larvae have penetrated the seeds, chemical control was ineffective.

According to Schoeman (1987) small, cream-coloured eggs are laid singly on green fruit just under the skin of the fruit. Eggs hatch within 5 to 7 days (Balock & Kozuma, 1964), but can take as long as 14 days (Schoeman, 1987). De Villiers (1987) reported that MSW females laid their eggs on the surface of the fruit skin. He found that the miniscule larvae hatched within a week, penetrating through the skin and pulp towards the seed, leaving scars that were nearly invisible to the naked eye. Other authors also reported that, with time, it becomes impossible to distinguish infested from non-infested fruit without having to cut the fruit open (CABI & EPPO, 2005). Some authors claim that the female makes a boat-shaped cavity into which the egg is deposited (possibly with the ovipositor although no evidence for this exists in the literature), after which the egg is covered with a brown exudate (CABI & EPPO, 2005). The MSW female generally excavates (possibly with the mouth parts although no evidence for this exists in the literature) a crescent-shaped wound posterior to the egg to induce latex flow, which covers and protects the egg (CABI & EPPO, 2005).

The minimum period required from hatching to seed penetration is reported to have been one day (CABI & EPPO, 2005; Woodruff & Fasulo, 2006). Some authors report 5 larval instars (Woodruff & Fasulo, 2006), while others report 7 instars based on head capsule width frequencies (Balock & Kozuma, 1964; Hansen *et al.*, 1989). Variation in individual larval development based on food quantity, together with food quality, makes determination of the number of instars difficult, leading to varying numbers of instars being reported (Hansen *et al.*, 1989). Larval development in the seed is reported to be between 20 to 30 days (Balock & Kozuma, 1964; Follet & Gabbard, 2000), and 10 weeks (Hansen *et al.*, 1989).

Pupation usually occurs within the seed, although some incidences of development in the pulp have been reported in the past (Balock & Kozuma, 1964; Hansen *et al.*, 1989). Early pupae are nearly white, discoloring to a very slight red shortly before the adult ecloses (Woodruff & Fasulo, 2006). Pupation lasts about one week (Hansen *et al.*, 1989). The duration of the life cycle, from egg to adult, is reported to be between 5 to 8 weeks (De Villiers, 1984; Schoeman, 1987; Woodruff & Fasulo, 2006).

5.1.2. Weevil eclosion and emergence

Many authors believe that adult weevils rapidly move out of the seeds upon reaching adulthood (CABI & EPPO, 2005), and that no problems are generally experienced on local South African markets with early cultivars since fruit are marketed and consumed before weevils reach maturity (De Villiers, 1984; Joubert & Pasques, 1994). However, Balock & Kozuma (1964) reported that the MSW adults remained in the seeds for considerable periods after eclosion prior to emergence, ranging from 22 to 76 days, therefore exiting only after the fruit have been consumed or it has fallen from the tree.

Schotman (1989), however, stated that, for late maturing cultivars, the development of the MSW is considerably shorter than that of fruit maturation, resulting in mature MSW adults emerging from the fruit before the fruit are marketed. De Villiers (1987) noted that adult weevil emergence was only encountered in the case of late hanging cultivars that were harvested from February onwards. Hansen (1991) reported that adult MSW emergence while the fruit were still on the trees were negligible, with the majority of adults emerging from fruit that had already fallen (post-marketable), or from bare seeds after fruit decay.

In a study investigating MSW emergence, Joubert and Pasques (1994) collected over a thousand ripe mangoes, removing the fruit pulp and storing the seeds in a gauze cage. They found that 78% of the adults emerged before winter (May 31, 1993), while 22% hibernated in the seeds. Of the latter group, approximately 7% died within the seeds. Woodruff and Fasulo (2006) also found that, in general, only 25% of adult weevils hibernated in the seeds. Some authors associate moisture, and therefore fruit maturity, as the probably trigger for adult emergence (Balock & Kozuma, 1964; Schotman, 1989; Hansen, 1991).

Once leaving the seeds, the weevils' hibernation sites remain largely unknown. Schoeman (1987) collected soil and debris samples from beneath mango trees, but found no adult weevils. Joubert & Pasques (1994) found only 3 dead adult weevils after a thorough search of the top soil. In a field study during which infested seeds were enclosed in a gauze cage erected over a mango tree, they found that emerging adult weevils moved upwards into the mango tree, hiding under loose bark or in crevices. They concluded that, under natural conditions, adult seed weevils would probably exhibit the same behaviour, i.e. to hibernate within the mango trees.

Since the rate of successful emergence would influence future infestation levels, with the incidence and severity of natural seed weevil infestations, and therefore adult emergence, influencing the marketability of late-season cultivars, it is imperative to investigate this aspect of weevil biology and reproduction. For this reason Westfalia Technological Services investigated various aspects of adult MSW emergence.

5.2. Materials and Methods

5.2.1. Weevil development

In order to investigate mango seed weevil development, a study was conducted by Westfalia Technological Services in both the 2006 / 2007 and 2007 / 2008 mango growing seasons. The first aspect of the study was to determine the time required for eggs to hatch to determine the time window available for chemical control with contact and semi-penetrant insecticides aimed at controlling the MSW larvae.

A second aspect was to determine the time required for the miniscule larvae to reach and penetrate into the seed. The need to investigate the time lapse from oviposition to seed penetration resides in the fact that, once the MSW larvae have penetrated through the protective cover of the seed husk, chemical control with semi-penetrant insecticides would probably be ineffective.

A third aspect of the study was to determine the time lapse from egg to adult, since the presence of adult weevils in the seed, and the possibility of adult emergence from infested seeds, necessitates that orchard sanitation (removal of tree ripened and fallen fruit) is implemented reduce the impact of adults re-infesting the orchard. Once this time lapse, as well as the onset of MSW oviposition is known, the most appropriate time to commence with sanitation practices can be determined.

Blocks G94 (2006 / 2007 mango season) and G61 (2007 / 2008 mango season) on the farm Grovedale (latitude $24^{o}24'S$, longitude $30^{o}51'E$), in the magisterial district of Hoedspruit in the Limpopo Province, were used to investigate weevil development. The late-season cultivar, 'Keitt', was chosen in order to ensure sufficient tree hanging fruit for the whole period that MSW oviposition occurred (mid September to mid January), with sufficient time available for complete development of larvae hatching from eggs laid during the latter part of the mango growing season.

Oviposition was ensured through bagging, i.e. the artificial introduction of MSW adults to mango fruit by enclosing the fruit in gauze bags (Fig. 1). The adult weevils were obtained from various MSW colonies that are maintained in isolated containers (breeding boxes) and kept in an office at ambient temperatures and artificial (electrical) lights throughout the year. The majority of these captive weevils were sampled during previous seasons from infested fruit and seeds at the same time that natural adult emergence occurred.

Each bag, containing 6 adult seed weevils (of equal sex ratio), was tied around a cluster of fruit for a period of 2 to 3 days to ensure sufficient egg laying to guarantee infestation. After removing the bags, all egg infested fruit were tagged with coloured flagging tape (Fig. 2), after which the data fruit were marked with a number corresponding to the bagging or oviposition date to determine the sampling date for evaluation, and a fruit number.

Fig. 1. Gravid adult mango seed weevils (6 per bag, equal sex ration) enclosed with gauze bags around fruit clusters to induce oviposition (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

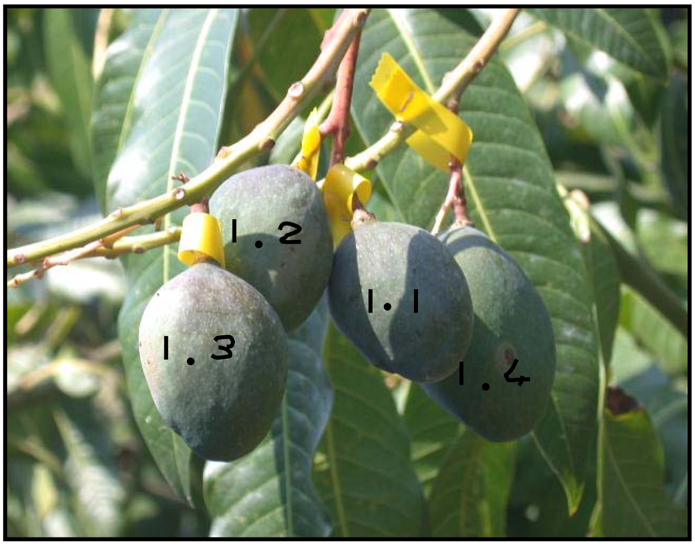


Fig. 2. Enclosed date fruit numbered according to the bagging date and fruit number, and tagged with coloured flagging tape for easy identification (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

The fruit were not covered again after removing the gauze bags and marking a specific set of data fruit, since both orchards were reported to have been weevil free in previous seasons. However, to prevent the possibility of natural infestation of data fruit, 4 rows in the middle (centre) of the orchard was chosen for the study, since weevil infestations were previously found to originate at the edges of the orchard (border rows), declining towards the centre of the orchard. During the study investigating mango seed weevil oviposition preferences to fruit / tree position (Chapter 4), it was speculated that adult weevils entered orchards from a specific infestation point outside the orchard, e.g. a road (fallen fruit whilst in transit), a field (discarded seeds) or a row of *Cassuarina* trees (where sanitation fruit are collected before being discarded). Weevil infestations were found to be most severe closest to a potential source of infestation, with infestation levels declining towards the centre of the orchard. To further ensure that data fruit did not get contaminated by mango seed weevils occurring naturally in the trial orchard, all the data fruit were inspected for the presence of existing MSW eggs before enclosing the fruit. This was done each time that the gauze bags were removed from an existing set of data fruit and moved on to the next set of data fruit.

Fruit were enclosed from 9 October 2006 and 10 October 2007 up to the time that no more eggs were laid (19 January 2007), or a sufficient number of fruit were marked (09 January 2008). Data fruit were sampled for evaluation to represent 3 sequences or induction periods, i.e. early-season (oviposition in October), mid-season (oviposition in November), and late-season (oviposition from December up to January).

In the 2006 / 2007 mango growing season, for the first assessment period (October induction), more than 280 egg infested fruit were marked to ensure a sufficient number of fruit in order to evaluate developmental stages up to 8 weeks after oviposition (35 fruit per assessment x 8 assessments (week 1 – 8 after oviposition) = 280 fruit). This procedure was followed since natural fruit weaning occurred fairly frequent at this stage. For the second sequence (mid season oviposition / November induction), more than 350 fruit were marked in order to ensure a sufficient number of fruit to evaluate development up to 10 weeks after oviposition, since no adult weevils were found 8 weeks after oviposition for the first sequence. Induced oviposition for the third sequence (December induction), to determine development from eggs laid during the latter part of the season, commenced on 08 December 2006 and continued up to the middle of January 2007, since oviposition occurred at a noticeably reduced rate at this stage. Despite this longer egg-laying period, the number of marked fruit having eggs on the fruit skin was sufficient only to evaluate development up to 5 weeks after oviposition.

In the 2007 / 2008 mango growing season, more than 350 fruit were marked for each induction period in order to ensure sufficient fruit to evaluate development stages up to 10 weeks after egg laying. Again, for the third sequence, due to fewer eggs being deposited during this period, induction continued into January 2008 to ensure a sufficient number of data fruit.

Evaluations were done by counting and inspecting each egg and noting the various development stages for each data fruit, with each data fruit representing oviposition for a specific sequence (October, November and December induction), and a specific time lapse after oviposition, taken as weekly intervals (1 to 10 weeks after oviposition).

The development stages were categorized as follows:

1) no development / non-viable eggs (Fig. 3),
2) viable eggs (Fig. 4),
3) hatching larvae / larval penetration into the fruit pulp (Fig. 5),
4) larval penetration into the seed (Fig. 6),
5) visible larvae, noted as small (Fig.7), medium sized (Fig. 8) and full grown larvae (Fig. 9),
6) pre-pupae (Fig. 10) and pupae (Fig. 11), and
7) pre-adults (Fig. 12) and adults (Fig. 13).

The data was not statistically analyzed, since the aim of the study was to establish development patterns and intervals, especially with regards to critical development stages, i.e. the time period that elapsed from oviposition to seed penetration (at which stage chemical intervention with contact and trans-laminar products would no longer be effective) and the time period before adults emergence (at which stage sanitation practices would need to be in place).

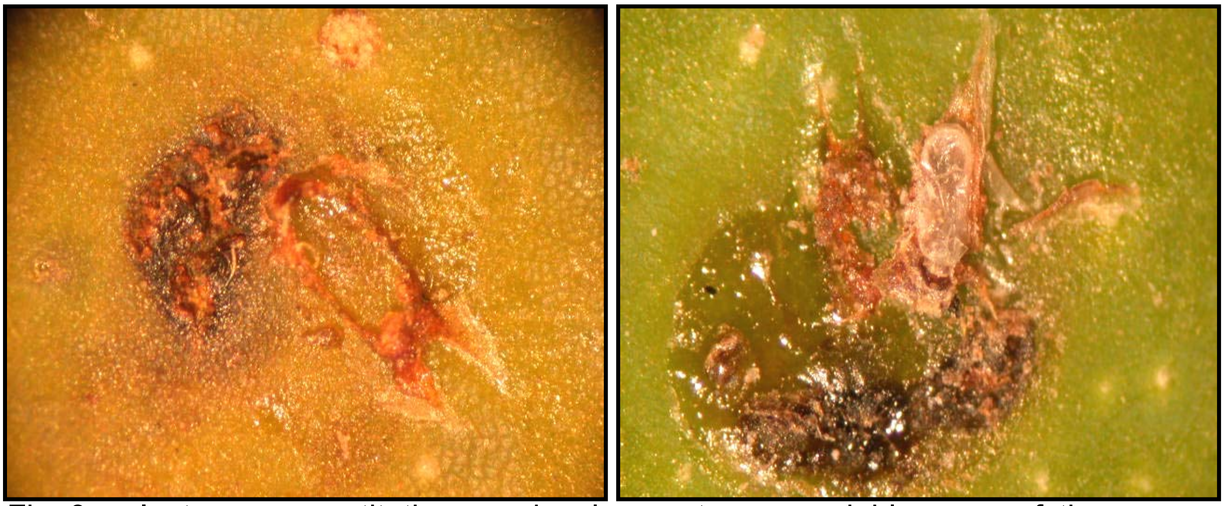


Fig. 3. Instances constituting no development or non-viable eggs of the mango seed weevil. In some instances only the outline of the latex capsule remained (left), while non-viable eggs were sometimes visible underneath the latex capsule (right).

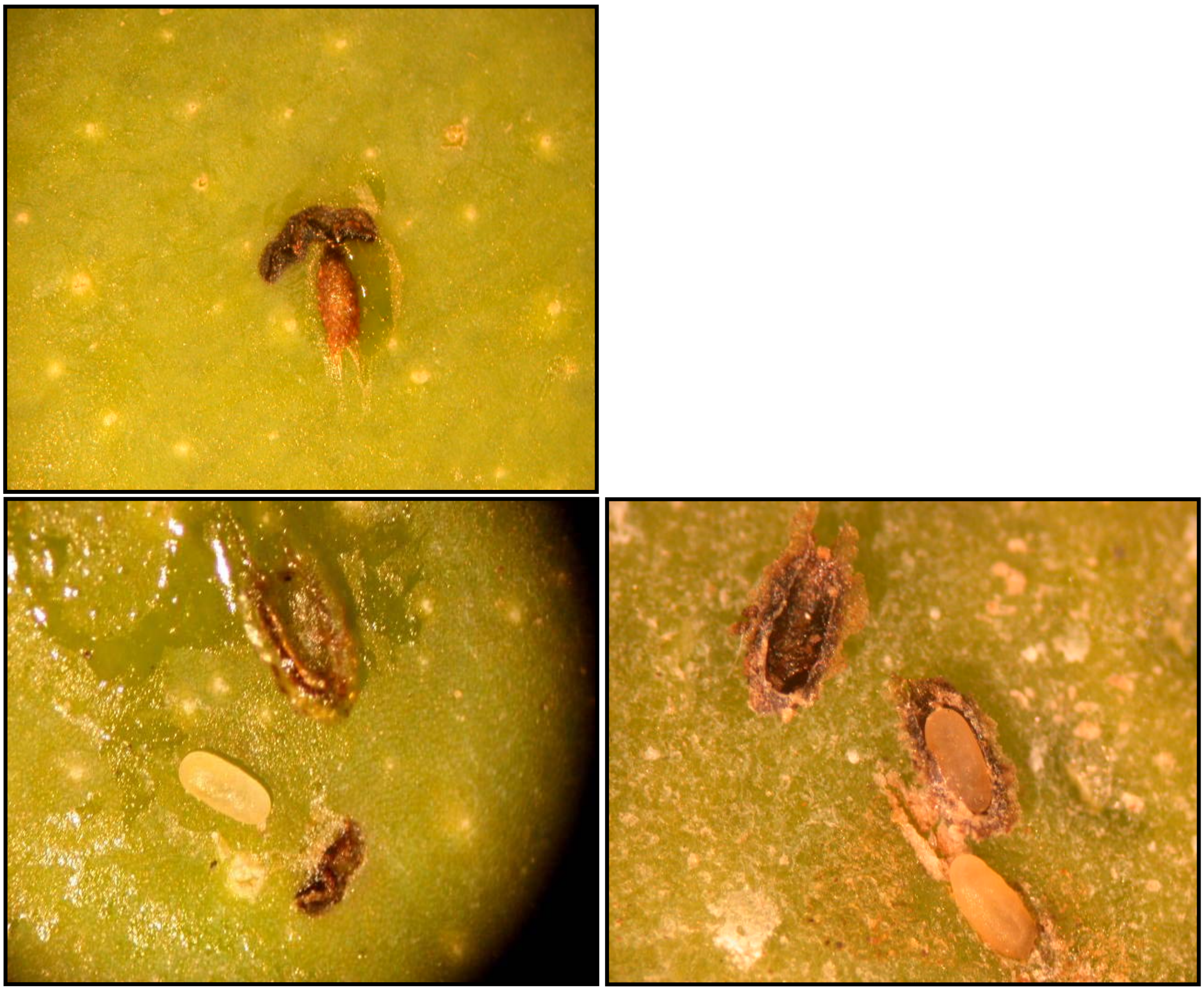
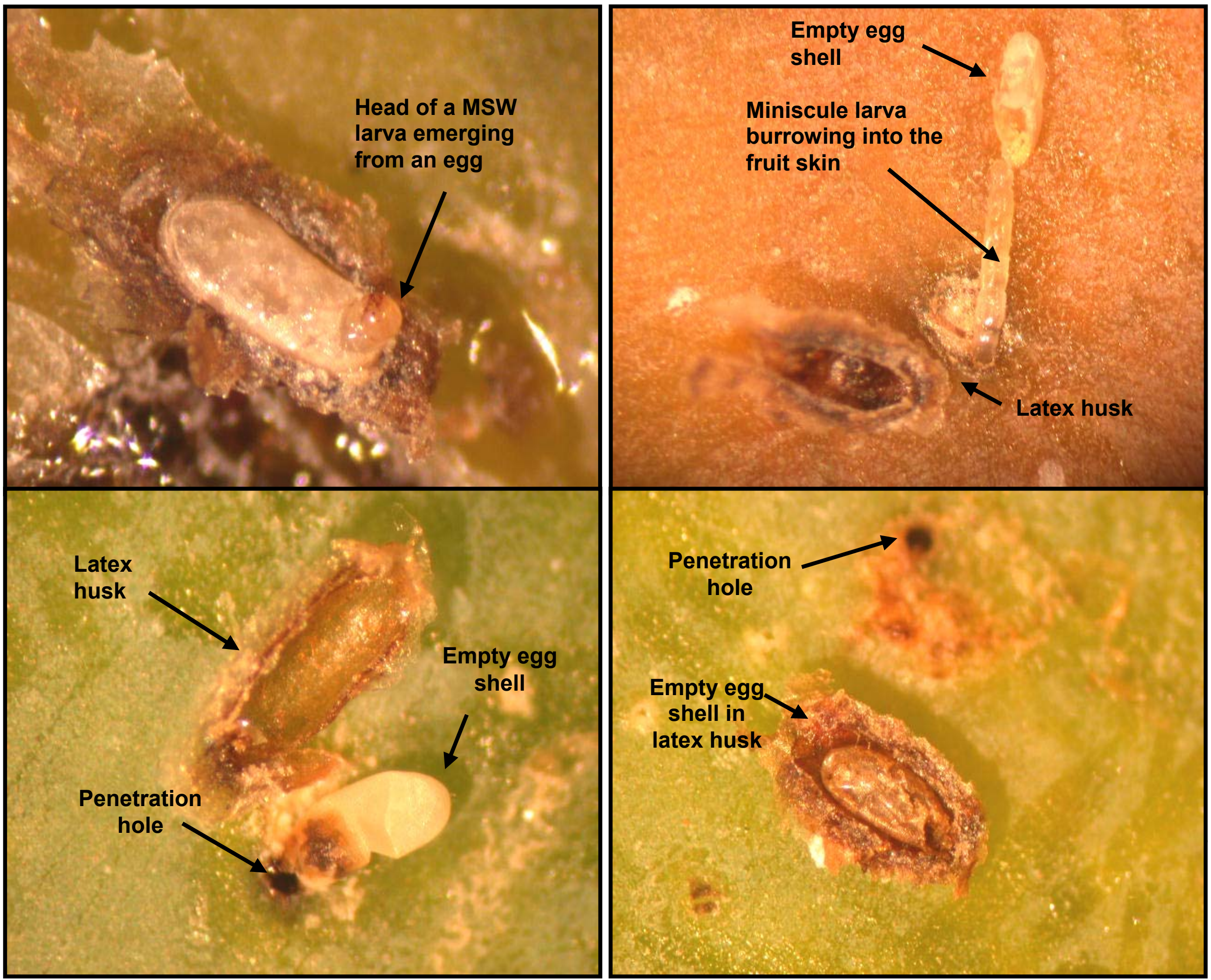


Fig. 4. A typical mango seed weevil egg as seen in the field (top left), and with the latex cover removed (top right). Although eggs are mostly laid singularly (bottom left), two or more eggs may be found in close proximity if infestation pressure is high (bottom right).



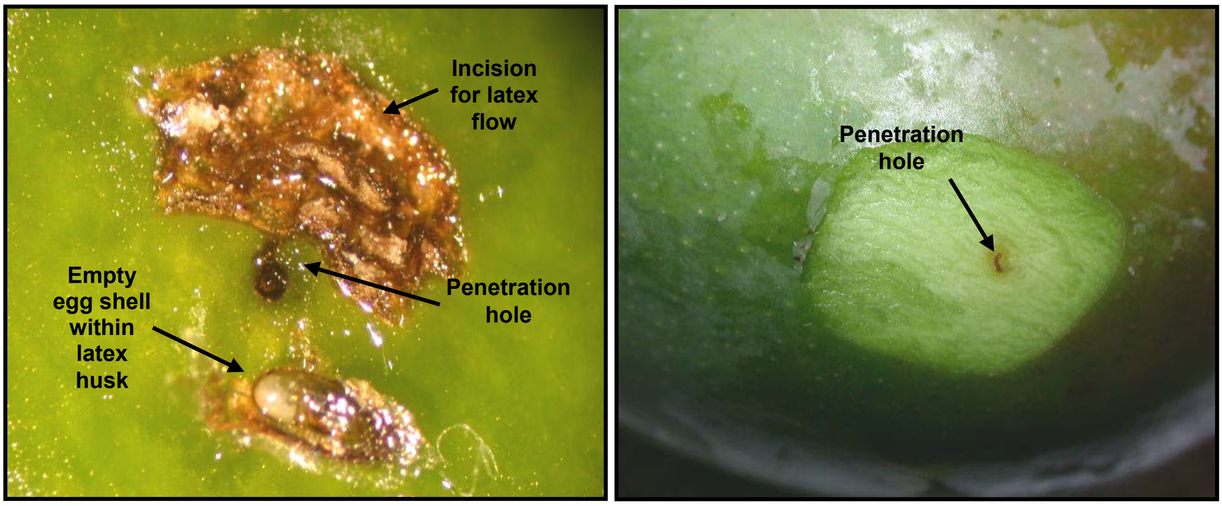


Fig. 5. The different stages perceived as mango seed weevil larval hatching and / or pulp penetration, from the time that the egg ecloses (top left) and the miniscule larva leaves the egg to burrow through the fruit skin into the pulp (top right), illustrating under a stereo-microscope the penetration lesion and the empty egg shell when the latex cover is removed (centre and bottom left). When making an incision just beneath the egg, these penetration cavities are visible with the naked eye (bottom right).

Fig. 6. 'Seed penetration' indicated, during the early stages of development[#], the miniscule mango seed weevil larvae (invisible to the naked eye) that penetrated into the seed, as was determined by counting the number of penetration cavities through the seed husk (left). At this stage seed damage was minimal (right).

[#] ‘Seed penetration’ also indicated, during the latter stages of development, the number of larvae that entered into the seed but did not develop inside the seed. This was determined by counting the number of penetration cavities on the seed husk and subtracting the number of weevils (visible larvae, pupae and / or adults).

Fig. 7. Mango seed weevil larvae were categorized as small as soon as they were, although still minute, visible with the naked eye (left), up to 5mm in length (right). Seed damage at this stage was seen as small but continuous tunneling on the exocarp of the seed (left).

Fig. 8. Medium size mango seed weevil larvae were categorized as a length greater than 5mm, with the head capsule prominent, but the body still semi-transparent. Seed damage due to feeding by medium size larvae was considerably less than for full grown larvae.

Fig. 9. Full grown mango seed weevil larvae compared to a small (left), and a medium size larva (right).


Fig. 10. Mango seed weevil pre-pupae: dorsal (left) and ventral view (right).


Fig. 11. Mango seed weevil pupae with prominent eye spots: dorsal (left) and ventral view (right). The pupa discolors from white to a slight reddish color just prior to eclosing as an adult.


Fig. 12. Different stages perceived as mango seed weevil pre-adults. Only once the exoskeleton hardens (discolors from pink to brown / black) (bottom right), are adult weevils able to survive outside the protective environment of the seed.

Fig. 13. An adult mango seed weevil in a mango seed (left). Depending on availability of food and / or the number of adults present within the seed, slight size differences may be noted (right).

5.2.2. Weevil eclosion and emergence

In an effort to understand all aspects of weevil development and behaviour, various studies were conducted to investigate the success rate and timing of adult MSW emergence from mango seeds, looking specifically at the rate of weevil emergence from the seeds. Specific aspects that were investigated were:

- adult emergence from fruit of various sizes
- adult emergence from fruit from different tree positions
- the effect of moisture on adult emergence.

5.2.2.1. <u>Adult emergence and fruit size</u>

In the 2004 / 2005 mango growing season, fruit from two different locations in the Hoedspruit magisterial district of the Limpopo Province were used for emergence studies. On the farm, Jonkmanspruit (latitude 24^{o}24'S, longitude 30^{o}48'E), 216 egg infested fruit from the early-season cultivar, 'Zill', were sampled on the 2nd of December 2004. The fruit were weighed and placed in three weight categories; small (101 – 200g), medium (201 – 300g) and large (301 – 400g). The fruit were then depulped (removing all fruit pulp from the seed), after which the bare seeds were placed in single trays containing moistened Lopis® cat litter sand (Fig. 14). No repetitions were done, with 40 fruit falling into the category of small fruit, 144 fruit falling into the category of medium size fruit and 32 fruit falling into the category of large fruit.

Fig. 14. Depulped mango seeds placed in trays containing moist cat litter sand to investigate adult mango seed weevil emergence.

The trays were enclosed gauze bags to prevent emerging adults from escaping (Fig. 15). The seeds were kept in an office at ambient temperatures and under electrical (artificial) lights, evaluating each tray on a weekly basis, for the remainder of the mango season, for the presence of mango seeds with emergence holes.

Fig. 15. Trays containing depulped mango seeds, to monitor adult mango seed weevil emergence, enclosed with gauze bags to prevent the adult weevils from escaping once they have emerged.

The cat litter sand was wetted regularly to ensure continued high moisture levels, since it was determined with the MSW adults in captivity that activity levels in the breeding boxes increased when ambient moisture was increased, i.e. by wetting mango flushes (foliage) before placement (Chapter 2; 2.3.1. Activity and behaviour of adult seed weevils in captivity). After noting the number of seeds with emergence holes and the number of emerged weevils per category (Fig. 16), the seeds and weevils were removed from the respective trays and the seeds showing emergence holes were cut open to determine the number of weevils, live and / or dead, inside the seed.

All the seeds that showed no emergence holes at the onset of winter (May 2005) were cut open at the end of May. The number of seeds that were not infested (no mango seeds weevils inside the pulp / seed), as well as the number of live and dead weevils inside infested seeds were noted. The data was not statistically analyzed since the study was not scientifically laid out, with the aim of the study only to investigate general emergence patterns of MSW adults from fruit of various sizes.

Fig. 16. Onset of adult mango seed weevil emergence (left), with the adults starting to eat their way through the seed husk, and an adult weevil in the process of emerging from a mango seed (right).

5.2.2.2. Adult emergence from fruit from different tree positions

Fruit from Block B46, where MSW oviposition and fruit / tree position were investigated in the 2004 / 2005 mango growing season (Chapter 4; 4.1.2. Oviposition and fruit / tree position), the egg infested data fruit were sampled on 15 December 2004, just prior to the commercial harvesting date for the cultivar. The fruit were categorized according to the various fruit positions (eastern outsides, eastern insides, western insides and western outsides) and depulped.

The bare seeds were placed in trays containing moist cat litter sand, enclosed with insect proof bags and evaluated on a weekly basis, removing the emerged weevils and seeds with emergence holes after evaluations. No repetitions were done, with 119 of the 287 fruit retained falling in the category of eastern outer fruit, 64 fruit falling into the category of eastern inner fruit, 36 fruit falling into the category of western inner fruit, and 68 fruit falling into the category of western outer fruit.

The seeds were, again, wetted frequently. A drawback from the previous study was that, on account of the frequent wetting, outbreaks of fungal growth were encountered. To combat this effect, the seeds were wetted in a benomyl (Benlate® WP 500g/kg a.i.) solution @ 20g / 100ℓ water, treating the seeds for fungal growth while simultaneously wetting the seeds to enhance the moisture content.

All the seeds that showed no emergence holes at the onset of winter (May 2005) were cut open at the end of May. The number of seeds that were not infested (no mango seeds weevils inside the pulp / seed), as well as the number of live and dead weevils inside infested seeds were noted. The data was not statistically analyzable since the study was not scientifically laid out, with the aim of the study only to investigate general emergence patterns of MSW adults from fruit from various tree positions.

5.2.2.3. Effect of moisture on adult emergence

In the 2007 / 2008 mango growing season, mature mango fruit of two different cultivars were sampled to investigate the incidence and duration of adult mango seed weevil emergence. The fruit were sampled just prior to the commercial harvesting date for each of the cultivars, on 14 January 2008 (cv. 'Tommy Atkins') and on 05 March 2008 (cv. 'Keitt'). Three hundred egg infested fruit from each cultivar were sampled (20 fruit x 5 replications x 3 categories).

The categories from which adult seed weevil emergence was noted, were:

1) whole mature fruit,
2) depulped mango seeds wetted frequently, i.e. at weekly intervals with evaluations, and
3) depulped mango seeds allowed to dry out after depulping.

The mango fruit and depulped seeds of each cultivar were placed in 15 separate, enclosed containers (20 fruit / seeds per container x 5 replications x 3 categories) and evaluated weekly for the presence of emergence holes (Fig. 17). With each assessment the number of emerged adult weevils was counted and removed, after which all the fruit and seeds with emergence holes were removed and cut open to count the number of weevils (immature and mature life stages) present within the seeds.

Fig. 17. A mango fruit (left) and a depulped seed (right) showing emergence holes where adult mango seed weevils exited from the fruit / seed.

For the bigger 'T.A.' seeds, the time needed for complete desiccation of the seeds in category 3 were about 5 weeks, while the smaller 'Keitt' seeds dried out completely within two to three weeks after placement. Since severe fruit decay of the 'T.A.' fruit occurred within two to three weeks after placement for evaluation (Fig. 18), the rotten fruit flesh was removed on 4 February 2008.

For the bigger 'Keitt' fruit, placed on 5 March 2008 for evaluation, complete fruit decay took longer, with depulping of the whole fruit from category 1 occurring about 4 weeks after placement on 3 April 2008. For both cultivars the depulped seeds were replaced in their respective containers, evaluating the seeds at weekly intervals for adult seed weevil emergence for the remainder of the study period.

Fig 18. Fruit rot of 'Keitt' fruit (soft brown rot (*Botryosphaeria* spp.) and anthracnose (*Colletotrichum gloeosporiodes*)) two weeks (left) and three weeks (right) after placement.

On 08 April 2008, with few adult weevils emerging from 'T.A.' seeds once the seeds had dried out, the desiccated seeds in categories 1 (whole fruit with the fruit depulped after fruit decay started setting in) and 3 (depulped seeds allowed to dry out) were wetted to determine the effect of moisture on adult seed weevil emergence from re-hydrated seeds that were allowed to dry out completely. For this reason the remaining mango seeds, irrespective of the category, were wetted weekly from this date up to the end of the study period. For the 'Keitt' fruit, sampled at a later date in the season on 5 March 2008, a minimal number of fruit and seeds showed signs of adult weevil emergence up to two months after placement on 7 May 2008. For this reason, and irrespective of the category, all the remaining seeds were wetted from this point onwards.

All remaining seeds, from both cultivars, were cut open at the end of May, corresponding to the onset of winter, to determine the infestation levels of the remaining seeds. Where seeds were infested, distinction was made between immature and mature life stages and live and dead weevils.

No statistical analysis of the data was done, since the aim of the study was to determine the incidence of, and duration for, adult seed weevil emergence for two different cultivars, the first being an early-season cultivar, i.e. 'Tommy Atkins', and the other a late-season cultivar, i.e. 'Keitt'. This was done by comparing the percentage of fruit / seeds showing emergence holes at consecutive time intervals, i.e. 30 days, 60 days, 90 days and 120 days after sampling, with the date of sampling corresponding to the commercial harvesting date for the cultivar. To determine the effect of moisture on adult emergence, sampled fruit was divided into three different categories, i.e. whole fruit, wetted seeds and dried seeds.

5.3. Results, Discussion & General observations

5.3.1. Weevil development

Figures 19 to 21 graphically summarize the results obtained for each of the induction periods (October, November and December) in the 2006 / 2007 mango growing season, while figures 22, 23 and 27 depict the results obtained in the 2007 / 2008 season. The total number of eggs counted per fruit was categorized as either having not developed (non-viable), or viable (eggs intact). The number of weevils present within each mango fruit, for each development stage, was then calculated as a percentage of the total number of viable eggs that were counted per fruit.

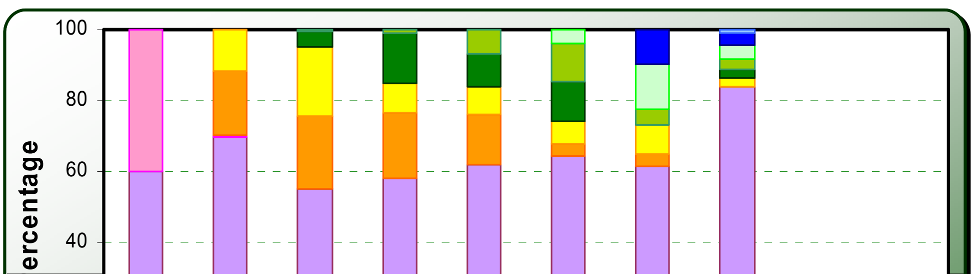


Fig. 19. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during October, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

For the early-season sequence (October induction), all the eggs were still intact 1 week after egg laying, with only a very small percentage (0.72%) still intact 2 weeks after oviposition. At this stage, 11.6% of the larvae that have hatched had penetrated the seed, with all of these larvae miniscule and not visible to the naked eye. The first visible larvae, 4.2% small and 0.7% medium sized larvae, were recorded in the seeds 3 weeks after egg laying, with the first full sized larvae (3.7%) recorded 6 weeks after egg laying. The first pre-pupae (9.6%), and first pupae (0.8%), were recorded 7 weeks and 8 weeks after egg laying respectively. No adult weevils were present in the seeds up to 8 weeks after egg laying. On average, 5.3 eggs per fruit were laid during this early-season induction period, with 64.4% of all eggs laid not developing.

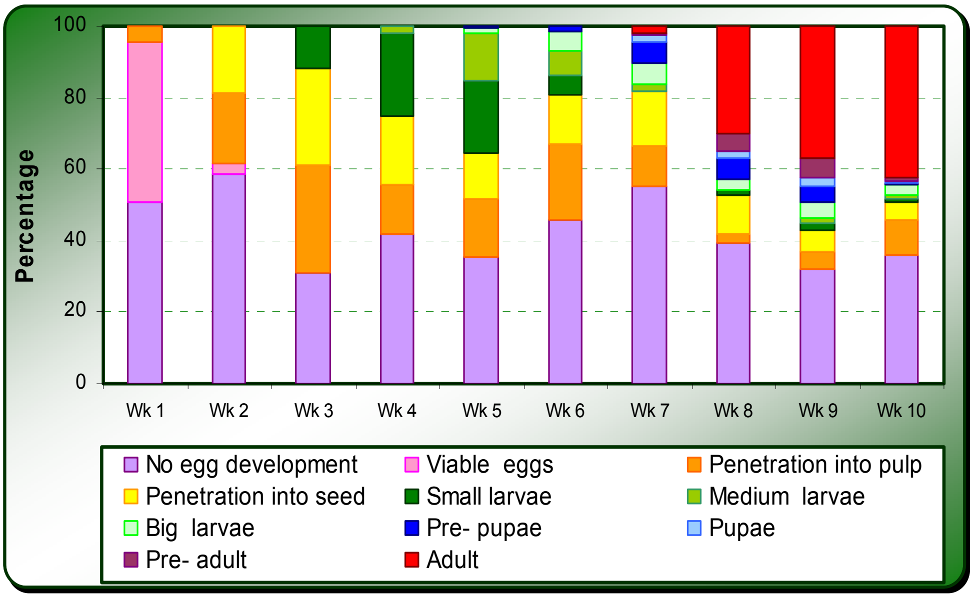


Fig. 20. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during November, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

For the mid-season sequence (November induction), weevil development was slightly more rapid than from eggs laid in October. One week after oviposition a small percentage of eggs (4.6%) had already hatched, with the majority of these larvae having penetrated into the pulp (Figs. 5 – bottom left & right). Some miniscule larvae, however, were still in the process of hatching and / or penetrating the pulp (Figs. 5 – top left & right). Two weeks after oviposition, 18.7% of all the hatched miniscule larvae had reached the seed. As with the October induction, the first small (visible) larvae were found 3 weeks after egg laying (11.7% vs. 4.2%) but, contrary to the early-season sequence, both the first full grown larvae (1.5%) and pre-pupae (0.5%) were found 5 weeks after egg laying.

The first adults were present 7 weeks after egg laying (1.7%), with 42.5% of all hatched larvae reaching maturity 10 weeks after the eggs were laid. The average number of eggs per egg infested fruit was slightly less than for the early season sequence (4.4), but with more weevils developing successfully from the eggs, with only 42.6% of the total number of eggs that were laid not developing.

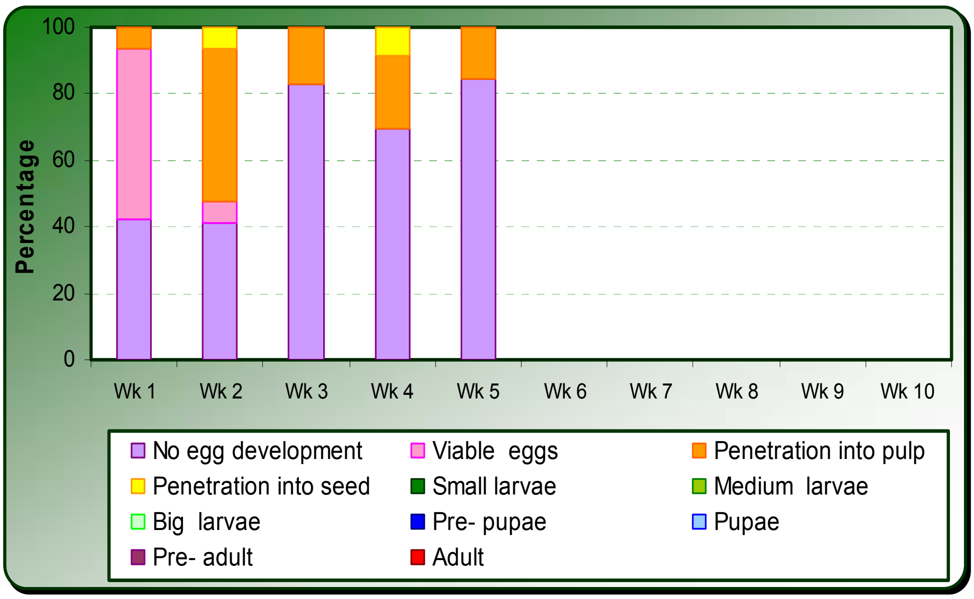


Fig. 21. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during December and January, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

For the third sequence (December to January induction), 6.7% of the hatched larvae had penetrated into the pulp 1 week after the eggs were laid. However, no larvae were recorded up to 5 weeks after oviposition, at which stage no more fruit were available for evaluation. Few eggs were laid late in the season (2.5 eggs on average per fruit), with 64.1% of the total number of eggs laid not developing.

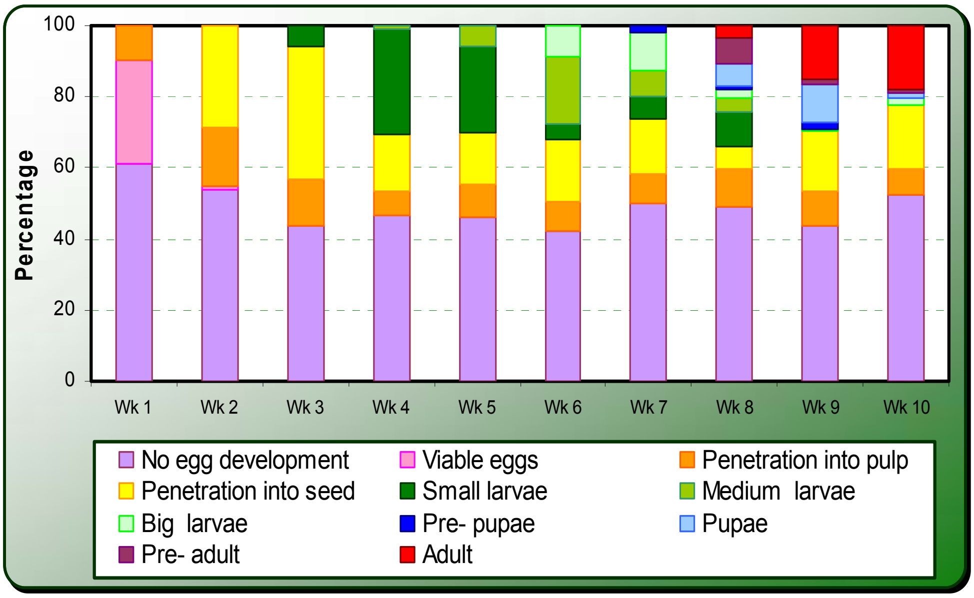


Fig. 22. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during October, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G61, Grovedale), 2007 / 2008.

In the 2007 / 2008 mango growing season, development from eggs laid during October were more rapid than in the previous season, with 9.7% of the eggs that were laid in the process of hatching (Figs. 5 – top left & right), or with the miniscule larvae already having penetrated the fruit pulp (Figs. 5 – bottom left & right), 1 week after the eggs were laid. Two weeks after the eggs were laid, 28.4% miniscule larvae had already penetrated the seed. As in the previous season, the first small, visible larvae (6.0%) were found 3 weeks after the eggs were laid. Also, similarly than in the 2006 / 2007 season, the first pre-pupae (1.8%) were found 7 weeks after the eggs were laid, and the first pupae (6.5%) 8 weeks after egg laying.

Contrary to the previous season, the first pre-adults (7.3%) and adults (3.2%) were already present 7 weeks after egg laying. The average number of eggs per egg infested fruit was comparative to the previous season (5.2 vs. 5.3), but a higher percentage of weevils successfully developed from eggs laid in the 2007 / 2008 season than in the previous season (only 49.0% of all the eggs that were laid did not develop, compared to 64.4% in the 2006 / 2007 mango growing season).

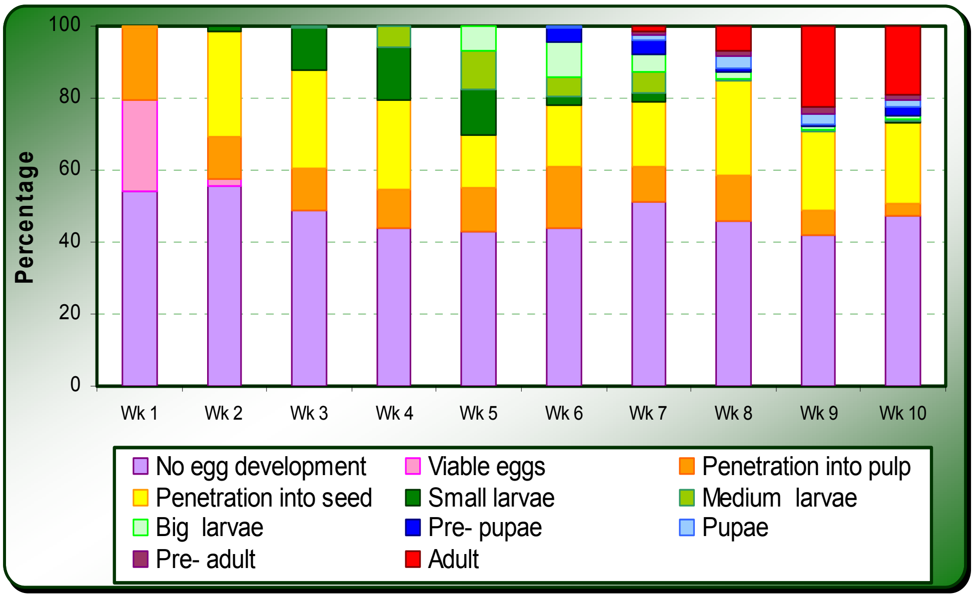


Fig. 23. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during November, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G61, Grovedale), 2007 / 2008.

For the mid-season sequence (November induction), as in the previous season, development were again more rapid than from eggs laid earlier in the season during the October induction period, with 19.9% of the eggs having hatched, and with the majority of these larvae having already penetrated into the fruit pulp 1 week after oviposition. Two weeks after the eggs were laid, 29.4% of all the miniscule larvae that hatched had reached the seed. Contrary to the previous season (Fig. 20), the first small, visible larvae (1.6%) were also present 2 weeks after egg laying.

Development from eggs that were laid during November 2007 were also more rapid than from eggs laid during November 2006, with a higher percentage of eggs having hatched 1 week after oviposition (19.9% vs. 4.6%) and with the first visible, small larvae present 2 weeks after the eggs were laid, compared to 3 weeks after egg laying in the 2006 / 2007 season.

As in the previous season, the first adults (1.3%) were seen 7 weeks after egg laying but, contrary to the previous season with 42.5%, only 19.0% of all hatched larvae reached maturity 10 weeks after the eggs were laid. With the average number of eggs per egg infested fruit higher (9.0) than in the previous season (4.4), and a comparative percentage of eggs developing successfully (47.5%) when compared to the previous season (42.6%), this phenomenon was attributed to larval, (Fig. 24) pupal (Fig. 25) and adult seed weevil (Fig. 26) mortalities. Although the reason for larval mortalities was probably poor development or insufficient sustenance, cannibalism seemed to have played a role in adult mortalities.

Fig. 24. A miniscule, desiccated mango seed weevil larva (left), as seen under a stereo microscope. The majority of larval mortalities were at nearly full grown stage, with insufficient food and suffocation due to excessive moisture levels probably the causes of the mortalities (right).

Fig. 25. A dead mango seed weevil pupa (left) recorded together with a viable specimen (right) in the same mango seed. These pupae developed from eggs that were laid during the mid-season sequence in the 2007 / 2008 mango growing season (November 2007 induction).

Fig. 26. Instances of adult mango seed weevil mortalities, with apparent evidence of cannibalism. Cannibalism varied from partial dismemberment (left) to nearly total consumption (right).

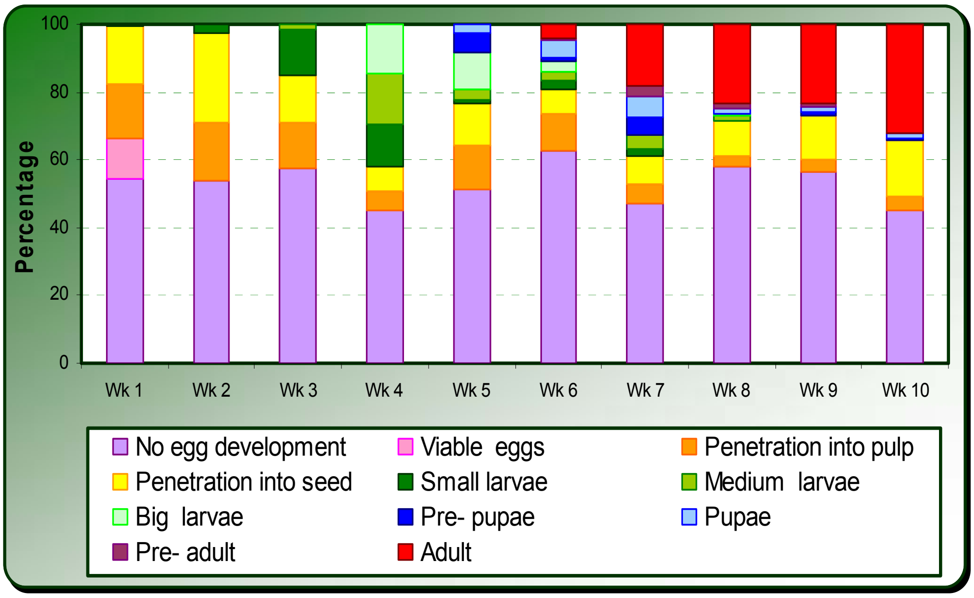


Fig. 27. Mango seed weevil developmental stages at weekly intervals after oviposition, with oviposition artificially induced during December and January, expressed as a percentage of the total number of eggs laid (cv. 'Keitt', Block G61, Grovedale), 2007 / 2008.

Contrary to the 2006 / 2007 season, normal weevil development was found from eggs that were laid during the third sequence period (December induction) in the 2007 / 2008 season. Development was faster than from eggs laid during the second sequence period (November induction), with the majority (33.3%) of all the viable eggs laid (45.6%) having hatched within the first week. Of all the eggs that have hatched within the first week, 16.4% of the miniscule larvae were in the process of hatching or had already penetrated into the pulp, 16.9% had penetrated into the seed and 0.5% small, visible larvae were present within the seed.

The first pupae (2.7%) were present 5 weeks after oviposition, with the first adults (4.2%) present 6 weeks after egg laying. Ten weeks after egg laying, 32.3% of the 55% eggs that hatched produced viable adult weevils. In the 2007 / 2008 mango growing season, MSW oviposition in December / January (9.9 eggs on average per egg infested fruit) was more prominent than in the previous season (2.5 egg on average per egg infested fruit), with fewer eggs not developing successfully (53.0% vs. 64.1%).

These results which show the hatching period of mango seed weevil eggs to be less than 7 days to slightly more than 14 days, depending on the time of oviposition and seasonal conditions, are consistent with the literature which states that egg eclosion takes between 5 to 7 days (Balock & Kozuma, 1964), but may take as long as 14 days (CABI & EPPO, 2005).

When eggs were laid late in the season (December 2007 induction, the first adult weevils were present 6 weeks after oviposition, whereas it took as long as 8 weeks for adult weevils to be present in mango seeds if the eggs were laid early in the season (October 2007 induction). These findings correspond to literature references stating that the duration of the life cycle, from egg to adult, is between 5 to 8 weeks (De Villiers, 1984; Schoeman, 1987; Woodruff & Fasulo, 2006).

5.3.2. Weevil eclosion and emergence

5.3.2.1. <u>Adult emergence and fruit size</u>

Since all the mango fruit that were sampled from Jonkmanspruit (cv. 'Zill') had MSW eggs on the fruit skin, each data fruit had the potential to be infested. Adult weevil emergence was therefore calculated as the percentage of seeds, out of the total number of egg infested fruit sampled, showing adult emergence holes. The results of MSW adult emergence from fruit of various sizes are graphically plotted in figure 28.

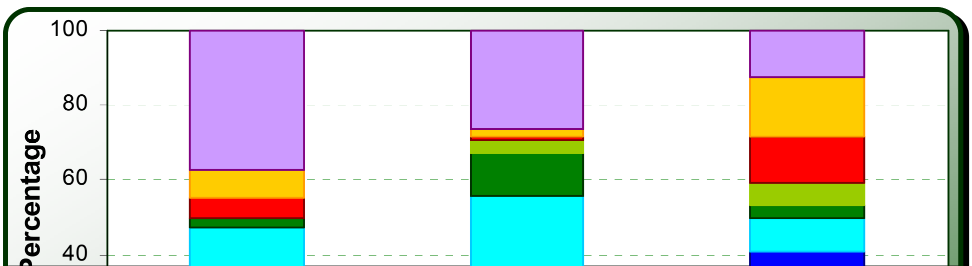


Fig. 28. Mango seed weevil emergence, expressed as a percentage of the total number of infested, depulped seeds with emergence holes (cv. 'Zill', Jonkmanspruit), 2004 / 2005.

For depulped, 'Zill' mango seeds, MSW adult emergence, irrespective of the fruit size category, was highest during the first 30 days, as was indicated by the highest mean percentage of seeds showing emergence holes for this category. The majority of adult weevils emerged within 60 days after the fruit were depulped, with a low mean percentage of seeds showing adult MSW emergence after 60 days for all three categories.

For all three categories, most of the adults had emerged before the onset of winter, with only 8.0% (101 – 200g), 0.9% (201 – 300g) and 14.3% (301 – 400g) of infested seeds showing live weevils still present within the seeds at the end of the study period (Fig 28; red bars). For the various categories, the percentage of infested seeds where the adult weevils inside the seeds died prior to emergence, were 12.0% (101 – 200g), 2.8% (201 – 300g) and 17.9% (301 – 400g) respectively.

Should weevil development and survival, and ultimately MSW adult emergence, relate to seed size, with the bigger seeds providing more sustenance and therefore leading to a higher success rate, one would expect a linear correlation between seed size and MSW adult emergence, with more adult weevils emerging successfully from bigger seeds. However, even though more seeds showed emergence holes for the medium size fruit (70.8%) than for the small fruit (50.0%) at the end of the evaluation period, only 59.4% of the seeds from fruit size category; 301 – 400g, showed emergence holes. The highest mortality rate for adult weevils (seeds with dead weevils inside) was also recorded for seeds in this category (15.6%), compared to seeds from categories 101 – 200g (7.5%) and 201 – 300g (2.1%).

On the other hand, since bigger fruit tend to have more fruit pulp surrounding the seed, the bulk of the fruit flesh may hinder larval penetration towards the seed, resulting in fewer weevils reaching the seed. This assumption did not hold true, since the mean percentage of non-infested fruit was lowest for the biggest seeds (12.5%), compared to seeds from categories 101 – 200g (26.4%) and 201 – 300g (37.5%).

Since mango seeds of any specific cultivar, irrespective of the fruit size, tend to be of comparative size (personal observations), this negates the assumption that the weevils would survive better, and ultimately emerge more readily, from any specific size fruit. When the MSW adult emergence rate for each of the fruit size categories are expressed linearly over time (Fig. 29), the comparative rates between the different size categories are evident.

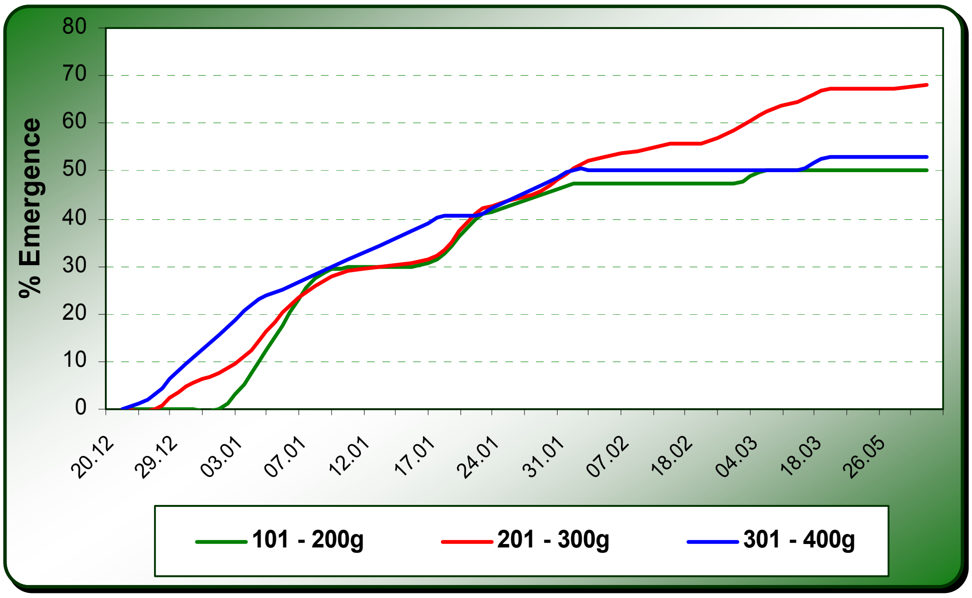


Fig. 29. Mango seed weevil emergence, expressed as a percentage of the total number of infested, depulped seeds with emergence holes for each of the assessment dates (cv. 'Zill', Jonkmanspruit), 2004 / 2005.

5.3.2.2. <u>Adult emergence from fruit from different tree positions</u>

For the early-season 'Tommy Atkins' fruit, sampled from various tree positions, a high mean percentage of seeds again showed emergence holes 30 days after the fruit were depulped (Fig. 30). But, contrary to the results found for 'Zill' mangoes, a high percentage of seeds showed emergence holes 60 days, and even up to 90 days, after the seeds were placed for evaluation.

Except for 'Tommy Atkins' fruit of medium size (Fig. 28), the percentage of infested 'Zill' fruit that did not show emergence holes (seeds containing dead weevils) at the end of the study period, was comparative for the two cultivars. The majority of the non-emerged weevils died within the seeds (12.0% (eastern outer), 11.7% (eastern inner), 16.7% (western inner) and 13.2% (western outer)), with a smaller percentage alive (5.0% (eastern outer), 6.7% (eastern inner), 8.3% (western inner) and 7.4% (western outer) inside the depulped seeds, indicating that these weevils would probably have hibernated in the seeds.

Again, when the mango seed weevil adult emergence rate for fruit of each of the fruit position categories are expressed linearly over time (Fig. 31), the comparative rates between the different categories are evident.

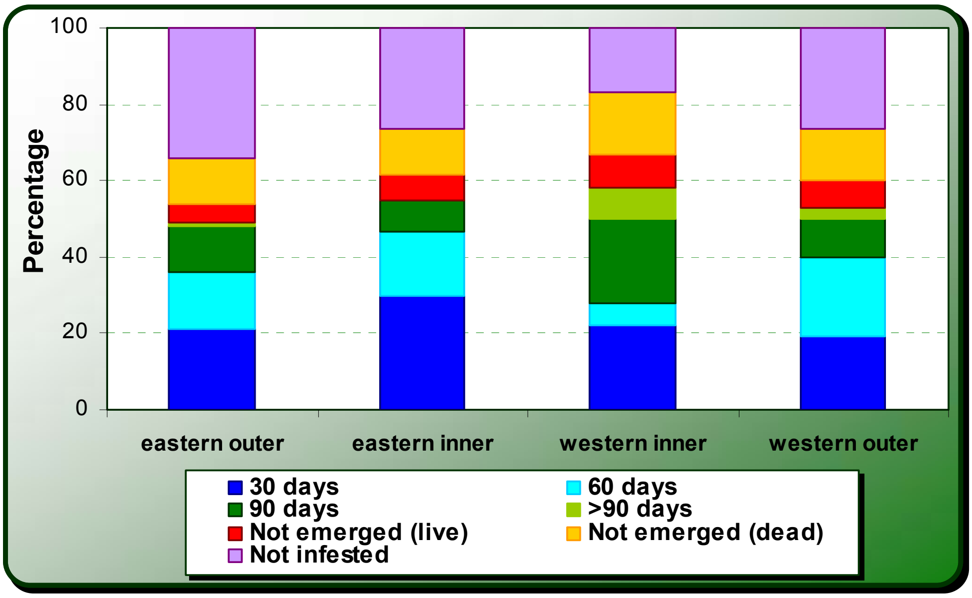


Fig. 30. Mango seed weevil emergence, expressed as a percentage out of the total number of infested, depulped seeds (cv. 'Tommy Atkins', Block B41, Moriah), 2004 / 2005.

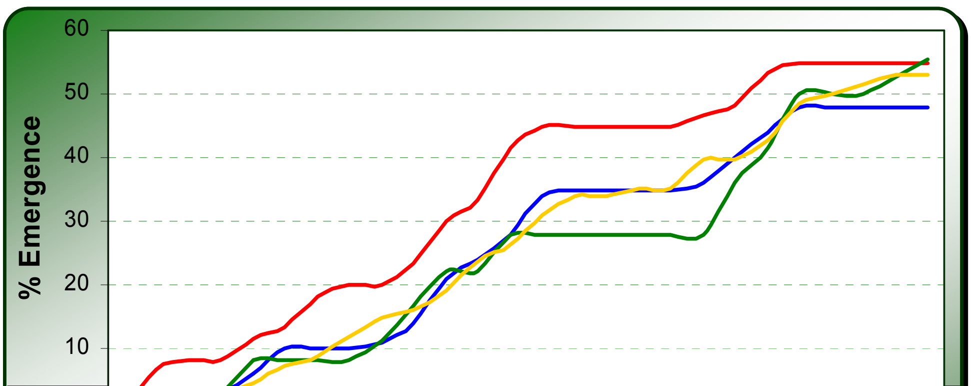


Fig. 31. Mango seed weevil emergence, expressed as a percentage of the total number of infested, depulped seeds with emergence holes for each of the assessment dates (cv. 'Tommy Atkins', Block B41, Moriah), 2004 / 2005.

It did seem as if ambient moisture had influenced adult MSW emergence, since adult emergence were more prominent after wetting the mango seeds and the sand, than when the seeds were allowed to dry out (personal observations). This may influence sanitation during wet seasons, since it would be imperative to remove all the sanitized fruit and discarded seeds from the orchard floor as soon as possible, especially from December onwards when some of the adult weevils have already reached maturity. It would also influence sanitation practices overall, since the standard practice is to pile discarded seeds and 'sanitation fruit' along the edges of the orchards, amongst the line of *Cassuarina* trees, sometimes for long periods, before removal. Since these wind breaks are also irrigated regularly, this may influence adult MSW emergence.

5.3.2.3. <u>Effect of moisture on adult emergence</u>

For 'Tommy Atkins', none of the weevils emerged from the whole fruit, with only two 'Keitt' fruit (2%) showing emergence holes before the onset of fruit decay necessitated that the fruit pulp had to be removed. While depulping the fruit, it was found that the majority of weevils had already penetrated through the seed husk and, in some instances, into the fruit pulp (60% for 'Tommy Atkins' and 43% for 'Keitt'). These weevils were then considered as having emerged and noted as such. Although the majority of the adults were alive, some died in the seeds and the fruit pulp, probably due to suffocation as a result of the high moisture content of the decaying flesh (Fig. 32).

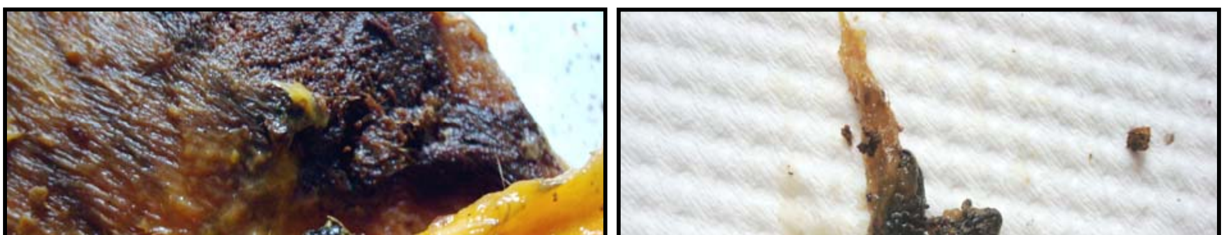


Fig. 32. Live adult mango seed weevils emerging from the seeds while depulping the rotten fruit (left). Some weevils perished, probably due to the excess moisture levels (right).

Figures 33 and 34 graphically depict the incidence and duration of adult seed weevil emergence for the two different cultivars, expressed as the percentage of fruit / seeds with emergence holes, over a time period of 120 days for 'Tommy Atkins', and 90 days for 'Keitt'.

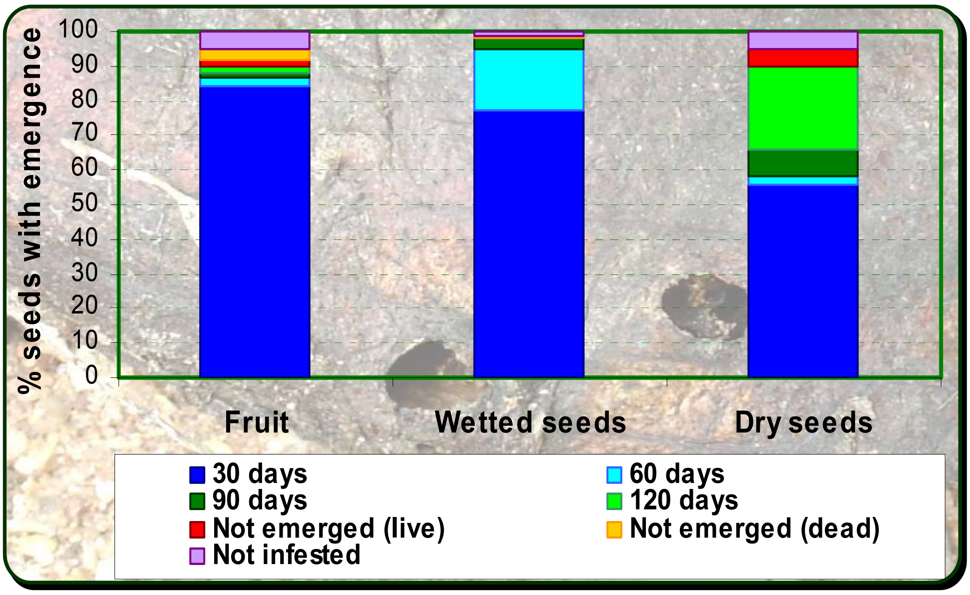


Fig. 33. The percentage of fruit / seeds with adult mango seed weevil emergence (cv. 'Tommy Atkins', Block GD7, Bavaria Fruit Estate), 2007 / 2008.

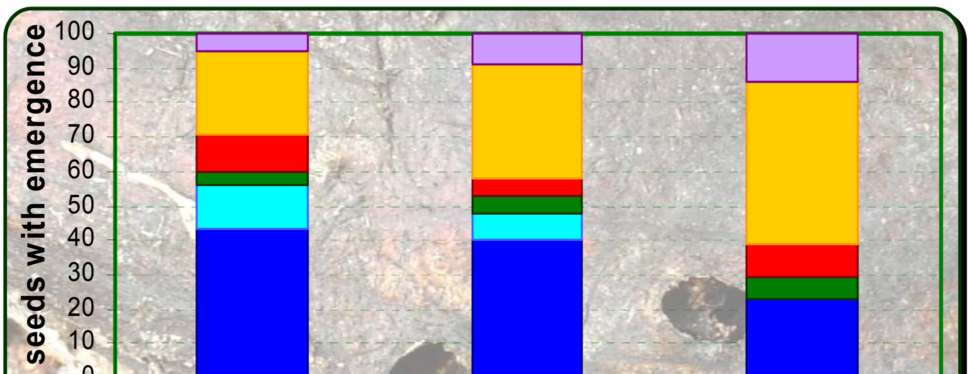


Fig. 34. The percentage of fruit / seeds with adult mango seed weevil emergence (cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008.

For both cultivars the highest percentage of seeds showed emergence holes 30 days after placement, with emergence the highest from fruit, followed by wetted seeds, and with the lowest percentage obtained from dry seeds. The majority of fruit / seeds placed for evaluation showed emergence holes 60 days after placement (harvest), except for the 'T.A.' seeds that were depulped immediately after sampling and allowed to dry out. For this category, 24% of the seeds showed emergence holes 120 days after placement (Fig. 33). This increase in the percentage of seeds having emergence holes were due to the fact that the seeds were re-hydrated on 8 April 2008, after no adults emergence was recorded from these dried seeds for a considerable period of time (Fig. 35). For 'Keitt', the re-hydration of the dried seeds (categories 'whole fruit' and 'dried seeds') on 7 May 2008 also led to a small number of adults emerging after a considerable period that no adults emerged from dried-out seeds in either of these categories (Fig. 36). The effect, however, was not as prominent as with 'Tommy Atkins'.

For 'Tommy Atkins', only a small percentage of infested, depulped seeds showed no emergence holes at the end of the study period, whether the weevils inside the seeds were dead or alive (Fig. 33). For 'Keitt' however, a higher percentage of seeds did not have emergence holes at the time of the last assessment on 22 May 2008. Although some of these seeds had live adult weevils inside (11.0% for category 'whole fruit', 5.0% for category 'wetted seeds' and 10.0% for category 'dry seeds') (Fig. 34), the majority of these seeds either contained a single dead adult weevil in a partially consumed seed, or at most two dead adult weevils, usually in seeds that were nearly totally consumed (Fig. 37).

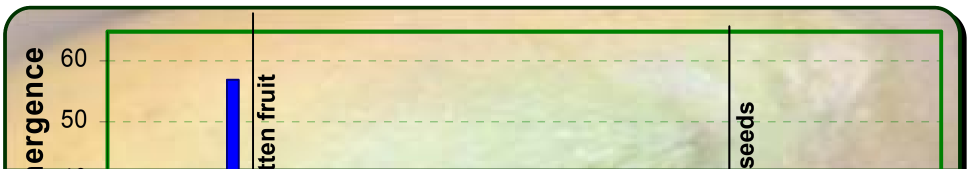


Fig. 35. The percentage of fruit / seeds with adult mango seed weevil emergence (cv. 'T.A.', Block GD7, Bavaria Fruit Estate), 2007 / 2008. The arrows on the graph indicate when the decayed fruit were depulped (4 February 2008) and when desiccated seeds were re-hydrated (8 April 2008).

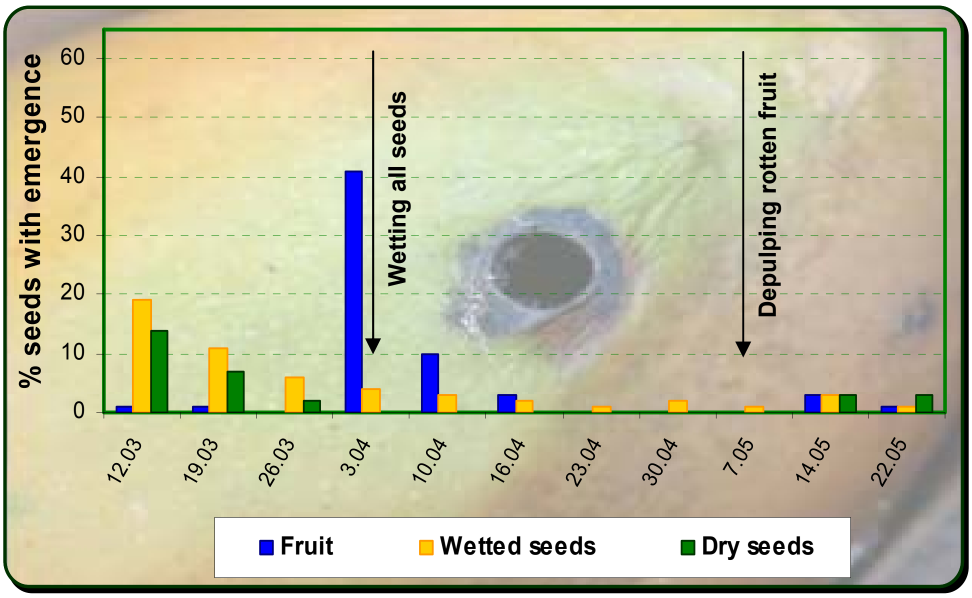


Fig. 36. The percentage fruit / seeds with emergence holes (cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008. The arrows indicate where the rotten fruit were depulped (3 April 2008)and dried seeds re-hydrated (7 May 2008).

Fig. 37. A single dead adult mango seed weevil in a partially consumed seed (left) and two dead adult weevils in a seed that was nearly completely consumed (right) (cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008.

For 'Keitt', even though a high percentage of seeds contained dead MSW adults, i.e. 24.0% for category 'whole fruit', 33.0% for category 'wetted seeds' and 47.0% for category 'dry seeds' (Fig. 34), the majority of MSW mortalities in the seeds seemed to have been due to larval competition for food. A high number of small larvae penetrated into the seed, as was indicated by the penetration scarring on the inside of the seed husk (Fig. 38), but only one or two MSW adults were found inside infested seeds. Adult mortalities seemed to have been caused by other factors such as excess moisture or fungal growth on decaying seeds rather than competition for food (Fig. 39).

Fig. 38. Excessive penetration scarring on the inside of the seed husk due to a high number of mango seed weevil larvae penetrating into the seed(cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008.

Fig. 39. A dead mango seed weevil pupa and adult that were removed from an infested seed with an excessive moisture level within the seed (left), and an adult covered with fungal growth, also probably due to excessive moisture at an early stage during seed development (right) (cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008.

To determine the success of adult MSW emergence for the two cultivars, the total number of weevils at the end of the assessment period were counted and divided into various categories. Figures 40 and 41 graphically depict these categories for each of the cultivars. For the live adult weevils that were found inside the seeds, distinction was made between those present within seeds having emergence holes (live inside, mature, emerging) and therefore depicting a high probability to emerge through the exit hole already present, and those present within seeds having no emergence holes (live inside, mature, no emergence) and therefore depicting a higher probability of hibernating within the seeds.

Even though the highest percentage of seeds with emergence holes were found in the category 'whole fruit' for both cultivars, this category showed the lowest percentage of adult weevils that emerged, with a considerable percentage of the weevils still residing within seeds having existing emergence holes. It is assumed, however, that these weevils would have a high probability of emerging before the onset of winter through the existing emergence hole. For the category 'whole fruit', a small percentage (5.2% for 'Tommy Atkins' and 7.3% for 'Keitt') of adult weevils died within the fruit pulp while emerging, probably due to excessive moisture.

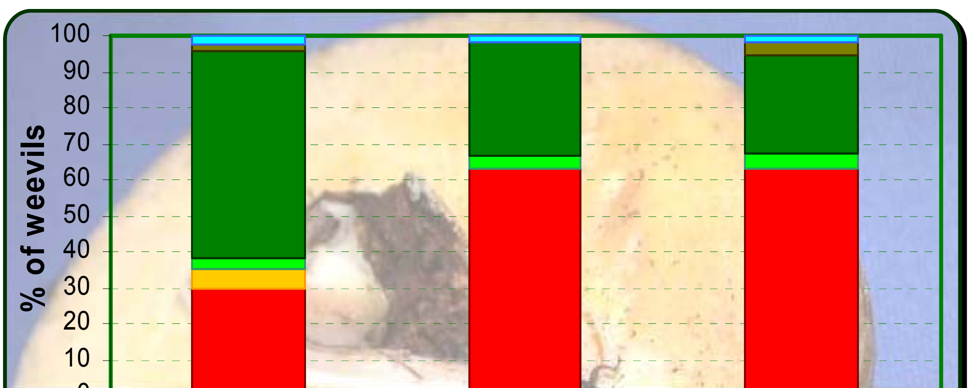


Fig. 40. Total number of mango seed weevils present in 100 infested fruit / seeds, expressed as the percentage present within various categories (cv. 'Tommy Atkins', Block GD7, Bavaria Fruit Estate), 2007 / 2008.

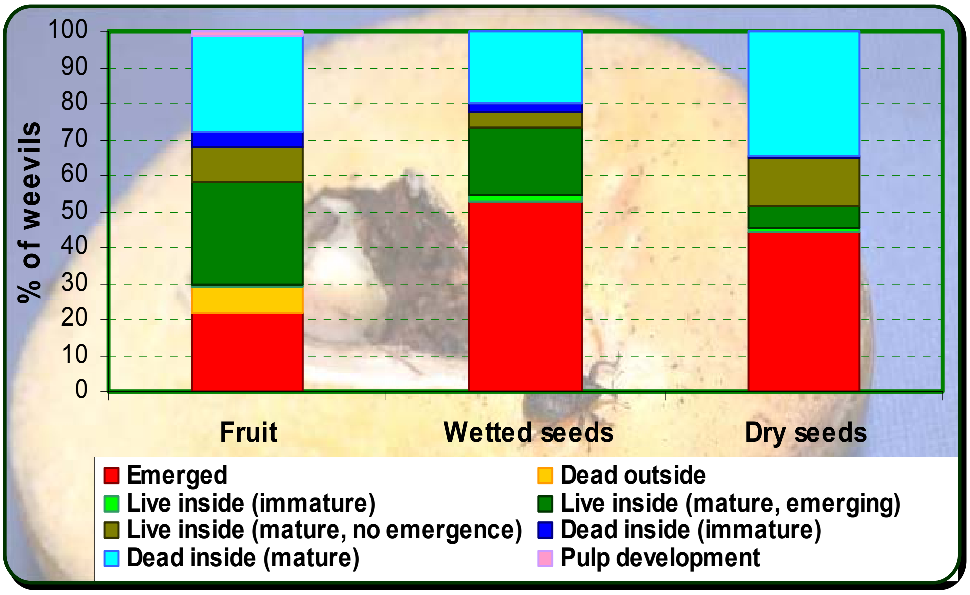


Fig. 41. Total number of mango seed weevils present in 100 infested fruit / seeds, expressed as the percentage present within various categories (cv. 'Keitt', Block IJ2, Bavaria Fruit Estate), 2007 / 2008.

For the early season cultivar, 'Tommy Atkins', nearly all the egg infested fruit had weevils developing inside the seeds, with the majority of the weevils having emerged (29.9% for whole fruit, 62.9% for wetted seeds and 62.9% for dried seeds) or having the potential to emerge through an existing emergence hole (57.9% for whole fruit, 31.4% for wetted seeds and 27.3% for dried seeds) at the end of the study period. For all three categories a very small percentage of infested seeds showed no emergence holes at the end of the study period. In these seeds, an insignificant percentage, if at all, of adult weevils were found to be alive (1.3% (whole fruit), 0.0% (wetted seeds) and 3.3% (dried seeds)), with 2.7% (whole fruit), 2.0% (wetted seeds) and 2.0% (dried seeds) of adults having died before emerging.

For ‘Keitt’, higher mean percentages of egg infested fruit contained no weevils inside the seeds (non-infested) (5.0% for whole fruit, 9.0% for wetted seeds and 14.0% for dried seeds). A higher mean percentage of infested seeds that did not show signs of emergence (no emergence holes) prior to winter contained live weevils inside the seeds than did infested ‘Tommy Atkins’ seeds (Fig. 34), with 9.9% (whole fruit), 4.6% (wetted seeds) and 13.4% (dried seeds) of the total number of weevils showing a probability to hibernate in the seeds.

A higher percentage of weevils were also found to have died prior to emergence (26.9% for whole fruit, 20.2% for wetted seeds and 34.5% for dried seeds), than was found for ‘Tommy Atkins’. The reason for the latter was probably due to excess moisture and fungal growth (Fig. 39), affecting MSW survival.

When adding the percentage of emerged adults and the percentage of live weevils found inside infested seeds with existing emergence holes (where the potential to emerge is higher), a value can be obtained to indicate the most likely percentage of weevils to emerge before the onset of winter. To determine the most likely percentage of weevils that will remain inside infested seeds for the duration of winter, the percentage of mature adults inside infested seeds without emergence holes, together with all live immature stages can be added. Overall mortality can be calculated by adding the percentage of dead weevils inside the fruit pulp for the category ‘whole fruit’, and the percentages of dead mature and immature stages. All these values are summarized in table 1.

Table 1. Summary of the percentage of mango seed weevils, out of the total number of weevils present, to emerge prior to winter, compared to the percentage to hibernate in the seeds and mortalities, for each of the cultivars investigated, based on certain assumptions (see text).

	Tommy Atkins	**Keitt**

	Whole fruit	Wetted seeds	Dry seeds	Whole fruit	Wetted seeds	Dry seeds
Probable emergence	87.75	94.30	90.17	50.09	71.30	49.70
Probable hibernation	4.36	3.67	7.75	10.43	6.43	14.93
Mortalities	7.89	2.03	2.08	38.33	22.28	35.36

For both cultivars, the seeds that were frequently wetted showed the highest probable emergence rate, with the least number of adult weevils likely to over-winter in the seeds, indicating that moisture did affect adult MSW emergence. Mortalities for whole 'Tommy Atkins' fruit were higher than for the other two categories, indicating the effect of fruit decay, and the excessive fruit moisture associated with fruit decay, on adult survival after emergence from the seed. For 'Keitt', mortalities were also highest for the category, whole fruit, although mortalities for the category, dried seeds, were comparative, probably since complete desiccation of the smaller 'Keitt' seeds occurred more readily than for the bigger 'Tommy Atkins' seeds.

5.3.2.4. General observations

With the onset of natural oviposition between mid to end September (Louw *et al.*, 2007), and with the first adults present 6 to 8 weeks after oviposition (Chapter 5; 5.3.1. Weevil development), the first adults should hypothetically be present in infested mango fruit by mid to end December. This was confirmed in the 2006 / 2007 season by De Graaf (2007), who recorded 8.9% and 4.2% adult seed weevils in 'Tommy Atkins' fruit sampled from two different orchards on 19 December 2007. Just prior to commercial harvest (beginning of January 2008), 21.8% and 20.4% of the seed weevils present within infested fruit were already mature. These adults were not only able to survive outside the protective environment of the seed, they were also able to mate and lay eggs (Louw & Mukhethoni 2006; Louw *et al.*, 2007).
The emergence studies showed that high numbers of mature adults emerged within 30 days after the commercial harvesting date from the depulped seeds of early-season cultivars, i.e. 'Tommy Atkins' and 'Zill'. This negates the assumptions that adult weevils emerge shortly after reaching maturity (CABI & EPPO, 2005), and that no problems are experienced on local South African markets with early cultivars as fruit are marketed and consumed before the weevils reach maturity (De Villiers, 1984; Joubert & Pasques, 1994).

Although the majority of adult weevils emerged within 30 days after depulping the seeds, some weevils took as long as 120 days to emerge, with a small percentage of the seeds containing weevils that would probably over-winter within the seeds. When investigating the effect of moisture on adult emergence, it did seem as if sufficient ambient moisture enhanced emergence, although excess moisture seemed to have had the opposite effect, inhibiting emergence and leading to weevil mortalities. These results confirmed the observations made by Balock and Kozuma (1964) and Schotman (1989), namely that adult weevils remain in the seeds for considerable periods before emerging, and that the trigger for emergence is probably moisture levels (fruit ripening).
In the 2006 / 2007 mango season, natural adult weevil emergence, from both sanitation and tree-hanging fruit (Fig. 42), was observed only for mid-to late-season and late-season cultivars ('Kent', 'Keitt' and 'Sensation'), supporting the observations made by De Villiers (1987). Adult weevil emergence was mostly observed from the beginning of February up to the commercial harvest, although incidences were relatively low.

For these reasons, it is imperative to constantly remove sanitized fruit out of the orchard, from the time that the first adult weevils are present within the seeds (mid to late December) in order to reduce the effect of MSW adult emergence. Sanitation measures at the beginning of the season, however, should not be neglected, since weevils were found to have developed inside weaned fruit, provided that the seed remained intact and that sufficient flesh remained around the seed to protect the seed from desiccation (Fig. 43).

Fig. 42. Adult mango seed weevil emergence from sanitized (left) and tree-hanging fruit (right), resulting in a fairly large, unattractive emergence hole.

Fig. 43. Sanitized fruit in external (left) and internal (right) view, with a mango seed weevil larva (arrow) that was still developing inside the seed 2 months after fruit-drop.

Up to fruit maturation, and just prior to the commercial harvesting date for any specific cultivar, the majority of oviposition sites were readily visible, clearly showing the lesions where ovipositing females made incisions to induce latex flow (Fig. 44). These characteristic symptoms can be used to selectively remove egg infested fruit prior to harvest in order to reduce MSW infestation levels of marketable fruit. Even where no incisions, or no prominent incisions, were induced, remnants of MSW eggs remained inside latex husks on the fruit skin, in most instances, nearly up until the commercial harvesting date.

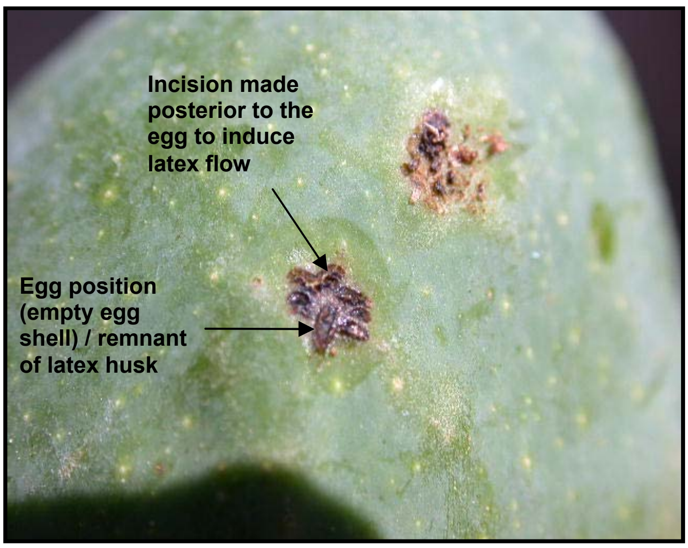


Fig. 44. Prominent mango seed weevil oviposition sites on the surface of a green mango fruit.

Eggs were laid singularly on the fruit skin, with no eggs found under the fruit skin, as claimed by Schoeman (1987). Also, no cavity was excavated into the fruit skin to contain the egg as claimed in the literature (CABI & EPPO, 2005), although a few instances were found where latex flow over and around the weevil egg left the impression that a cavity had been excavated (Fig. 45).

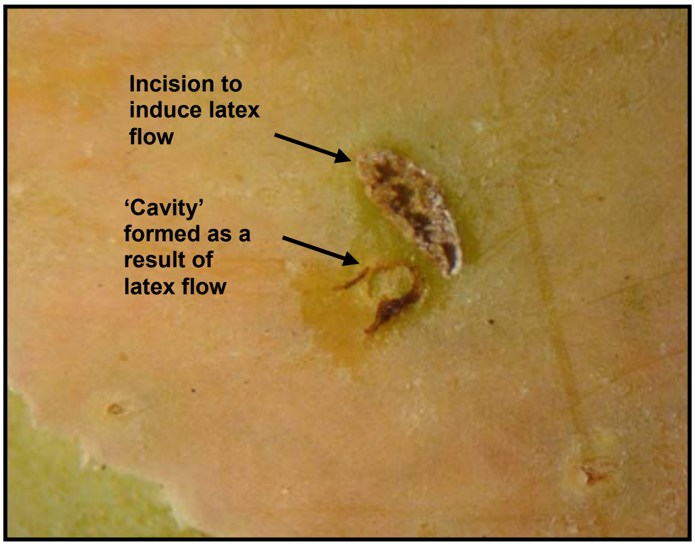


Fig. 45. A mango seed weevil oviposition site with an incision posterior to the egg to induce latex flow over the egg. An apparent cavity, formed by the pattern of the latex flowing over and around the egg, remains when the egg dislodges.

A few instances were also found where eggs were covered with a brown exudate, corresponding to the literature (CABI & EPPO, 2005). This exudate was not likely to have been a latex capsule, since no fruit scarring was found to indicate the induction of latex flow (Fig. 46).

Fig. 46. A mango seed weevil egg covered with a brown exudate. Since no incision is visible which indicates latex flow, it can be assumed that the exudate is not as a result of latex covering the egg.

Penetration tunnels, indicating the entrance site of the miniscule larvae into the fruit pulp, were clearly visible when cutting the fruit skin just below the oviposition site (Fig. 47). This remained the case up to the end of the season, just prior to the commercial harvesting date.

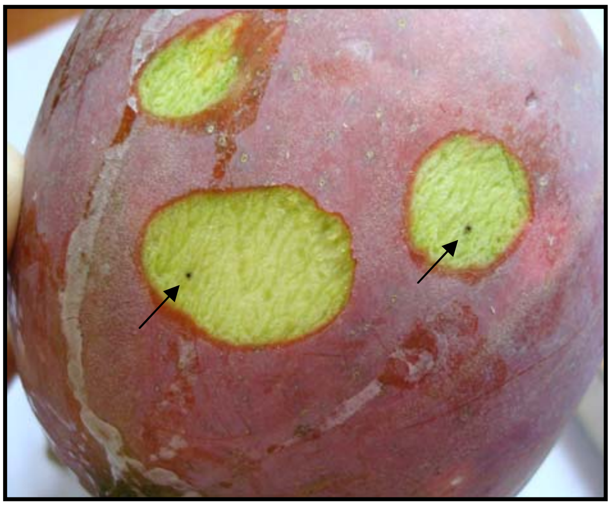


Fig. 47. Prominent pulp scarring (arrows), just below the oviposition site, where a mango seed weevil larva penetrated into the fruit pulp.

5.4. Conclusion

The majority of weevil eggs required between 7 and 14 days to hatch. For eggs laid early in the season, miniscule larvae penetrated the seed two weeks after the eggs were laid, but for eggs laid late in the season, seed penetration occurred within 7 days. This means that chemical control with contact and semi-penetrant chemicals, aimed at controlling the seed weevil larvae, should not commence later than 7 days after the first eggs are noted. However, with oviposition commencing by the middle of September, and continuing up to January, more than one application would be warranted.

Mango seed weevil development from eggs laid during December were more rapid than from eggs laid during November, with development from eggs laid in November more rapid than from eggs laid during October. During the December to January induction period in the 2006 / 2007 mango growing season, fewer eggs were laid, on average, than earlier in the season, with mango seed weevil development from these eggs seemingly unsuccessful. Contrary to observations made on natural MSW oviposition (Chapter 4; 4.3.4. Oviposition in the field), where egg laying declined during the latter part of the season, the average number of eggs per egg infested fruit, during the December to January induction period in the 2007 / 2008 season, was greater than for either the October induction period, or the November induction period. Mango seed weevil development from these eggs was deemed normal, contrary to what was observed in the 2006 / 2007 season. Environmental conditions, and consequently fruit set and development, probably influenced MSW activity and fecundity, resulting in the differences found between the two seasons.

Mature adult seed weevils were found within the seeds of infested mango fruit between 6 (egg laid late in the season) to 8 weeks (eggs laid early in the season) after the eggs were deposited. This indicates that sanitation practices would need to be in place at this stage, since MSW adults have the potential to emerge from infested seeds after eclosion.

With early-season cultivars and under artificial conditions, the majority of adult weevils emerged within 30 days. Some weevils, however, took more than 90 days to emerge. Only a small percentage of weevils seem to over-winter in mango seeds, with weevil mortalities the main reason why no adult seed weevils emerged from some egg infested fruit prior to the onset of winter. For the early season cultivar, ‘Tommy Atkins’, even though no incidences of adult MSW emergence from tree-hanging fruit or discarded seeds have been reported in the field, the emergence studies did show that the adult weevils had the capacity to emerge, given the appropriate stimulus.

Emergence varied only slightly for fruit size and tree position but, since no linear correlation between MSW emergence and these parameters were recorded, these parameters probably had no influence on the rate or the success of MSW adult emergence. Moisture, however, had an effect on MSW adult emergence, enhancing and / or triggering adult emergence from infested seeds. On the other hand, excess moisture levels inside the seed husk and / or fruit decay hindered emergence and resulted in a number of mortalities, probably due to drowning (suffocation) and fungal growth.

In the 2007 / 2008 mango growing season, MSW adult emergence from, and therefore weevil development in, infested seeds of the late-season variety 'Keitt' was less successful than for the early-season cultivar 'Tommy Atkins'. The main reason for this seemed to have been due to competition for food, since penetration scarring on the inside of the seed husk of infested seeds suggested that a high number of larvae penetrated into the seed. Despite this high incidence of seed penetration, however, only a few adult weevils were present within infested seeds (mostly only a single adult, but in some instances two adults), with the majority of these larvae probably having died within the seeds, suggesting that, during periods of high infestations, competition for food will reduce adult seed weevil emergence and therefore stabilize population levels.

5.5. References

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CHAPTER 6

Biological and mechanical control of the mango seed weevil

6.1. Introduction

6.1.1. Natural enemies

Schoeman (1987b) and Hansen *et al.* (1989) recorded no parasitoids of the adult mango seed weevil (MSW). Joubert and Labuschagne (1995) screened weevil eggs on 800 fruit for the presence of parasitoids, and similarly recorded no parasitoids during the entire period that egg laying was observed.

According to Hansen (1991), the reason why no parasitoids of MSW larvae and pupae are known is probably due to the fact that these vulnerable life stages are protected within the mango seed, making it difficult for potential parasitoids and / or predators to reach them. However, he did mention that occasional predation of adult seed weevils occurred by the ant, *Monomorium* sp., lizards and centipedes, and that rodents sometimes damaged mango seeds to such an extent that no weevils could survive.

The ants species, *Oecophylla smaragdina* and *Camponotus* spp., were recorded to occasionally interfere with mating and oviposition of the mango pulp weevil, *Sternochetus frigidus* (Schotman, 1989). Peng and Christian (2007) reported that, in the Northern Territory in Australia, the introduction and maintenance of weaver ant colonies, *Oecophylla smaragdina* (Fabricius) (Hymenoptera: Formicidae), in organic mango orchards reduced the incidence of *Sternochetus mangiferae* downgraded fruit.

Shukla *et al.* (1984) reported the presence of a Baculovirus in MSW larvae within mango seeds, with infected grubs behaving lethargic, showing a loss of appetite and eventually dying within the seed. It was also reported that the fungus, *Aspergillus* sp., frequently infected over-wintering adults (Hansen, 1991). However, no further references could be traced regarding the presence of either the Baculovirus or the fungus. Joubert and Labuschagne (1995) investigated the use of the entomopathogenic fungus, *Beauveria bassiana* (Naturalis-L®), but observed no mortalities in the field.

6.1.2. Organically derived products and / or compounds

In 1995, Joubert and Labuschagne investigated alternative control measures, i.e. mechanical control via sticky polybutane gum that was applied to a plastic strip and wrapped around the tree trunk. They also investigated the stem barrier, Bug stop®, based on the assumption that MSW adults hibernate under debris on the soil surface and enter the tree via the main stem at the onset of spring. They recorded, however, that these physical barriers were ineffective in trapping MSW adults. Schoeman (1987a) and Hansen (1991) also reported that the use of sticky bands around the base of the tree trunk is ineffective in capturing MSW adults. The reason for this probably being that, although adult weevils were observed moving about on tree branches within mango trees, they tend to fly from tree to tree.

Schoeman (1987b) found that adult weevils were not attracted to light traps or flight interceptor traps. Although some authors did find adult weevils in suspended fruit fly traps and ultraviolet flight traps (Hansen, 1991), no indication was given on the specifics and efficacy of these traps as lures in the field. No further mention could be traced regarding the potential of traps to attract MSW adults.

Verghese *et al.* (2004) investigated the effect of neem and its derivative, azadirachtin, and various soaps for mango seed weevil control, but found that all the treatments failed to repel adult seed weevils in laboratory trials. In the field azadirachtin failed to prevent oviposition and did not result in mortalities of either the eggs, or the first instar grubs.

Joubert *et al.* (2002) investigated the use of a kaolin-based product (Surround®) for seed weevil control, since this product is organically certified and registered for several crops in the USA. Kaolin is a non-toxic, natural clay mineral. Surround® solo was compared to a spray mix of Surround®, wettable sulphur and lime-sulphur. They found that both treatments effectively prevented adult weevils from depositing eggs on mango fruit, irrespective of the fact that very high infestation levels occurred within the trial orchard. However, they did conclude that, with the adult weevils having no alternative host plants for oviposition, oviposition may take place despite applications should an entire area be sprayed. Both applications also resulted in a secondary outbreak of mango scale (*Aulacaspis tubercularis*) and mealybug, *Pseudococcus longispinus* (Targioni-Tozzetti) (Hemiptera: Coccidae), with the effect more prominent when using Surround® solo, since wettable sulphur and lime-sulphur probably had a slight suppressing effect on these pests.

6.1.3. Plant resistance

Hansen *et al.* (1989) found no significant differences in MSW infestation rates among 20 different Hawaiian cultivars. However, he deduced that the most practical method of naturally reducing MSW infestations would be through the development of resistant cultivars, more specifically cultivars of which the seed husk would harden sufficiently in the early stages of fruit development to prevent MSW larvae from penetrating into the seed. Another possibility that is mentioned is cultivars that produce no seed (Hansen, 1991).

6.1.4. Sanitation practices

Sanitation is the removal of all dropped or fallen mango fruit from the orchard floor, which includes immature fruit during fruit weaning (with a mango tree producing copious amounts of flowers and fruit, but only able to bear a certain number of fruit to maturity, the majority of fruit are weaned early in the mango growing season), spontaneous (tree-ripened) fruit, fruit fly infested fruit and mechanically damaged fruit. Since mango is the only known host for the MSW, with mango seeds the only environment in which weevils can successfully complete their life cycle (De Villiers, 1987), sanitation is not only a practical solution for reducing future infestations by reducing current population numbers, it can also be implemented with good effect if managed correctly.

Verghese (2000) investigated the effect of MSW on premature fruit drop. Although he found no conclusive proof that weevil infestations resulted in premature fruit drop, he did conclude that the regular removal and destruction of fallen fruit would lead to a reduction in infestation levels the following year, since dropped fruit showed, on average, a high incidence of weevil infestation.

In order to follow effective orchard sanitation, not only fruit from within the orchard should be removed, but fruit from non-commercial hedge trees and trees standing in isolation should also be removed (Schoeman, 1987a). Seeds need not only to be removed, they should also be destroyed by burial at a depth of at least 600mm, burning, or slashing in a hammer mill (Schoeman, 1987a; De Villiers, 1987). Sanitation should start from October, coinciding with the peak of weevil activity and oviposition, and continue until the last fruit have been harvested (De Villiers, 1987). According to De Villiers (1987), the most important time for sanitation is from January until the end of the mango growing season, as the majority of weevils are already mature adults at this stage, and are able to leave the seed to seek hibernation sites.

Hansen and Armstrong (1989), on the other hand, recorded that field sanitation had no impact on reducing mango seed weevil infestations, while Joubert and Pasques (1994) reported that sanitation is highly labour intensive. This usually results in sanitation practices not being followed rigidly, with the majority of producers relying on chemical control as the only means to combat seed weevil infestations. The availability of labourers, as well as the economic impact of increasing minimum daily wages, also restricts the effectiveness of sanitation practices. Hansen (1991) also found sanitation to be extremely labour intensive, because it does not only require the complete removal of dropped mango fruit and seeds, it also requires a method of dispensing of the seeds and transport of sanitation fruit to a specific location suitable for fruit and seed destruction. He further mentions that documentation, proving the efficacy of orchard sanitation in reducing MSW infestation levels in subsequent seasons, is hard to come by.

6.1.5. Post-harvest treatments

With post-harvest disinfestation treatments, aimed at killing MSW within mango seeds while maintaining fruit quality, it was found that hot water, vapor heat and fumigation treatments were ineffective as tactics (Joubert & Grové, 1999; Follet, 2001). Various authors investigated the efficacy of irradiation. De Villiers (1984) reported that, although some surviving weevils were recorded at dosages of 500Gy, these adults were lethargic and inactive after treatment. At dosages of 850Gy, none of the adult weevils survived.

Joubert and Grové (1999) also investigated the effect of gamma irradiation on MSW adult emergence from weevil infested ‘Sensation’ fruit, and found that dosages of 200, 300, 400 and 500Gy all proved ineffective in preventing adult emergence. Gamma irradiation at dosages between 200 to 500Gy had no impact on the fruit quality of ‘Kent’ fruit (big size, mid- to late-season cultivar). However, irradiation at these dosages did affect the fruit quality of smaller fruit, i.e. ‘Heidi’ (medium size, late-season cultivar) and ‘Tommy Atkins’ fruit (medium size, early-season cultivar), since cold damage (Fig. 1) and lenticel damage (Fig. 2) was respectively noted for these two cultivars.

Fig. 1. Cold damage on the late-season cultivar, ‘Heidi’, manifesting during cold storage (left), with the internal effect seen close-up (right).

Fig. 2. Lenticel damage (cosmetic damage) manifesting during cold storage. The marketability of a mango fruit, showing prominent lenticels as these on the fruit skin, is significantly reduced.

Follet (2001), on the other hand, recorded that MSW adults that emerged from fruit treated at dosages of 100Gy to 300Gy were lethargic, short-lived and sterile (no egg laying was observed). But, based on results that were obtained with the various studies investigating irradiation, he concluded that a dosage of probably no less than 600Gy would be needed under South African conditions to prevent mango seed weevil emergence from infested seeds.

Irradiation with a cobalt-source is extremely expensive, necessitating co-operative establishment and management. This is probably the reason why this method has not previously been employed in South Africa in order to guarantee mango seed weevil free fruit.

6.2. Materials and Methods

During the course of the various studies carried out between 2004 and 2008, both for weevils in captivity and in the field, general observations on all aspects of the mango seed weevil were constantly noted and / or recorded. Aspects especially pertaining to reproduction successes, MSW survival in mango seeds and general observations on population dynamics were noted.

6.2.1. Natural enemies

In the 2004 / 2005 mango growing season, contract research was conducted by Miss. L. Machlachlan, in coordination with Westfalia Technological Services, to investigate the probability of guinea-fowl feeding on mango seed weevils and influencing MSW infestations on the organic farm, Moriah, in the Hoedspruit magisterial district of the Limpopo Province. This study involved the monitoring of guinea-fowl movement, behaviour and feeding patterns.

An impact study was proposed to investigate: (1) population dynamics, i.e. the number of individuals per flock, the number of flocks visiting the farm and movement within and between farms and, (2) habit preferences for various activities, e.g. feeding, mating and roosting, and (3) to determine whether guinea-fowl had any influence of MSW infestation levels as such.

6.2.2. Organically derived product and / or compounds

In the 2004 / 2005 mango growing season, on the organic farm Moriah, weevil infestation levels in various orchards treated with kaolin was determined. This was done in order to investigate the efficacy of commercially applied kaolin for reducing the incidence of MSW fruit infestations.

Weevil infestation levels were determined by noting the number of fruit that showed MSW feeding damage in the seed, out of a 100 fruit per orchard that was sampled. The fruit were collected at random from orchards with a history of high levels of weevil infestation. Sampling was done from within the first two rows adjacent to a suspected source of infestation. Fruit from untreated orchards, Blocks B41 and B46 (cv. 'Tommy Atkins'), with comparative weevil infestation levels were used as untreated control fruit.

Kaolin (Surround®) was commercially applied as a light to medium foliar application, at a dosage rate of 30kg Surround, 5kg sulphur (Thiovit®) and 5ℓ lime sulphur per 1000ℓ water, at an application rate of 800ℓ / ha (Fig. 3). Both sides of the trees were sprayed. The application dates were:

- Block B43 (1.16ha) – 14 October 2004
- Block B23 (1.16ha) – 04 November 2004
- Block A25a (0.44ha) – 15 November 2004.

Fig. 3. Commercially applied Surround® (kaolin) showing coverage on a mango tree (left) and a fruit (right).

Fruit were sampled on 21 December 2004, after the peak of weevil activity and oviposition, with weevil development sufficiently advanced to be easily identified. The sampled fruit were sliced in half and the presence or absence of weevils in the seed were noted (Fig. 4). The data was statistically analyzed using a One-way Analysis of Variance with Tukey's HSD test at 95% confidence levels (Statistica Version 6).

Fig. 4. Sliced mango fruit showing seed damage due to mango seed weevil feeding and development.

In the 2007 / 2008 mango growing season, the efficacy of two organically derived products / compounds were tested in a preliminary study. In order to investigate the efficacy of the entomopathogen,*Beauveria bassiana*, for mango seed weevil control, three rows in a 'Kent' orchard, in Block C14b on the farm, Moriah, in the Hoedspruit magisterial district, was used. The first and third rows were used as data rows, with the second (middle) row used as a buffer row to minimize the effect of spray drift into adjacent trial plots.

The study consisted of two treatments (untreated control vs. treatment). Trial plots consisted of 10 trees (1.5m spacing between trees in the same row and 6m between trees in adjacent rows), with the first and last two trees in each trial plot considered as buffer trees. Each treatment was replicated three times in row one (replicates 1 – 3) and three times in row three (replicates 4 – 6), alternating between treatments. Thirty fruit (15 fruit per side), free of weevil eggs, were marked with coloured flagging tape for each of the trial plots prior to the first application.
To determine the effect of the fungi on MSW oviposition, the number of eggs per fruit was counted after applications. Since the effect of the product on weevil development was also to be investigated, the eggs were not removed after assessments, with only newly laid eggs counted during consecutive evaluations. Weaned fruit were removed from the data sheet, and the remaining data fruit were evaluated at the end of the season.

To achieve maximum efficacy with *Beauveria bassiana*, Arrow® (Dagutat Biolab. cc.) was applied with NuFilm17® (Hygrotech Properties (Pty.) Ltd.), a non-ionic sticker-spreader agent containing Di-1-p-Menthene (905g/ℓ), and Boudica™ (Dagutat Biolab.

cc.), a mixture of beneficial fungi still in the experimental phase. The powders containing the fungi were pre-mixed in 5ℓ water (Fig. 5) before adding the mixture to the water containing the NuFilm17®.

The spray mix for 100ℓ water was:

1) 450g Arrow®, a wettable powder with a spore and mycelium concentrate of *Beauveria bassiana* (isolate DB 106, 1 x 109 colony forming unit / g),
2) 450g Boudica™, a wettable powder with a combination of various beneficial fungi (experimental stage) and
3) 42ml NuFilm17® (application dosage: 500ml / ha).

Fig. 5. Powders containing *Beauveria bassiana* and other beneficial fungi were completely dissolved in 5ℓ of water before adding the mixture to the spray tank.

For the second product tested, i.e. InsectCover®, the last three rows at the opposite side of Block C14b (cv. 'Kent') were used. As with the previous layout, two rows were used as data rows, with a row in the middle to act as a buffer to contain spray drift into plots situated next to one another.

The two treatments (untreated control vs. treatment) were again alternated within rows, with each treatment having three replicates per row. Trial plots consisted again of 10 trees, with the first and last two trees of each trial plot used as buffer trees. Thirty fruit (15 fruit per side) free of weevil eggs were marked prior to the first application, with data fruit evaluated after each application. The eggs were removed after each evaluation to prevent re-counting of existing eggs. Where data fruit were lost due to fruit weaning, other fruit free of weevil eggs were marked. This was done on the assumption that the product would not influence weevil development from the egg, but would rather act as a deterrent to prevent adult weevils from laying eggs.

Applications were done as a full cover foliar spray to just before the point of run-off (1.5ℓ solution / tree) with a tractor driven Nobili mist blower. The time of each application and prevailing climatic conditions are summarized in Tables 1 and 2.

At the end of the season, just prior the commercial harvesting date for the cultivar, the data fruit were evaluated for the following parameters:

- Thrips - percentage of fruit damaged
  - average damage index
- *Monolepta* beetle - percentage of fruit damaged
  - average damage index
- Mango scale - percentage of infested fruit
  - average incidence index
- Mealybug - percentage of infested fruit
  - average incidence index
- Mango seed weevil - percentage of infested fruit

The data obtained was processed and statistically analyzed. A one-way analysis of variance, with Fisher's HSD test at 95% confidence levels (Statistica version 6), was used.

Table 1. Climatic conditions at the time of each of the *Beauveria bassiana* applications (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

	Application1	Application2 (5DAA1)[1]	Application3 (14DAA2) [1]	Application4 (7DAA3) [1]	Application5 (7DAA4) [1]
Date	11 October	16 October	30 October	6 November	13 November
Fruit stage	10% pea, 40% marble & 50% golf ball size	50% marble, 40% golf ball & 10% tennis ball size	40% golf ball & 60% tennis ball size	20% golf ball & 80% tennis ball size	90% tennis ball size & 10% final size
Time (Start)	08h30	10h15	10h00	08h45	08h00
Time (End)	08h50	10h30	10h15	09h00	08h15
Temp (min)	17.0°C	18.5°C	12.0°C	20.0°C	12.5°C
Temp (max)	22.5°C	30.5°C	30.5°C	33.0°C	34.5°C
Cloud cover (Start)	100%	50%	0	100%	100%
Cloud cover (End)	100%	100%	0	100%	100%
Wind speed (Start)	0	1m/s	0	0	0
Wind speed (End)	0.5m/s	1m/s	0	0	0
Wind direction (Start)	E	NE	-	-	-
Wind direction (End)	E	NE	-	-	-
RH (min – max)	55 - 55%	30 - 79%	34 - 75%	27 - 86%	18 - 76%
Rain	0	0	0	10mm prior, 25mm after	0

[1] Days after application

Table 2. Climatic conditions at the time of each of the InsectCover® applications (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

	Application1	Application2 (6DAA1) [1]	Application3 (13DAA2) [1]	Application4 (14DAA3) [1]
Date	4 October	10 October	23 October	6 November
Fruit stage	20% pea, 50% marble, & 30% golf ball size	10% marble, 40% golf ball & 50% tennis ball size	60% golf ball & 40% tennis ball size	20% golf ball & 80% tennis ball size
Time (Start)	14h00	8h45	8h45	08h00
Time (End)	14h45	09h00	09h00	08h15
Temp (min)	17.0°C	19.0°C	15.5°C	20.0°C
Temp (max)	32.0°C	26.5°C	30.0°C	33.0°C
Cloud cover (Start)	50%	100%	0	100%
Cloud cover (End)	50%	100%	0	100%
Wind speed (Start)	0	0	0	0
Wind speed (End)	0.5m/s	0	0	0
Wind direction (Start)	-	-	-	-
Wind direction (End)	NE	-	-	-
RH (min – max)	26 - 87%	40 - 90%	20 - 70%	27 - 86%
Rain	0	0	0	10mm (light) prior, 25mm after

[1] Days after application

6.2.3. Plant resistance

Upon investigating weevil feeding preferences (Chapter 3; 3.2.1. Adult seed weevil feeding preferences for mango), one aspect of the study was to determine whether adult weevils exhibited preferences towards any of the cultivars commercially produced at Hoedspruit, which would indicate possible resistance of certain cultivars to either MSW feeding, or MSW oviposition. Feeding preferences were expressed as the number of MSW adults that visited each of the substances (whole fruit, half a fruit and foliage) for each of the cultivars. Egg laying preferences were expressed as the average number of eggs per fruit, for each of the cultivars. The data obtained was processed and statistically analyzed using a One-way Analysis of Variance with Tukey's HSD test at 95% confidence levels (Statistica Version 6).

6.2.4. Sanitation practices

During the course of the various studies carried out between 2004 and 2008, for both weevils in captivity and in the field, general observations on all aspects of the mango seed weevil were constantly noted and / or recorded. Aspects especially pertaining to MSW development in, and adult emergence from, mango seeds and the efficacy of sanitation practices were noted.

6.3. Results, Conclusion & General observations

From the various studies investigating weevil behaviour and oviposition, various repeated phenomena were observed, indicating that these aspects probably all contribute to maintaining a balance of population numbers under natural conditions in the field:

1) The reproductive success (percentage of all eggs that produced viable offspring) of MSW adults was, on average, only between 50% and 60%, with nearly half of all the eggs not hatching (Chapter 5; 5.3.1. Weevil development).
2) The infestation success (number of live adult weevils per egg infested fruit) of MSW adults, on average, is between 1 and 1.5, indicating that the mango fruit, as the only food source and place of development, can only sustain a certain number of weevils. Even in instances where egg laying was induced (Chapter 4; 4.3.1. Oviposition and fruit size), resulting in excessive egg laying, these

averages were maintained.

3) A factor influencing the success of MSW development, and ultimately adult emergence, was competition for food, as was seen where a large number of larvae penetrated into the seed (Chapter 5; 5.3.2.3. Effect of moisture on adult emergence) but where 2 to 3 adult weevils were, at most, found inside these seeds. Another aspect that resulted due to competition for food was the apparent incidences of cannibalism by adult mango seed weevils (Chapter 5; 5.3.1. Weevil development).
4) Whenever a large number of MSW adults were found to have developed successfully within a single seed, more than one of the adults were found to be considerably smaller (Chapter 5; 5.2.1. Weevil development). It was observed that many of these adults died prior to the onset of spring (personal observations of weevil colony kept in an office at ambient temperature and under artificial light).
5) Another aspect of mango seed weevil mortalities within mango seeds prior to emerging seemed to have been related to ambient moisture, where excessive moisture was retained inside the seeds during the early stages of fruit growth. Mortalities affected all the life stages and seemed to have been due to either drowning (suffocation), or a fungus present in the seed (Chapter 5; 5.3.1. Weevil development & 5.3.2.3. Effect of moisture on adult emergence).
6) The greater majority of captive MSW adults died each year, seemingly after peak activity, between the middle and the end of November (personal observations in the field and for captive adult weevils; data not published). Results from the study investigating oviposition by MSW females in captivity (Chapter 4; 4.3.3. Oviposition of adult females in captivity) were quantified by adding all the mortalities, for all of the containers, for the duration of the study period (Fig. 6).
7) Peak oviposition and activity corresponded to a time, early in the mango growing season, when a large percentage of immature fruit are prone to natural weaning, effectively reducing the number of infested fruit that will reach maturity. This was seen in the 2006 / 2007 mango growing season during the studies investigating MSW oviposition in the field (Chapter 4; 4.2.4. Oviposition in the field). Data summarizing incidences of fruit drop that was noted during each of the assessment dates are graphically expressed in Figure 7. The effect of fruit weaning was also noted during the study investigating chemical control measures of the mango seed weevil (Chapter 7; 7.2.5. Effect of different

application times of thiamethoxam on MSW). The data regarding incidences of fruit drop that was recorded at the time of each assessment is graphically expressed in Figure 8. This effect of fruit weaning was found to be more pronounced for immature, green fruit, than for nearly full size to mature mango fruit, as was indicated by the percentage of data fruit that were retained for various fruit size categories (Chapter 4; 4.3.1. Oviposition and fruit size).

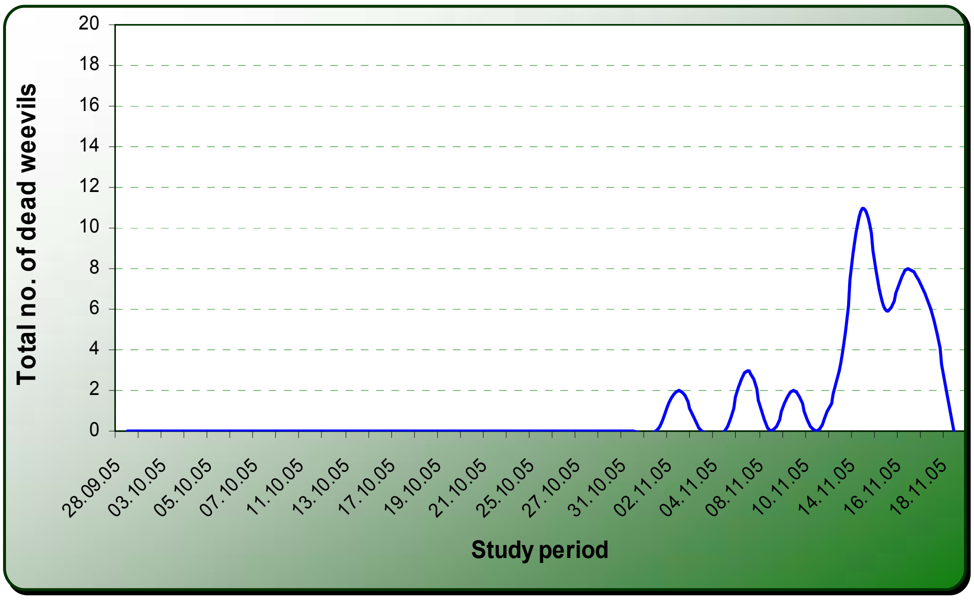


Fig. 6. Mortalities recorded during the study investigating oviposition of captive mango seed weevil females.

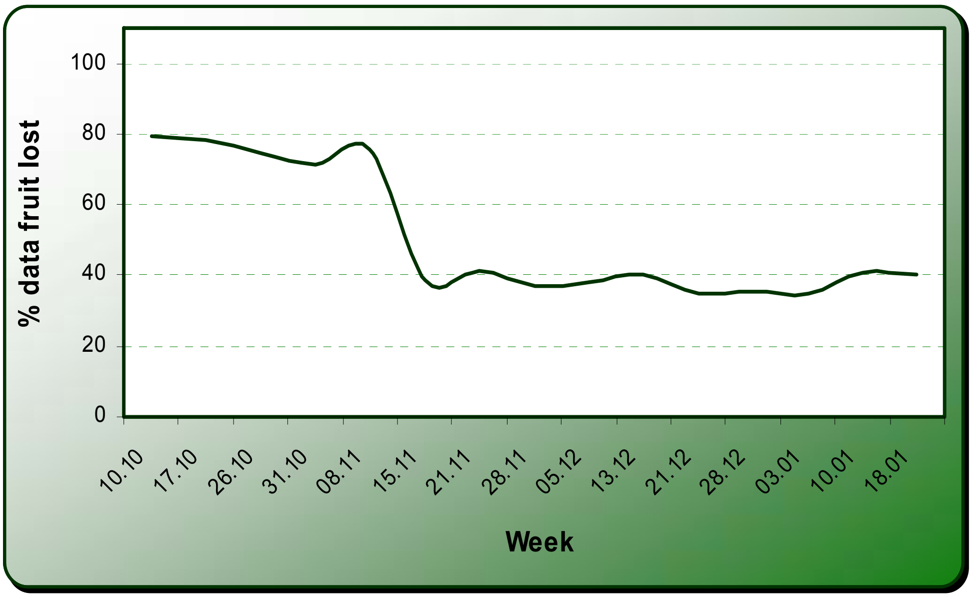


Fig. 7. Percentage of data fruit lost during early-season fruit weaning (cv. 'Kent', Block C14b, Moriah), 2006 / 2007.

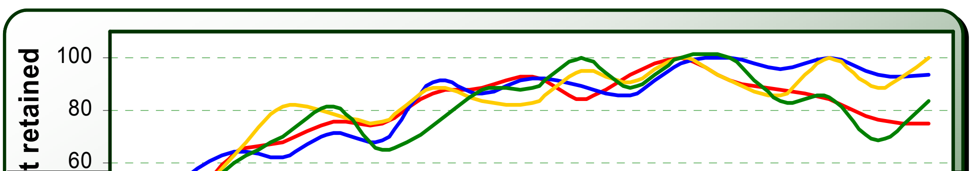


Fig. 8. Percentage of data fruit retained with each assessment, for the duration of the study period (cv. 'Kent', block G94, Grovedale), 2006 / 2007.

8) During the latter part of the season, when fruit were nearly full size and more inclined to reach maturity, MSW oviposition were found to have occurred at a noticeably reduced rate (Chapter 7; 7.3.5. The effect of different application times of thiamethoxam).
9) With the various MSW development and emergence studies (Chapter 5; Development, eclosion and emergence of the mango seed weevil) conducted over a four year period, some MSW mortalities were attributed to fungal growth. The species responsible for adult weevil mortalities in the seed, however, was not determined. Environmental conditions in the Limpopo Province, generally very hot with a low annual rainfall, do not generally favor fungal growth. However, where seeds were exposed to continuous high ambient moisture, i.e. discarded fruit and seeds found in the irrigation zone, this specific fungus was found to be presumably responsible for a small percentage of mortalities. This particular fungus, however, may not hold promise for organic MSW control, since it is a tedious, time-consuming and expensive process to identify, isolate and rear the fungus in a laboratory for commercial control, especially in the light of the prevailing environmental conditions. A comparative reduction in MSW infestation levels can be obtained by sanitation, removing infested fruit and seeds from the orchard floor and disposing of it properly.

6.3.1. Natural enemies

The project investigating guinea-fowl yielded no insight into whether these birds feed on adult mango seed weevils and thereby reduce population levels (data not published). Even though different flocks of guinea-fowl of various sizes were present in the organic orchards, breeding in adjacent fields and feeding during the day, MSW infestation levels increased in some orchards, while decreasing in others (personal communications with the farm manager). When relating activity patterns and feeding behaviour of guinea-fowl, the chances of predation would be expected be minimal. Weevils are nocturnal and hide in crevices and other shelters within the mango trees during the day. Guinea-fowl fed during the day, seeking insects on the ground and among vegetation (personal observations). At no time were the birds noted to remove bark and other debris from mango stems and trunks to gain access to insects.

However, chance predation could take place should guinea-fowl happen on adult weevils dislodged from the trees, or emerging from the seeds on the ground. Chance predation by other birds and spiders could also be likely, although no single predator species was found feeding only or mainly on adult weevils.

6.3.2. Organically derived products and / or compounds

Figure 9 graphically summarizes the results that were obtained in the 2004 / 2005 mango growing season, when investigating the effect of kaolin on MSW infestation levels. Even though the initial infestation levels were not known, samples were obtained from various orchards that received kaolin applications at different times in the season. From the results it seems evident that a linear relationship between MSW infestation levels and the time of kaolin application was found. Infestation levels in fruit treated early in the season when MSW oviposition had just commenced (Block B43), were noticeably less than when treated during the latter part of the season when the bulk of egg laying had already occurred (Block 25A). The number of MSW infested fruit in Block B43, treated during the early stages of MSW oviposition, were statistically lower than for any of the other orchards in which fruit were sampled (F (4, 495) = 62.746, p = 0.00001), with progressively more fruit that were infested the later the application was conducted.

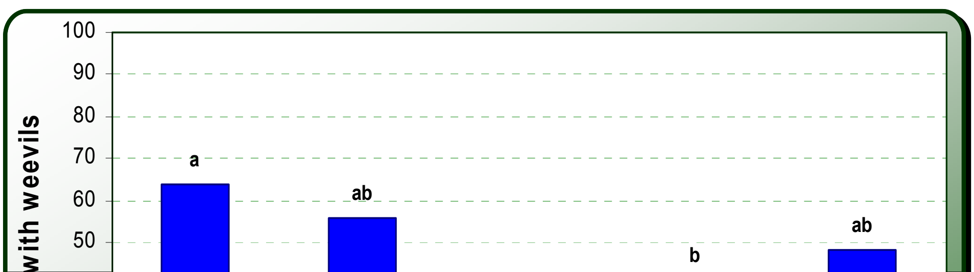
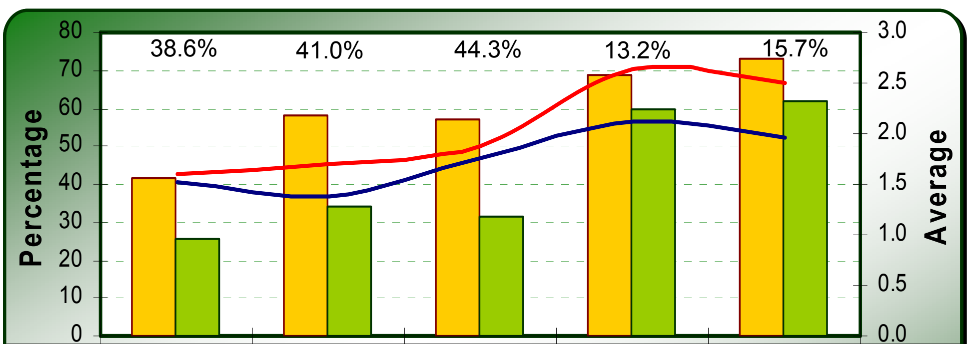


Fig. 9. Percentage fruit with mango seed weevil(s) developing inside the mango seed, 2004 / 2005. The letters at the top of each bar represents the significance of the differences between treatments at 95% confidence levels (Tukey), with letters differing from one another indicating significant differences.

Since kaolin was sprayed only after the first eggs were noticed and, since the initial infestation levels in each orchard were unknown, the efficacy of the product could not conclusively be ascertained. In order to determine the extent of commercial kaolin applications after the onset of oviposition, it is crucial to be aware of initial MSW infestation levels prior to application, or infestation levels in preceding seasons.

However, it is most feasible to spray kaolin before the onset of MSW oviposition, since kaolin acts as a deterrent, restricting the insect's movement by accumulating in the articulating body parts and spiracles. Kaolin is not a poison and cannot, therefore, affect weevil development once oviposition has taken place.

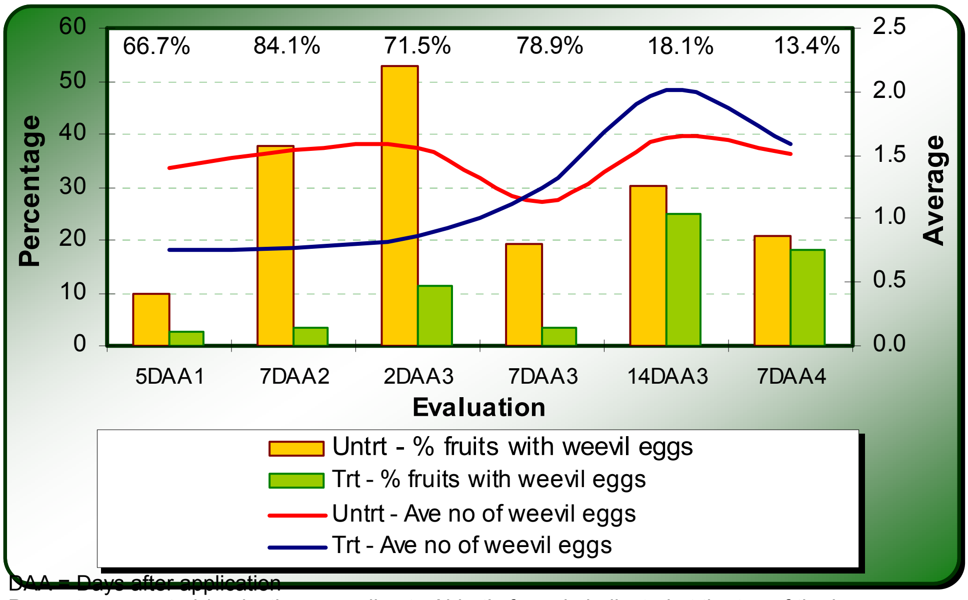
Figure 10 graphically depicts the results that were obtained in the 2007 / 2008 season, investigating the efficacy of *Beauveria bassiana* for mango seed weevil control, while Table 3 summarizes the results obtained at the end of the season. Figure 11 graphically depicts the results that were obtained in the 2007 / 2008 season, investigating the efficacy of InsectCover® for mango seed weevil control, while Table 4 summarizes the results obtained at the end of the season.



DAA = Days after application
Percentages control / reduction according to Abbot's formula indicated at the top of the bar

Fig 10. Percentage egg infested fruit, and the average number of eggs per egg infested fruit, for the study investigating fungal treatment as a tactic of mango seed weevil control in organic orchards (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

25mm rain AA3



DAA = Days after application
Percentages control / reduction according to Abbot's formula indicated at the top of the bar

Fig 11. Percentage egg infested fruit, and the average number of eggs per egg infested fruit, for the study investigating a garlic / neem extract as a tactic of mango seed weevil control in organic orchards (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

Table 3. Summary of statistical analysis conducted for various parameters investigated at the end of the season in order to determine the efficacy of fungal applications (Arrow® and Boudica™), enhanced by the addition of NuFilm 17®, for mango seed weevil control. The effect other insect pests were investigated to determine the impact of these products on population / damage levels (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

	% fruit with scale	Ave. scale rating[1]	% fruit with mealybug	Ave. mealybug rating[1]	% fruit with thrips damage	Ave. thrips damage rating[1]	% fruit with *Monolepta* sp. damage	Ave. *Monolepta* sp. damage[1]	% MSW infestation
Untreated	8.36 **a**	0.95 **a**	19.35 **a**	1.04 **a**	75. 65 **a**	1.09 **a**	4.61 **a**	0.64 **a**	94.15 **a**
Treated	5.67 **a**	0.37 **a**	28.15 **a**	1.03 **a**	71.89 **a**	1.07 **a**	7.29 **a**	0.70 **a**	78.31 **b**
F (1, 10)	0.420	3.373	4.582	0.012	0.386	0.206	0.643	0.027	4.975
p	0.532	0.096	0.058	0.739	0.548	0.659	0.441	0.872	0.050

Values in the same column with the same symbol did not differ statistically at 95% confidence levels (Fisher).

Incidence or damage rating according to scale (0 = clean, 1 = few individuals / minor damage, 2 = moderate infestation / damage and 3 = severe infestation / damage).

Table 4 Summary of statistical analysis conducted for various parameters investigated at the end of the season in order to determine the efficacy of a garlic / neem extract (InsectCover®), for mango seed weevil control. The effect other insect pests were investigated to determine the impact of this product on population / damage levels (cv. 'Kent', Block C14b, Moriah), 2007 / 2008.

	% fruit with scale	Ave. scale rating[1]	% fruit with mealybug	Ave. mealybug rating[1]	% fruit with thrips damage	Ave. thrips damage rating[1]	% fruit with *Monolepta* sp. damage	Ave. *Monolepta* sp. damage[1]	% MSW infestation
Untreated	31.00 **a**	1.51 **a**	44.00 **a**	1.94 **a**	33.67 **a**	1.39 **a**	2.33 **a**	0.83 **a**	59.67 **a**
Treated	36.00 **a**	1.61 **a**	42.00 **a**	1.88 **a**	53.67 **a**	1.60 **a**	3.33 **a**	0.88 **a**	49.67 **b**
F (1, 10)	0.313	0.477	0.095	0.348	4.749	3.791	0.372	0.014	3.794
p	0.588	0.506	0.764	0.568	0.054	0.080	0.556	0.909	0.080

Values in the same column with the same symbol did not differ statistically at 95% confidence levels (Fisher).

Incidence or damage rating according to scale (0 = clean, 1 = few individuals / minor damage, 2 = moderate infestation / damage and 3 = severe infestation / damage).

With the fungal applications, the percentage of egg infested fruit was initially notably lower in the treated plots, irrespective of a time-interval of 5 days (time elapsed between the first (11 October 2007) and second (16 October 2007) application) or 14 days (time elapsed between the second (16 October 2007) and third (30 October 2007) application) between applications (Fig. 10). Hard rain after application 4 (6 November 2007) could have influenced the efficacy of the product, although values for the last assessment (7DAA5) were higher and less pronounced between treated and untreated plots, despite the fact that the last application was done after the rain, indicating that the performance of the product could have been inhibited as population levels increased. No significant differences between the two treatments, neither for the percentage of egg infested fruit, nor for the average number of eggs per egg infested fruit, were found (data not shown), except for a reduction in the percentage of egg infested fruit for the assessment period 7DAA3 ($F_{(1, 10)} = 17.622$; $p = 0.0018$).

At the end of the season, just prior to the commercial harvesting date for the cultivar, the remaining data fruit were evaluated to determine whether the reductions noted during the season had a meaningful impact on infestation levels / damage of various insect pests at the time of the commercial harvest. Mango scale and mealybug, as indicators of disturbed micro-environments, were included to determine whether the applications had a negative impact on beneficial organisms. Since thrips and *Monolepta* sp. beetles were already present prior to the first application, no significant differences were found between the treatments regarding damage (Table 3). With the percentage of scale and mealybug infested fruit, as well as the average incidence rating, showing no statistical differences between treated and untreated fruit, these products (Arrow® and Boudica™ enhanced by the addition of NuFilm 17®) neither suppressed, nor lead to a significant increase in pest numbers.

A significant reduction in the percentage of weevil infested fruit was obtained at the end of the season, indicating that the fungi did impact on weevil development from the eggs, although this reduction was only 16% (Abbott's formula). However, the product was not applied prior to egg laying, and applications did not continue up to the end of the season due to a limited supply of the product. Time-intervals between applications were also not constant in order to determine the residual action after application. These factors could all have contributed to reduce the end effect on the insect pest monitored, implying that additional information should be gathered before making a final conclusion on the efficacy of these products.

Figure 11 clearly shows that, for the initial assessments, 5DAA1 and 7DAA2, with the initial applications only 6 days apart, the treated fruit showed significantly fewer fruit with weevil eggs than did untreated fruit ($F (1, 10) = 15.00$; $p = 0.003$ and $F (1, 10) = 13.58$; $p = 0.004$ respectively). Even two days after the third application on 23 October 2007, with the third application 13 days after application 2 (10 October 2007), treated fruit still showed significantly fewer fruit with weevil eggs ($F (1, 10 = 13.58$, $p = 0.004$). Seven days after the third application, the reduction was still noticeable although not significant (data not shown). Values between treated and untreated fruit were comparative and not significant 14 days after application 3, with the varying results obtained after a 2-week interval indicating that the residual efficacy of the product will probably be less than 14 days. With rain experienced after the fourth and last application on 6 November 2007, and with this application applied 14 days after the third application, values were again comparative and not significantly different 7 days after application.

At the end of the season, investigation into the seasonal effect of the product (InsectCover®) on population levels of and / or damage by various insect species again showed that , with thrips and *Monolepta* sp. beetles that were already present prior to the first application, no significant differences could be found between treated and untreated fruit. With the percentage of scale and mealybug infested fruit, as well as the average incidence rating, showing no statistical differences between treated and untreated fruit, this product also neither suppressed, nor lead to a significant increase in pest numbers.

Even though the percentage of weevil infested fruit showed only a small, although significant, reduction (16.8%) at the end of the season (Table 4), in-season results indicated that this product may reduce MSW oviposition. It may be necessary to reduce the time-interval between applications and it will be necessary to apply the product up to the time that no more eggs are recorded before making a final conclusion on the efficacy of this product.

6.3.3. Plant resistance

From the studies investigating seed weevil feeding and oviposition preferences between the commonly produced cultivars in South Africa, no indication could be found that weevils preferred specific cultivars over others (Louw & Mukhethoni, 2006). Since no significant differences between the number of eggs laid on the fruit of the early-season cultivar, 'Tommy Atkins', was found when compared to that of the late-season cultivars, 'Keitt' and 'Sensation', the apparent effect of early fruit maturation, and therefore the hardening of the seed husk, did not seem to hinder MSW oviposition (Chapter 3; Table 2). Comparative results were again obtained when comparing the early-season cultivar, 'Zill', to the mid- to late-season cultivars, 'Kent' and 'Heidi'.

The onset and duration of MSW oviposition in the field was also comparative for the early-season cultivar, 'Tommy Atkins', and the mid- to late-season cultivar, 'Kent', in the 2007 / 2008 mango growing season (Chapter 4; Figures 18 & 19). This was the case despite the fact that fruit from the early-season cultivar, 'Tommy Atkins', were already physiologically mature at the time of cessation of egg laying (mid January), compared to the mid-to late-season cultivar; 'Kent', which is only harvested at the end of February. Also, in both orchards where oviposition in the field was investigated, even though in two different geographical areas and not having comparative infestation levels, MSW oviposition reached a peak at similar times in the season.

6.3.4. Sanitation practices

Although adult emergence from early-season cultivars has not been recorded in the field up to date, the studies pertaining to weevil development did show that a small percentage of adults were present in the seeds at the time of the commercial harvest (Chapter 5; 5.3.2.4. General observations). Mango seed weevil emergence studies showed that the majority of weevils, irrespective of the cultivar, emerged under laboratory conditions within 30 days, with most of the remaining adults emerging within 60 days (Chapter 5; 5.3.2. Weevil eclosion and emergence).

However, there does seem to be a specific stimulus required by MSW adults to emerge in the field. This stimulus is most probably the ambient moisture levels in the fruit as the fruit reaches physiological maturity and starts to ripen, with spontaneous (ripe) fruit abundantly present at the time of the commercial harvest for late-hanging cultivars (personal observations).

This indicates that sanitation measures should be in place when the first mature adults are present in the seed, and more specifically at the onset of fruit maturation, to prevent MSW adults from emerging from ripe fruit. Even though natural emergence from late-hanging cultivars have only been recorded from February onwards, for the early-season cultivar, ‘Tommy Atkins’, this would mean that sanitation should commence no later than the middle of December, depending on the season. However, sanitation does not only imply the removal of dropped (weaned) fruit and discarded seeds, it also means that tree-ripening fruit should be picked and removed as well.

Figures 7 & 8 (Chapter 6; 6.3. Results, Conclusion & General observations) show that many immature fruit are dropped during natural fruit weaning. This occurs at the beginning of the season when the bulk of MSW oviposition occurs (Chapter 4; 4.3.4. Oviposition in the field). These observations corresponded to the findings of Verghese (2000), namely that a substantial number of egg infested fruit are weaned during the early part of the season. Since these fruit are usually quite small and desiccation and / or rotting to occurs fairly rapidly, and with the majority of weevils present within the seed probably still in the larval stages, chances of these weevils reaching maturity appear to be slim.

Orchard sanitation at this stage would therefore not influence infestation levels leading into the next season. However, weevil development did persist in sanitation fruit for a considerable time after fruit drop, provided that the seeds remained intact and that sufficient plant material (fruit pulp) existed around the seed to prevent desiccation (Chapter 5; 5.3.2.4. General observations). Taking this into consideration, sanitation should rather commence as soon as fruit are big enough to ensure timely degradation, and weevil development is far enough advanced to ensure maturity within a short time-span.

It was observed in a previous high yielding season, specifically at the end of the season with late-hanging cultivars, that, as more fruit became physiologically mature and ready for harvest, human resources were re-allocated exclusively to the harvesting of fruit, with little time and resources spent on sanitation practices (personal observations, 2005 / 2006 mango growing season). Sanitized fruit were collected from the orchard floor, but discarded in heaps along the wind-breaks (*Cassuarina* tree rows), where fruit remained for considerable periods before removal.

These fruit were not only exposed to constant irrigation, increasing ambient moisture, but infested seeds also contained almost exclusively mature adult weevils that were ready to emerge. The effect of poor sanitation practices was seen in the following season, with a noticeably increase in MSW infestation levels, and with MSW infestations occurring in orchards that were previously uninfested.

6.4. Conclusion

Insect parasitoids of the mango seed weevil are unknown, probably on account of the larvae and pupae developing protected within the mango fruit, whilst eggs are protected by an exudate and, in most instances, a protective husk formed by latex flowing over the egg. Chance predation by ants, spiders, reptiles and birds may occur in the field, although no indication was recorded of any single organism reducing adult weevil numbers.

Various other aspects, however, did seem to contribute towards maintaining a natural balance of mango seed weevil population numbers:

- reproductive success between 50% and 60%, with not all eggs producing viable offspring
- a mango seed, as the only available food source, can maintain only a limited number of weevils before competition results in mortalities
- where excessive moisture was retained during early seed development, some weevils died before they could emerge, either due to suffocation, or due to fungal growth
- natural adult weevil mortalities increased just after peak season (end November), probably due to the normal life span of the mango seed weevil
- peak oviposition corresponded with a time frame when natural fruit weaning was high

- oviposition during the latter part of the season, when maturing fruit were less likely to fall, occurred at a noticeably reduced rate.

It did appear as if a linear relationship between MSW infestation levels and the timing of commercially applied kaolin existed, with the earlier applications that coincided with the onset of MSW oviposition proving to be more effective than when applying the product after the majority of eggs had been laid. To ensure effective control, however, with the product being only a deterrent and not a chemical that inhibits growth, it is necessary to spray before the onset of oviposition.

Both *Beauveria bassiana* and an extract of garlic and neem significantly reduced mango seed weevil infestations. The reduction, however, was minimal (16.8% in both instances), but this could have been attributed to varying time-intervals between applications, to the initial applications commencing after the onset of MSW oviposition, and to a shortened spray-period due to insufficient availability of product. It would be feasible to test both these products for the duration of the season, commencing with the onset of egg laying and spraying at time-intervals no longer than 10 days.

No indication of preferences to any of the cultivars commercially grown in the Hoedspruit magisterial district was encountered. Since oviposition occurred readily on both early- and late-season cultivars, with egg laying occurring up to January irrespective of the cultivar, when fruit maturity and the resultant hardening of the seed husk had already set in, these factors did not seem to influence MSW preferences.

Orchard sanitation early in the season would probably not influence infestation levels leading into the next season. However, sanitation should start as soon as fallen fruit are big enough to ensure complete weevil development, and weevil development is far enough advanced to ensure that the developing weevil will mature before fruit decay.

Sanitation, however, should be diligently followed at the end of the season when the first adults are present (from mid December), and more specifically during February and March when adult weevil emergence occur in the field. It is equally important to remove tree-ripening fruit, and to transport sanitation fruit to a suitable site for disposal to combat a build-up of population numbers.

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CHAPTER 7

Chemical control of the mango seed weevil

7.1. Introduction

The mango seed weevil (MSW) is a serious phytosanitary pest that prevents the South African mango industry from gaining access to certain foreign markets. The MSW has no known natural enemies (Schoeman, 1987b; Hansen, 1991), necessitating to the implementation of physical and chemical control measures to combat this economically important pest. Since the MSW is a univoltine, monophagous pest (Follet & Gabbard, 2000) that completes its whole life cycle within the protective environment of the mango seed (De Villiers, 1984; De Villiers, 1987; Hansen *et al*., 1989), and with dispersal of the pest and colonization of new environments largely through the transport of infested seeds or fruit (Schotman, 1989), the impact of this pest has been greatly reduced in previous years by implementing good orchard sanitation practices.

The effectiveness of sanitation practices, however, is greatly dependent on availability of labor, transport, a suitable disposal site and an effective means of destroying the mango fruit and seeds. Joubert and Pasques (1994) found that, since sanitation practices are labor intensive, the majority of producers rely solely on chemical control measures to combat seed weevil infestations.

Several contact and semi-penetrant pesticides are registered for MSW control (Nel *et al.*, 2002). But, since the adult weevil is an elusive insect (De Villiers, 1984; De Villiers, 1989), inactive (Joubert and Pasques, 1994) and nocturnal (CABI & EPPO, 2005), chemical control is problematic. For effective chemical control of the adult seed weevil, applications should coincide with seasonal and daily activity peaks of the adult weevil, specifically when the weevils are moving around to feed, reproduce or to deposit eggs on the mango fruit, in order to ensure indirect contact through the feeding medium or direct contact with the MSW adult. For this it is imperative to understand the feeding preferences and activity patterns of the insect.

Contact and semi-penetrant insecticides have a limited efficacy against MSW larvae, either when leaving the egg to penetrate the fruit pulp, or while still developing inside the egg. Verghese (2000) recorded that, once the larva (grub) has penetrated the seed, chemical control with semi-penetrant insecticides becomes ineffective. The efficacy of contact insecticides, aimed at controlling the miniscule larvae developing inside the eggs, is hampered by the exudate covering the egg. In most instances, a latex husk, formed by latex flowing over the egg as a result of the incision made anterior to the egg by the ovipositing female (CABI & EPPO, 2005), adds further protection.

Varying opinions from the literature debate the ideal time frame for chemical applications with the most commonly used insecticide, fenthion (Lebaycid® 500EC). De Villiers (1989) found that chemical applications should coincide with the first eggs that are observed on the fruit. Disadvantages of this approach are: (1) laborious, frequent fruit inspections to determine the onset of MSW oviposition, (2) a trained eye and the ability to identify MSW eggs and (3) a second application to ensure seasonal control when insect pressure is high. A second application furthermore increases the severity of secondary pest out-breaks, i.e. mango scale (*Aulacaspis tubercularis*) and mealybug (various spp.), with these insects already manifesting after a single application. Follow-up applications may also lead to chemical residues accumulating at detectable levels.

Schoeman (1988) claimed that chemical control with fenthion should be applied during peak weevil activity. Disadvantages during such an approach are: (1) some larvae may already have hatched and penetrated the mango seed should the time from onset to peak oviposition be extended enough, reducing the effectiveness of chemical applications and (2) an extensive knowledge regarding the onset, peak and duration of mango seed weevil oviposition is required.

With the studies investigating weevil development (Chapter 5), it was recorded that the majority of eggs hatched between 7 and 14 days, with the miniscule larvae already penetrating into the seed about 2 weeks after egg laying (Chapter 5; Figs. 20 - 23 & Fig. 27). This would mean that chemical applications with semi-penetrant insecticides should preferably commence within 7 days after the first eggs have been laid. However, with the studies investigating weevil oviposition (Chapter 4; 4.3.4.

Oviposition in the field), it was found that the onset of MSW oviposition was sooner than previously stated in the literature, and continued for a longer period than what most authors reported. The peak of oviposition (end of October to the middle of November) did correspond to literature sources.

Should chemical applications coincide with the onset of MSW oviposition, a single application may lead to ineffective seasonal control, warranting a follow-up application. This may ultimately lead to secondary pest manifestations and chemical residues exceeding the maximum residue tolerance levels. Should chemical applications coincide with the peak of weevil oviposition, with oviposition onset by late September to early October, and oviposition peaking about 1 month later by late October to mid November, it stands to reason that minimal control would be achieved for fruit containing earlier laid eggs. The only unanswered question is how great the effect of fruit weaning would be on these early infested fruit, and whether fruit weaning, and the resultant decrease in the number of egg infested fruit on the tree, would warrant this approach.

The necessity of tedious fruit inspections, the ability to discern weevil eggs and an in-depth knowledge regarding MSW feeding, activity patterns, oviposition and development could be intercepted with the application of systemic insecticides. Systemic insecticides with a long residual action could also resolve problems surrounding the number of sprays to be applied in order to ensure seasonal control, as well as determining the optimum time frame for chemical application. Insect control and orchard management, however, should always be driven by an extensive knowledge about the biology, reproductive cycle and dispersal patterns of the insect, with chemical control forming part of an integrated pest management system comprised of chemical, physical and biological control measures, governed by economic threshold levels.

7.1.1. Efficacy of thiamethoxam for mango seed weevil control

Several contact (deltamethrin (pyrethroid), esfenvalerate (pyrethroid), fenvalerate (pyrethroid) and triflumuron (benzoylurea)) and semi-penetrant or trans-laminar (fenthion (organophosphorous compound)) pesticides are registered for MSW control (Nel *et al.*, 2002). But, with the adult weevil being an elusive insect, the efficacy of

contact insecticides are limited, with semi-penetrant insecticides providing control only for the period prior to the miniscule larvae reaching the safety of the mango seed.
The product most generally used in commercial mango orchards in the Hoedspruit magisterial district, fenthion (Lebaycid® EC 500g/ℓ a.i.), is very effective in controlling the mango seed weevil. Joubert and Labuschagne (1995), however, recorded that, despite fenthion applications, the screening of export mangoes prior to shipment still revealed MSW infested fruit. Joubert and Labuschagne (1995) furthermore reported that a single foliar application with fenthion eradicated almost all the adult parasitoids of mango scale. They concluded that the use of fenthion, a broad-spectrum organophosphate, would be incompatible to the concept of integrated pest management (IPM). The use of organophosphates on fruit destined for certain overseas markets is also under investigation.

With no biological control known for MSW (Schoeman, 1987b; Hansen, 1991), and organically certified control measures either ineffective, or exerting a detrimental impact on the environment (Joubert *et al.*, 2002), Westfalia Technological Services investigated the use of the neo-nicotinoid, thiamethoxam, for MSW control in the 2004 / 2005 mango growing season.

Thiamethoxam (Actara™ SC 240g/ℓ a.i.) is a nerve toxin that targets the nicotinic acetylcholine receptors in an insect's central nervous system, resulting in muscle fatigue and eventually death. Neo-nicotinoids have a systemic and trans-laminar action, with a long residual activity (Horowitz *et al.,* 1998) and are widely used on various crops in South Africa (Nel *et al.*, 2002). Although the neo-nicotinoids are broad spectrum insecticides, specific application methods, e.g. soil drenches, together with their low toxicity to non-target species, renders them well suited for Integrated Pest Management programs.

7.1.2. Effect of thiamethoxam on feeding mango seed weevil adults

With the results obtained in the 2004 / 2005 mango growing season, thiamethoxam was registered for MSW control in the 2005 / 2006 mango growing season, with the product applied as a soil drench in the irrigation zone during flowering, at a dosage of 6ml product per tree (LeLagadec *et al.*, 2005a). As a systemic insecticide with a long residual action, the use of thiamethoxam disposed of the need to implement frequent fruit inspections to determine the onset and / or peak of weevil activity and oviposition.

With the registration trials conducted in the 2004 / 2005 mango growing season, MSW adults were, in some of the trial plots, enclosed with gauze bags around fruit clusters to artificially induce oviposition. Fruit were enclosed for a period of 3 to 5 days, with each bag containing 5 adult seed weevils, mango foliage for shelter and half a mango fruit for feeding. The foliage and fruit were, in some instances, obtained from the same treated trees on which bagging occurred. In other trial plots untreated fruit and foliage from adjacent, untreated orchards were provided. It was observed that a number of MSW adults died when treated fruit were placed inside the bags for the adults to feed upon (Fig. 1), with oviposition noticeably less in bags where treated fruit were placed for feeding, than in bags where untreated fruit were placed (personal observations, 2004 / 2005 mango growing season).

Fig. 1. Dead mango seed weevil adults, characteristically with the proboscis extended and the legs either extending straight downwards (left), or sideways (right).

Since thiamethoxam, as a systemic insecticide, is translocated through the transport system of the tree to the fruit, registration studies demonstrated that the product is effective in killing the MSW larvae as they penetrated, and fed, through the fruit pulp towards the seed. In light of the above-mentioned observations, however, a question regarding the impact of the insecticide on MSW adult mortality and oviposition arose. For this reason a preliminary study, under artificial conditions, was conducted by Westfalia Technological Services in the 2005 / 2006 mango growing season to observe the effect of thiamethoxam on adult seed weevils exposed to, and feeding on, treated mango fruit and flushes (foliage).

7.1.3. Effect of fipronil and fenthion on feeding mango seed weevil adults

Fenthion, an organophosphorous compound registered for MSW control, renders very efficacious larval control (Schoeman, 1988), effectively reducing weevil infestations in fruit. However, producers frequently want to know not only the effect of a chemical product on fruit infestation levels in order to determine the potential number of fruit to be marketed with confidence, they also enquire about the effect of a chemical on MSW adults in order to be able to determine future infestation levels. For this reason a preliminary study, under laboratory conditions, was undertaken by Westfalia Technological Services in the 2005 / 2006 mango growing season to observe the effect of fenthion on adult seed weevils exposed to, and feeding on, treated fruit and flushes.

Another insecticide reputed to render effective MSW control, fipronil (Regent® SC 200g/ℓ a.i.), was included in the study. Fipronil is registered for thrips control on mangoes, where it is applied as a light, full cover spray during petal fall, but before fruit reach pea size.

7.1.4. Efficacy of various insecticides for mango seed weevil control

Different authors investigated the efficacy of various insecticides, additional to those mentioned above, for MSW control. Brooks and Snyman (1986) and Brooks *et al.* (1987) reported that fenvalerate (Fenvalerate® EC 200g/ℓ a.i.)), currently registered for MSW control at 30ml / 100ℓ water, sprayed just prior to and just after flowering, renders effective control. Schoeman (1987a) reported that, although two applications of fenvalerate rendered effective seed weevil control, mango scale numbers increased due to these applications. However, he does consider a single application to be sufficient to render effective control without leading to an increase in scale numbers.

Schoeman (1988) also investigated the efficacy of esfenvalerate (Samurai®) and fenthion (Lebaycid®) for MSW control. He recorded that fenthion yielded the best results, although a single application with esfenvalerate, applied before the activity period of the weevils, effectively reduced weevil infestations and had no long-term effect on mango scale numbers. De Villiers (1989) reports that a single spray with fenthion at a dosage rate of 100ml / 100ℓ water, applied when the first weevil eggs were noted, together with orchard sanitation, was sufficient to ensure effective MSW control. He cautioned that a second foliar application, two weeks after the initial application, should be applied if infestation levels prove to be severe. This, however, could give rise to a build-up of mango scale and mealybug.

Verghese (2000) investigated the efficacy of further alternative insecticides, i.e. a 0.05% solution methyl-parathion (50ml product / 100ℓ water), a 0.05% solution monocrotophos (50ml product / 100ℓ water), a 0.05% solution chlorpyrifos (50ml product / 100ℓ water) and a 0.2% solution carbaryl (20ml product / 100ℓ water), against the efficacy of fenthion diluted to a 0.08% solution (80ml product / 100ℓ water) for MSW control. He reports that fenthion yielded the best results.

With thiamethoxam registered for MSW control in the 2005 / 2006 season, a field trial was conducted by Westfalia Technological Services (WTS) in the 2006 / 2007 mango growing season to compare the efficacies of the various registered products against this product. Since thiamethoxam was also registered for mango scale and mealybug in the 2004 / 2005 mango growing season (LeLagadec *et al.*, 2005b), and because some of the registered insecticides have a known effect on these insects, the incidence and severity of these two insects were also recorded.

7.1.5. Effect of different application times of thiamethoxam on mango seed weevil

With the registration of the systemic product, Actara™ 240SC, applied as a soil drench during flowering, problems regarding MSW control seemed to have been solved. Use of this product negates frequent scouting to determine the onset and duration of egg laying, since applications are done at a specific time and at a specific growth-stage when weevils are still inactive and no oviposition has occurred yet.

However, variable opinions regarding the duration of oviposition are present in the literature. De Villiers (1984) recorded MSW oviposition to have occurred over a period of 3 to 5 weeks (October through to November), whilst Hansen *et al.* (1989) recorded oviposition to have lasted for only a month. In 1994, Joubert and Pasques investigated the onset, rate and duration of MSW oviposition. They found that an increase in MSW activity occurred during the latter part of September with weevils starting to mate. The first eggs were laid during the first week of October 1994, and peaked 3 weeks later by the end of October. The total duration of oviposition was 60 days. The following year, Joubert and Labuschagne (1995) found that oviposition commenced at the end of October 1995. Oviposition extended over a 3 month period, from the end of October up to January 1996. Balock and Kozuma (1964) recorded the oviposition period of the MSW to be about 90 days under laboratory conditions.

During the various studies investigating the reproductive and behavioral aspects of MSW adults in captivity (Louw & Mukhethoni, 2006), it seemed that the adult weevils terminated diapause by the middle of September. Mating started within a day or two, with the first eggs laid by the end of September. Egg laying continued up to January, with oviposition extending for nearly 4 months. In the field, during the 2006 / 2007 season, the first weevil eggs were also noted by the middle of September, with the last eggs again noted around the middle of January, corresponding to the observations made for MSW adults in captivity. A definite peak occurred at the end of October, with oviposition declining in December and becoming negligible in January (Louw *et al.*, 2007).

It therefore appeared that MSW oviposition may extend for a longer period than previously reported in the literature, because it occurs from the middle of September to the latter part of January, the question arose of whether thiamethoxam would be able to render effective control for the entire period of MSW oviposition activity.

To determine the efficacy curves of different thiamethoxam applications, oviposition was induced at specific times in the 2006 / 2007 mango growing season. The aim was to determine the effect of an early-season application on eggs that were laid late in the season, and the effect of a late-season application on eggs that were laid early in the season.

In the 2006 / 2007 and 2007 / 2008 mango growing seasons, the effect of thiamethoxam, applied at different times throughout the season, was also investigated for naturally occurring MSW infestations. For this aspect of the study, mango fruit were sampled prior to the commercial harvesting date to determine MSW, mealybug (*Planococcus citri* (Rossi) (Hemiptera: Pseudococcidae) & *Pseudococcus longispinus*) and mango scale (*Aulacaspis tubercularis*) infestation levels.

7.2. Materials & Methods

7.2.1. Efficacy of thiamethoxam for mango seed weevil control

As part of an intensive study to determine the efficacy of thiamethoxam for MSW control for registration purposes, a field trial was carried out in Block G81 (cv. 'Keitt') on the farm Grovedale in the Hoedspruit magisterial district of the Limpopo Province in the 2004 / 2005 mango growing season. Trial site information is summarized in Table 1.

Table 1. Trial site details for a field trial investigating thiamethoxam efficacy for mango seed weevil control on mangoes (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

Trial site	Mango cultivar	Plant spacing (m)	Tree age (years)	Irrigation system	Weevil infestation
Mariepskop Estate, Hoedspruit Latitude 24°24'S, Longitude 30°51'E	'Keitt'	2 x 7m (714 trees / ha) Average canopy height 2.0m	11	Permanent dripper	Introduced (bagged)

Thiamethoxam was applied in mid August at about 50% flowering, but prior to fruit set. The treatments applied are provided in Table 2. Prior to product application the mango trees were irrigated, ensuring that the soil was sufficiently moist to facilitate distribution of the product in the root zone of the trees. The product was applied as a soil drench in a shallow well made directly below the dripper (Fig. 2).

The product was made up to a 1ℓ solution and applied at each tree under the dripper using a measuring jug. In Block G81, cv. 'Keitt', two drippers are situated on opposite sides of each tree. The 1ℓ solution, containing 6ml Actara dissolved in water, was divided and applied as 500ml solution per dripper. After application, the trees were irrigated again for two hours. For the duration of the trial, standard irrigation practices were followed.

Table 2. Treatments, application dates, number of trees treated and the number of fruit evaluated at the end of the season for the field study investigating the efficacy of thiamethoxam for mango seed weevil control on mangoes (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

Trial site	**Dosage (ml / tree)**	**Application**	**Trees (n)**	**Fruit (n)**
Mariepskop Estate	Untreated control	-	25	80
Grovedale	6 (1.44g a.i.)	11 August '04	25	80
Block G81	8 (1.92g a.i.)	11 August '04	25	80

Fig. 2. A shallow hollow was made directly underneath each dripper (left) to contain the thiamethoxam solution (right).

Since no weevils / weevil infestation levels were recorded for Block G81 in preceding years, gravid weevils were introduced into the trial plots. This was done by enclosing fruit clusters in gauze bags containing 5 weevils per bag (Fig. 3). Approximately thirteen bags per treatment were used, enclosing 2 - 5 fruit per bag for a period of 3 - 5 days to ensure that a sufficient number of eggs were laid to guarantee infestation. After removing a bag from an enclosed fruit cluster, the number of eggs per data fruit was noted. All the egg infested fruit were tagged with flagging tape for easy identification of marked fruit at the time of sampling or harvesting. The fruit were allowed to mature on the trees.

Fig. 3. Clusters of mango fruit enclosed with gauze bags containing gravid mango seed weevil adults in order to induce egg laying (cv. 'Keitt', Block G81, Grovedale), 2004 / 2005.

On 20 January 2005, with weevil development sufficiently advanced to be able to identify infested fruit, all the marked data fruit were sampled for evaluation. All the tagged fruit were sampled simultaneously. The fruit were sliced open and examined for the presence of MSW in the seed. The data was statistically analyzed using a One-way Analysis of Variance with Duncan's multiple range test at 95% confidence levels (Statistica Version 6), and percentage control was calculated using Abbott's formula.

7.2.2. The effect of thiamethoxam on feeding mango seed weevil adults

Since there is no direct contact between the systemic chemical, thiamethoxam, and the adult seed weevil, a study was conducted under artificial conditions to investigate the indirect effect of thiamethoxam on the feeding activity of MSW adults. Treated and untreated mango substances, together with captive adult weevils, were placed in containers in a room. Monitoring was conducted at room temperature and under artificial (electrical) lights during the day.

Mango fruit and flushes were sampled from a thiamethoxam treated 'Tommy Atkins' orchard. The product was applied on 09 September 2005 at a rate of 1.44g a.i (6ml product), diluted in 1ℓ of water and applied directly under the dripper in the irrigation zone. The only other chemical applications consisted of fungicides. Treated fruit and flushes were sampled on 03 October 2005, 24 days after the thiamethoxam application to allow for product uptake. Untreated flushes and fruit were collected at the same time from an adjacent orchard subjected to the same production procedures and control measures, with the exception that no thiamethoxam was applied.

The mango substances, treated and untreated, were placed in small plastic containers with translucent gauze material inserted into the sides and the lid to facilitate monitoring (i.e. Chapter 4; Fig. 6). A thin layer of Lopis® cat litter sand was placed at the bottom of each container to absorb excess moisture and to act as a soil medium. In each container 5 previously sexed males and 5 females were placed among the foliage.

The different treatment categories were:

- 1 container with thiamethoxam treated fruit (half a fruit for feeding plus 2 whole fruit to monitor egg laying)
- 1 container with thiamethoxam treated flushes (foliage)
- 1 container with untreated fruit (half a fruit for feeding plus 2 whole fruit to monitor egg laying)
- 1 container with untreated flushes (foliage).

Weevil activity was monitored daily. Activity was measured as the number of weevils, out of 10 weevils placed, showing activity at the time of observation. This included feeding weevils (either on fruit of flushes), mating weevils and weevils present on the lid or along the sides of the containers. Assessments were conducted by removing the lid of the container and moving the fruit and foliage around in order to locate all the weevils present within a specific container. The number of eggs per fruit was counted daily in the early morning and eggs were removed after assessments to prevent them from being re-counted during consecutive evaluations.

Fruit and flushes were replaced twice weekly to prevent fruit decay of cut surfaces, excessive oviposition scarring on whole fruit and desiccation (wilting) of foliage.

Dead weevils were replaced with live ones, obtained from a large container or breeding box containing the bulk of the MSW colony, after noting mortalities. This was done in order to ensure constant and continued monitoring.

The trial was terminated on 18 November 2005, when large numbers of dead adult weevils were encountered in the breeding box containing the bulk of the captive MSW adults. Mortalities and oviposition were expressed as averages for the period that monitoring occurred and was statistically analyzed using a One-way Analysis of Variance, with Tukey's HSD test at a 95% confidence level (Statistica Version 6).

7.2.3. The effect of fipronil and fenthion on feeding mango seed weevil adults

The study to investigate the effect of the registered chemical, fenthion, on MSW adults feeding activity on treated flushes and fruit, was again conducted under artificial conditions, i.e. room temperature and electrical lights. Chemically untreated 'Kent' flushes and fruit were collected from the nearby organic farm, Moriah, on 03 November 2005, at a time coinciding with peak weevil activity.

In order to determine whether the effect observed would be due to direct contact, or due to adult weevils feeding on the treated substances, the following differentiation was made:

- adult weevils sprayed with respective chemicals and then placed among untreated foliage and fruit
- flushes and fruit treated with the chemicals and placed along with untreated weevils inside respective containers.

The initial treatments for fenthion (Lebaycid ® EC 500g/ℓ a.i.) were:

- 5 untreated adult weevils placed among foliage (flushes) and fruit treated with fenthion at registered dosage for MSW control (100ml / 100ℓ water)
- 5 untreated adult weevils placed among flushes and fruit treated with fenthion at double registered dosage (2x) for MSW control (200ml / 100ℓ water)
- 5 adult weevils treated with fenthion at double registered dosage (200ml / 100ℓ water) and placed among untreated flushes and fruits.

Concurrent with the fenthion treatment, fruit and foliage was also treated with fipronil (Regent® SC 200g/ℓ a.i.). Since this product is not registered for MSW control, dosages similar to the fenthion applications were used for comparison. The treatments for fipronil were:

- 5 untreated weevils placed among flushes and fruit treated with fipronil at a dosage comparative to registered dosage of fenthion for MSW control (100ml / 100ℓ water)
- 5 untreated weevils placed among flushes and fruit treated with fipronil at a dosage double that of registered dosage of fenthion for MSW control (200ml / 100ℓ water)
- 5 weevils treated with a fipronil solution of 200ml / 100ℓ water and placed among untreated flushes and fruit.

Adult weevils (untreated and treated) and mango substances (treated and untreated fruit and flushes) were place on shallow trays containing a thin layer of Lopis® cat litter sand to absorb excess moisture and to act as a soil medium. The trays were enclosed with gauze bags to ensure that no weevils escaped (Fig. 4).

Fig. 4. Shallow plastic trays containing a layer of cat litter sand to absorb excess moisture and to act as a soil medium. Mango seed weevils and mango substances were placed on the cat litter sand, after which the trays were enclosed with gauze bags to prevent the weevils from escaping.

Monitoring was conducted at daily intervals, noting mortalities, activity and the incidence and severity of feeding on the mango substances. The number of eggs on the fruit placed in each of the containers was also noted daily.

The study was repeated on 8 November 2005, using dosage rates half of that used in the first experiment. In both instances (experiments) the untreated adult weevils were placed some distance away from treated foliage and fruit to ensure that no immediate contact with the chemicals resulted in order to be able to conclude that mortalities were the result of feeding on treated substances, and not due to direct contact. No statistical analysis was done since the aim of this preliminary study, done under artificial conditions, was to determine and quantify the effect of these chemicals on the MSW adult stage, via either indirect (feeding), or direct contact.

7.2.4. Efficacy of various insecticides for mango seed weevil control

In the 2006 / 2007 mango growing season, a field trial was undertaken by Westfalia Technological Services to compare the efficacy of thiamethoxam to the various chemicals registered for MSW control. The trial was conducted using a completely randomized block design with 6 treatments and 5 replications (trial lay-out and protocol courtesy of Dr. J. De Graaf, Senior researcher - Phytosanitary Research, Westfalia Technological Services). Trial plots consisted of 10 trees, with 5 untreated trees used as a buffer between plots within the same row. One untreated row was used between adjacent plots to minimize spray drift. The trial was laid out in a 'Tommy Atkins' orchard reputed to have had high levels of weevil infestations in the preceding season (Block GD6, Bavaria Fruit Estates). The various products, application rates and application times are summarized in Table 3.

Since fipronil, registered on mangoes for thrip control, was previously reputed to render effective seed weevil control (Joubert *et al*., 2002), and with the laboratory studies confirming these observations, the product, Regent®, was included into the study. The product was included at the same dosage rate as registration requirements for thrip control, but applied slightly later, when fruit were already pea size, rather than during 100% petal fall and before the fruit are pea size as registered. Thiamethoxam was applied as an early (25 July 2006) and a late (4 September 2006) application. The product was applied as a soil drench in the dripper zone, in a small hollow made prior to application. Applications were done after irrigation to ensure that the soil moisture was sufficient to facilitate uptake. Foliar applications were applied with a tractor-driven Nobili Euro 90–600P mist-blower (Fig. 5) containing 8 nozzles per side. Distribution of the nozzles on each arm consisted of 4 D4 nozzles in the middle, with 2 D3 nozzles at the top and 2 D3 nozzles at the bottom. The tractor and spray car were calibrated to ensure a full-cover application to the point of run-off (about 2ℓ spray solution per tree) in order to ensure complete coverage of the foliage, as well as the tree trunks and branches.

Table 3. Various insecticides, application dosages and application times for field trial investigating efficacy of various products registered for mango seed weevil control (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

	Active ingredient	Product	Formulation	Dosage	Application time
1	fipronil	Regent®	SC 200g / L	10ml / 100L	With fruit at about pea size
2	fenvalerate	Fenvalerate®	EC 200g / L	30ml / 100L	Week 30 (end July) during flowering. Repeat at pea size fruit
3	thiamethoxam	Actara®	SC 240g / L	6ml / tree	Week 30 (end July) - flowering
4	thiamethoxam	Actara®	SC 240g / L	6ml / tree	Week 36 (beginning September), about 90 days prior to harvest)
5	fenthion	Lebaycid®	EC 500g / L	100ml / 100L	Week 44 (End October)
6	untreated control	-	-	-	-

Fig. 5. Tractor-driven Nobili spray car, calibrated to ensure a full cover foliar application, as seen from the front (left) and the back (right).

Foliar applications were done at dusk, corresponding to the activity period of the adult weevils, as was determined by monitoring the behaviour and activity patterns of captive MSW adults (Chapter 2; 2.3.1.2. Daily activity patterns of the mango seed weevil). The first application with fenvalerate coincided with 80% of the orchard in full flower (25 July 2006), while the second application was conducted with the fruit size distribution at 40% fruit set - 20% pea size - 40% golf ball size (20 September 2006). Fipronil was applied at the same time as the second fenvalerate application. Fenthion was applied according to registration (late October to the beginning of November) on 31 October 2006, with the majority of the fruit between golf ball size and tennis ball size.

Prior to the first chemical application, strips of white shade cloth were placed underneath one data tree per plot in order to monitor adult weevil mortalities resulting from the chemical applications (Fig. 6). Placement and monitoring of the nets was also done for the untreated control plots in order to attribute mortalities to chemical applications and not to natural causes. Monitoring was done more frequently after specific applications (every day for a period of 3 days), with monitoring during the period following insecticide applications done once per week. Monitoring of the nets commenced on 26 September 2006, about 1 month after the first thiamethoxam application in order to allow for sufficient product uptake, and continued until 28 December 2006, about 2 months after the last application (fenthion) was conducted. Distinction was made between live and dead weevils (Fig. 7).

Fig. 6. White shade cloth placed beneath one data tree per plot (left), for each trial plot (right), to collect adult mango seed weevils influenced by chemicals (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

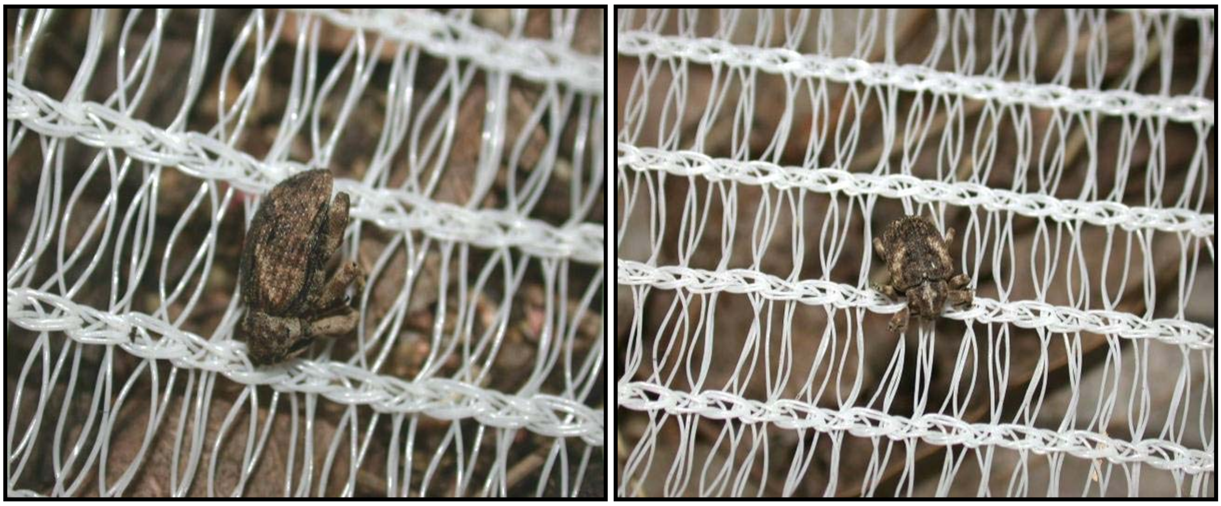

Fig. 7. Dead (left) and live (right) adult mango seed weevils sampled on white shade cloth placed underneath one data tree per plot to monitor weevil mortalities (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

To monitor the incidence and severity of MSW infestations, 3 fruit per data tree (10 data trees x 5 replications = 150 fruit per treatment) were sampled fortnightly from the time that fruit reached golf ball size, up to the commercial harvest of the cultivar. The first fruit were sampled on 05 October 2006, with the last fruit sampled on 28 December 2006. All the sampled fruit were carefully investigated for MSW eggs, noting the number of eggs per fruit, where-after the fruit were cut open to determine the absence or presence of MSW in the seed. Where seed weevils were present within the seed, distinction was made between the different developmental stages of each individual present within the fruit.

Although the co-incidence of other insect species did not seem to have an influence on seed weevil oviposition, measures aimed at controlling the MSW do influence the incidence and severity of some other insect pests, most notably mango scale and mealybug, by eradicating the parasitoids that keep their numbers in check (De Villiers, 1989; Joubert & Labuschagne, 1995). Therefore, since an indirect association between MSW and certain other insect pests can exist on account of certain control strategies, mango scale and mealybug infestations were also noted during the study.

7.2.5. Effect of different application times of thiamethoxam on mango seed weevil

To determine an efficacy curve for the various thiamethoxam treatments / application times, specifically to determine the effect of an early application on development from eggs laid late in the season, and the effect of a late application on development from eggs laid early in the mango growing season, oviposition needed to occur at specific times and / or intervals. This was obtained in the 2006 / 2007 mango growing season with bagging, i.e. the artificial introduction of captive, gravid adult weevils via gauze bags to ensure oviposition. Block G94, cv. 'Keitt', on the farm Grovedale in the Hoedspruit magisterial district was used, since this orchard was reputed to be MSW free in the preceding season. Data fruit were, however, carefully inspected for MSW eggs prior bagging to ensure that enclosed fruit contained no previously laid eggs.

The trial was laid out as a completely randomized block design, with 4 treatments and 3 replications. Each trial plot consisted of 3 rows containing 7 trees each. The first and last tree of every row in a plot was left as buffer trees. Within the same row, trial plots were separated by more than ten untreated trees, with an untreated buffer row separating adjacent plots between rows. The treatment list and application dates are summarized in Table 4.

Table 4. The treatment list and application dates for the study investigating the effect of thiamethoxam, applied at various times throughout the season, for mango seed weevil control (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

No.	Treatment	Product rate	Description	Application date
1	Untreated control	-	-	-
2	thiamethoxam	6ml / tree	mid August	16 August (week 33)
3	thiamethoxam	6ml / tree	mid September	19 September (week 38)
4	thiamethoxam	6ml / tree	mid October	16 October (week 42)

Thiamethoxam was applied as a soil drench directly in the irrigation zone. Since the orchard contained an established dripper irrigation system, the product was applied directly into a small hollow dug underneath each dripper prior to application. With each tree containing 2 drippers, 3ml product was applied per irrigation dripper. Applications were done using a 250ml measuring jug, with the product properly dissolved in water prior to application. The product was applied after irrigation to ensure that the soil moisture was sufficient to enhance product uptake.

In each trial plot, between 4 and 5 bags were used to enclose data fruit. Each bag, containing 6 adult weevils (of equal sex ratio), an untreated mango flush for shelter and an untreated slice of mango fruit for feeding, was tied around a cluster of fruit. The bags were removed after 2 - 3 days to ensure sufficient oviposition to guarantee infestation. After removing the bags from a specific fruit cluster, the bags were moved to another fruit cluster in the same trial plot. This was done in order to ensure a sufficient number of egg infested fruit for specific time periods, with each time period representing a week-long interval in the time frame that MSW oviposition occurred, from the onset to cessation of egg laying.

Although the first MSW eggs in the 2006 / 2007 season were already reported on 19 September 2006 in another orchard by a production scout, bagging only commenced on 03 October 2006 (week 40) to reduce the effect of natural fruit weaning of marked fruit. After removal of the bags, egg infested fruit were tagged with flagging tape, and the fruit were marked with a number corresponding to the bagging date and the fruit number. The number of eggs on each fruit was noted.

Marked fruit from specific time sequences (weekly intervals) were evaluated about 4 weeks after induced oviposition to reduce chances of natural egg laying, but with weevil development sufficiently progressed for easy identification of infested fruit. Distinction was made between infested and non-infested fruit, calculating the percentage of infested fruit for each of the treatments and for each of the time sequences.

The data obtained were not statistically analyzed, but plotted graphically to determine infestation levels for at the time of each assessment. Firstly the intensity and duration of weevil oviposition over time (average number of eggs per treatment for each time sequence over time) was plotted in order to establish whether oviposition between treatments was comparative. Secondly the efficacy curve for each of the thiamethoxam treatments (the percentage infested fruit obtained for each week or induction period per treatment over time) was plotted over time and compared to the untreated check.

Another aspect of the study, in investigating the efficacy of thiamethoxam applied at different times in the season, was to determine the measure of control obtained with naturally occurring MSW infestations. Since natural MSW oviposition was found in Block G94 in the 2006 / 2007 mango growing season, the same trial plots as for the induced oviposition was used. This entailed sampling 50 fruit per plot (150 fruit per treatment) on two separate occasions, just prior to harvest (8 February 2007), and again at the time of the commercial harvest (22 February 2007).

In the 2007 / 2008 season, an adjacent orchard, Block G91 (cv. ‘Keitt’), with reputed high levels of MSW infestation in the preceding year, was used. The trial design was again taken as a completely randomized block design, but with 5 treatments and 4 replications, with a mid July application included in the study. Trial plots consisted of 3 rows of 10 trees each, with the first and last trees in a row used as buffer trees. Within the same row, plots were separated by ten untreated trees, with an untreated buffer row separating adjacent plots between rows.

The late-season cultivar, ‘Keitt’, was again chosen based on the fact that the fruit remained on the tree up until the middle of February, and even up to the middle of March depending on the season. This ensured a maximum time-lapse between the onset of MSW oviposition and fruit harvest. Using a late-season cultivar also ensured high incidences of mango scale and mealybug, since both these insect pests, known to attack mango fruit towards the end of the growing season, are more pronounced on late- than early-season cultivars.

In the 2006 / 2007 season, mango scale (Fig. 8) and mealybug (Figs. 9 - 11) incidences were recorded as present or absent, with the severity of infestations rated on a scale of 0 = clean, 1 = low infestation levels, 2 = moderate infestation and 3 = severe infestation. Mango seed weevil was noted as absent or present within the seeds (Fig. 12).

In the 2007 / 2008 mango growing season, 60 fruit per replication (240 fruit per treatment) was sampled on 24 January 2008. On 13 March 2008, just prior to the commercial harvesting date for the cultivar, a total of 150 fruit per replication (600 fruit per treatment) was sampled. The sampled fruit were evaluated the same as in the previous season, noting the incidence and severity of mango scale and mealybug infestations prior to slicing the fruit to determine MSW infestation levels. However, with high incidences of thrips (various species) found at the beginning of the season during flowering and fruit set, the incidence and severity of thrip damage was also noted in the 2007 / 2008 season (Fig. 13).

At the end of the respective seasons, the data obtained was processed and statistically analyzed. A One-way Analysis of Variance, with Tukey's HSD test at 95% confidence levels (Statistica Version 6), was used.

Fig. 8. Mango scale infestation on a fruit classified as severe (Rating 3).

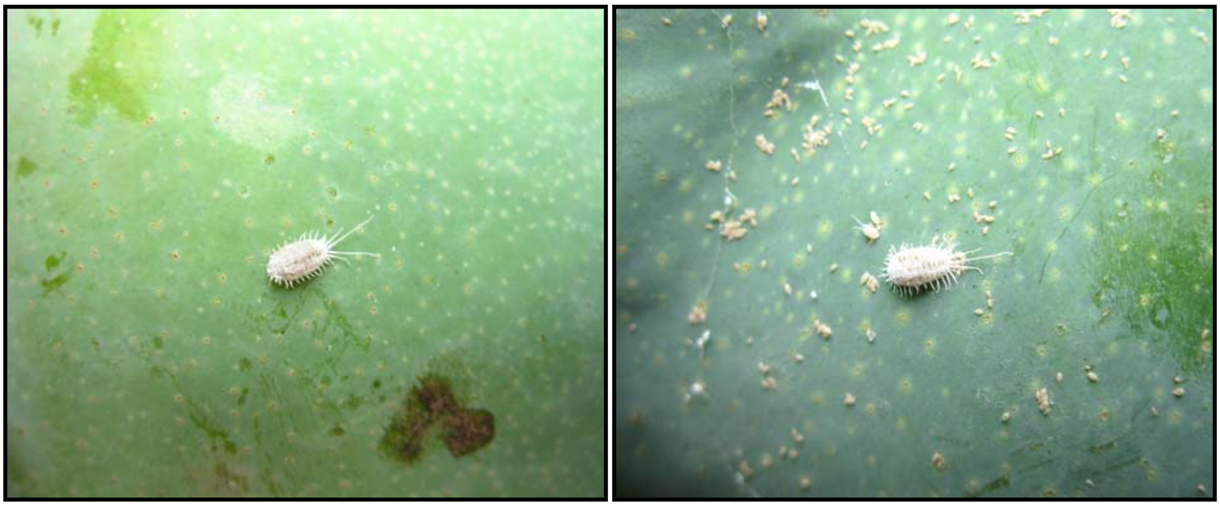

Fig. 9. Mango fruit bearing a mealybug female (left) and a female with crawlers (right) (Rating 1).

Fig. 10. Mango fruit with mealybug infestations constituting a Rating 2 (mild infestation).

Fig. 11. Mango fruit with mealybug infestations constituting a Rating 3 (severe to excessive infestation).

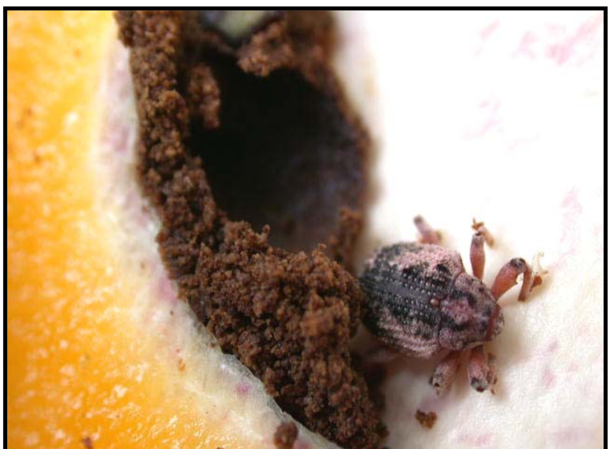

Fig. 12 A mango seed weevil infested mango fruit.

Fig. 13. Mature mango fruit with severe thrips feeding damage.

7.3. Results, Conclusion & General observations

7.3.1. Efficacy of thiamethoxam for mango seed weevil control

In Block G81, cv. 'Keitt', despite following the same procedures during bagging, and using the same number of randomly selected weevils in each bag, the untreated control fruit had significantly more weevil eggs than the thiamethoxam treated fruit ($F_{(2, 196)} = 27.553$, $p = 0.0000$) (Fig. 14). Although untreated foliage and fruit were provided in all the bags used for the adult weevils to use as shelter and food, it could have been that some adults fed on treated data fruit, with a consequent influence on fecundity and reproduction.

In another trial situated on the farm Jonkmanspruit (cv. 'Tommy Atkins'), data fruit from the respective trial plots were also bagged to induce oviposition, but foliage and fruit were collected from the same trees as where bagging occurred. For this trial, a high number of mortalities were noted in the bags containing thiamethoxam treated foliage and fruit, indicating that the chemical had an indirect effect on MSW adults (personal observations, 2004 / 2005 mango season).

In Block G81 (cv. 'Keitt'), the study conducted by WTS, both application rates of thiamethoxam rendered 100% MSW control (Fig. 15). This trial, together with trials conducted by Syngenta SA (Pty.) Ltd., yielded such good results that product registration was obtained in the 2005 / 2006 mango growing season (the trial in Block G81 formed part of a whole study investigating the efficacy of thiamethoxam for MSW control for registration purposes). The statistically analyzed results obtained from the fruit sampled in Block G81, Grovedale (cv. 'Keitt') is summarized in Table 5.

The excellent results obtained from the trial conducted WTS in Block G81, where 100% MSW control was achieved, compared to the results obtained by Syngenta on the farms Jonkmanspruit and Banareng (data available from Syngenta South Africa (Pty.) Ltd.), were probably due to the fact that this trial was conducted in an orchard with a permanent dripper irrigation system, with the product applied directly underneath the dripper in the concentrated root zone. The trial plots used by Syngenta contained either sprinkler systems, or production was normally conducted under dry-land conditions. Since only between 80% - 90% control of MSW was achieved with the trials conducted by Syngenta, it seemed evident that the efficacy of the product was very dependent on the efficacy of water uptake and distribution within the tree.

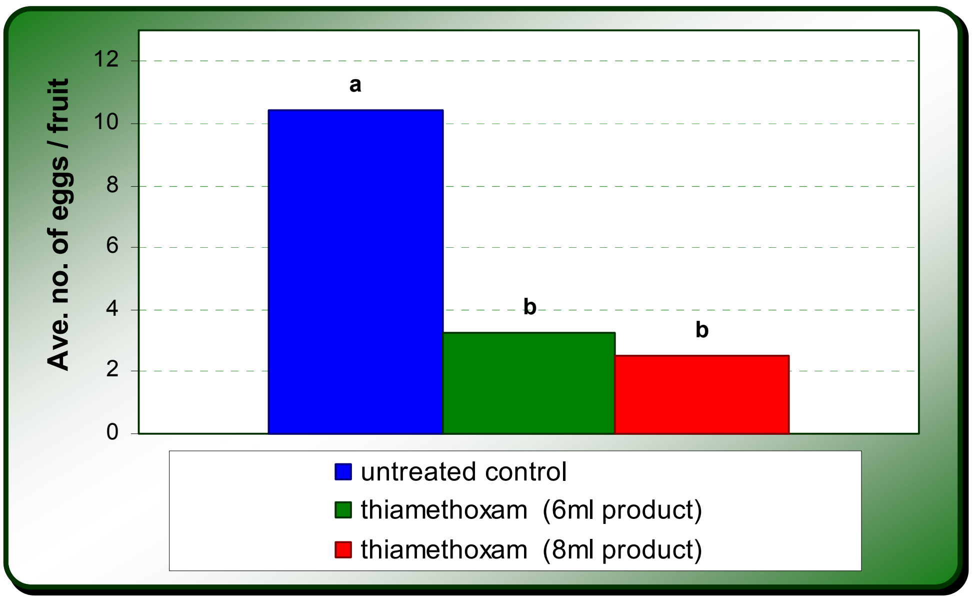

Fig. 14. Average number of eggs on thiamethoxam treated fruit at dosage rates of 6ml and 8ml respectively, compared to untreated fruit (cv. 'Keitt', Block G81,

Grovedale), 2004 / 2005.

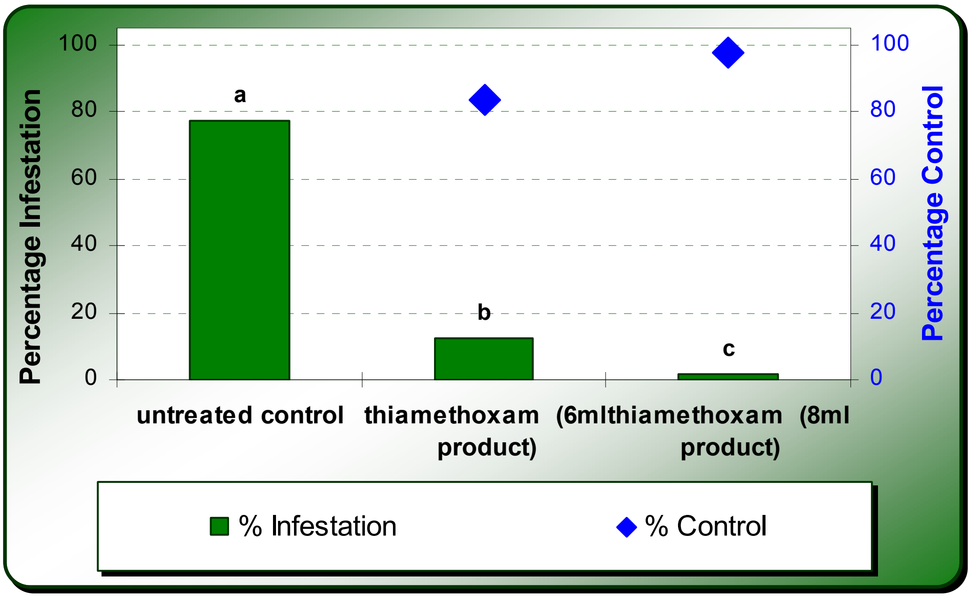

Fig. 15. Mango seed weevil infestation levels, indicated by the green bars, in mango fruit from Block G81, Grovedale. The percentage control, calculated with Abbott's formula, is indicated by the blue dots on the second Y-axis. Bars with the same letters did not differ significantly (F (2,196) = 304.9, p = 0.0000).

Table 5 Mango seed weevil occurrence and the incidence of weevil eggs on fruit where oviposition was artificially induced by enclosing gravid weevils around fruit clusters, cv. 'Keitt' (block G81, Grovedale).

No .	**Treatment**	**No of fruit retained**	**Mean % of retained fruit with eggs**	**Average number of eggs / fruit**	**Mean % of retained fruit with weevil**	**Average number of weevils / fruit**
1.	Untreated	60	98.33	10.417 **b**	81.67	1.917 **b**
2.	Actara 6ml	72	48.61	3.250 **a**	0	0.000 **a**
3.	Actara 8ml	67	65.67	2.493 **a**	0	0.000 **a**

F (2, 196) p			27.553 0.0000		102.93 0.0000

Statistical analysis conducted with a One-way Anova with Duncan's multiple range test at 95% confidence levels, with different symbols depict statistical differences.

Statistical analysis done separately for the average number of weevils and the average number of eggs.

7.3.2. Effect of thiamethoxam on mango seed weevil adults feeding

The results obtained, when exposing adult seed weevils to thiamethoxam treated flushes and fruit and noting activity, mortality and oviposition on a daily basis, are summarized in Table 6. Weevil activity, expressed as the average number of active MSW adults among the feeding substrates or moving around in the containers, were significantly lower in containers with thiamethoxam treated fruit and flushes. Weevil mortalities in containers containing thiamethoxam treated fruit were significantly higher than in containers containing untreated fruit. Feeding occurred readily on the fruit that were sliced (treated and untreated) to expose the inner pulp. A significantly higher number of eggs were laid on the untreated whole fruit than on thiamethoxam treated whole fruit. No statistically significant differences were found between weevil mortalities when the weevils were feeding on flushes only. This was probably due to the fact that the foliage was relatively old and hardened, deterring MSW adults from feeding, since weevils preferred to feed on young, succulent flushes (Chapter 3; 3.3.1. Adult seed weevil feeding preferences for mango). Minimal feeding damage was noted on the flushes, either on the stems, petioles or lamina of the leaves.

Table 6. Mango seed weevil activity (expressed as the average number of adults noted to be active), mortality and oviposition for adult weevils exposed to thiamethoxam treated mango substances. Differences are expressed as the value per day, averaged for the whole monitoring period.

	Activity (%)		**Mortality (Average number)**		**Egg laying (Average number)**
	Fruit	**Flush**	**Fruit**	**Flush**	**Fruit**
Actara 6ml	21.79 **a**	23.93 **a**	1.71 **b**	1.54 **a**	0.86 **a**

Untreated	36.78 **b**	47.14 **b**	0.54 **a**	1.54 **a**	5.54 **b**
F (1, 54) *	6.798	15.646	7.9147	0.0000	13.363
p*	0.01177	0.00022	0.00682	1.0000	0.00058
MS*	3150	7545	19.45	0	306.4

* Statistical analysis conducted with a One-way Anova at 95% confidence levels. Values with the same denomination did not differ statistically (Tukey's HSD test)

These results indicate that thiamethoxam did have an indirect effect on MSW adults feeding on thiamethoxam treated mango substances. Although thiamethoxam did not immediately kill the adult weevils, general movement of the weevils in these containers did become erratic. Activity and feeding was greatly reduced, since the MSW adults became lethargic and movement became uncoordinated. This reduction in the fecundity and reproductive behavior of the MSW adults probably contributed to the subsequent reduction in egg laying.

7.3.3. Effect of fipronil and fenthion on mango seed weevil adults feeding

Table 7 summarizes the observations that were made when exposing MSW adults to mango fruit and flushes treated with fenthion and fipronil at either the registered dosage for fenthion (100ml / 100ℓ water), or double this dosage. Adult weevils were treated with double the registered dosage and then placed a distance away from the untreated fruits and flushes. Indirect contact, i.e. through feeding, of untreated MSW adults with fenthion at the registered dosage of 100ml product / 100ℓ water, resulted in 100% mortalities within a day. Feeding damage observed on the flushes, and feeding scars present on the whole mango fruit indicated that the weevils ingested some of the chemical before mortality set in. No eggs were laid, indicating that mortalities occurred prior to mating and oviposition. Indirect contact with fenthion at double the registered dosage (200ml product / 100ℓ water) resulted in 100% mortality within a day. Less feeding occurred on the mango substances than when treated at 100ml / 100ℓ water, indicating that the higher concentration was more lethal. Despite this, 2 eggs were laid on the surface of the treated fruit prior to death.

Adult weevils treated with fenthion at double the registered dosage (direct contact) resulted in 4 out of 5 weevils dying Day 1 after treatment, with the fifth weevil already affected by the chemical, as witnessed by its erratic movement. This weevil died on

Day 2. Prior to death, some feeding did occur on the mango foliage, and this, together with the fact that one weevil died only on Day 2 after application, indicated that death was not instantaneous.

When treating either fruit or flushes with fipronil at either dosage rate, or treating MSW adults at 200ml / 100ℓ water, 100% mortality was obtained within one day. Very little feeding and no eggs were observed. This, together with the fact that 4 out of 5 adult weevils died soon after being treated with fipronil, indicated that fipronil at these dosages were slightly more effective than fenthion.

Table 7. Effect of fenthion (Lebaycid®), at the registered dosage rate and double the registered dosage rate, and fipronil (Regent®), at comparative dosage rates, on captive adult mango seed weevil activity and mortality.

Date / Time[1]	Container	Treatment[2] (product / 100ℓ water)	Observation[3]
03.11.06 16h00	1[4]	fenthion @ 100ml fruit + flushes treated	All adult weevils alive and relatively active
	2[4]	fenthion @ 200ml fruit + flushes treated	3 adults active (moving around), 1 disorientated, **1 dead**
	3[5]	fenthion @ 200ml weevils treated	All adult weevils alive, 3 adults active, 1 among flush, 1 on fruit
	4[4]	fipronil @ 100ml fruit + flushes treated	All adult weevils alive on soil surface, some active
	5[4]	fipronil @ 200ml fruit + flushes treated	All adult weevils alive on soil surface, some active
	6[5]	fipronil @ 200ml weevils treated	1 weevil inactive on soil surface, **4 dead**

Date / Time[1]	Container	Treatment[2] (product / 100ℓ water)	Observation[3]
04.11.06 10h00	1[4]	fenthion @ 100ml fruit + flushes treated	**All dead**, relative feeding on flush, some feeding marks on fruit
	2[4]	fenthion @ 200ml fruit + flushes treated	**All dead**, little feeding on fruit, little feeding on flush, **2 eggs**
	3[5]	fenthion @ 200ml weevils treated	**4 dead**, 1 disorientated, no feeding on fruit, relative feeding on flush
	4[4]	fipronil @ 100ml fruit + flushes treated	**All dead**, 1 puncture on flush (stem) and 1 puncture on fruit
	5[4]	fipronil @ 200ml fruit + flushes treated	**All dead**, 1 puncture on flush (stem) and 1 puncture on fruit

	6[5]	fipronil @ 200ml weevils treated	**All dead**, no feeding

[1] Date and time of observations (assessments) after treatment

[2] Treatments done on 03.11.2006 at 13h30

[3] Untreated / treated weevils placed a distance from treated / untreated fruit and flushes

[4] Indirect contact (treating substances)

[5] Direct contact (treating adult weevils)

Table 8 summarizes the observations made when exposing adult weevils to mango substances treated with either the registered dosage, or half the registered dosage (50ml / 100ℓ) for fenthion. Observations were made on activity and feeding, while weevil mortalities and the number of eggs was noted with each assessment. Adult weevils were treated at the registered dosage of fenthion for MSW control, 100ml / 100ℓ water. With mango flushes and fruit treated with fenthion at 50ml product / 100ℓ water, and untreated MSW adults placed a distance from these treated substances, only 4 out of the 5 weevils placed died within Day 1 after application. The other weevil died on Day 2. Since feeding damage was encountered on the flush, this indicated that some of the chemical had to be consumed before mortality set in. Three eggs were recorded on the fruit skin of the treated fruit, indicating that mating and oviposition had occurred prior to death. When mango flushes and fruit were treated with fenthion at the registered dosage, less feeding was recorded, again indicating that the higher concentration was more effective. These results were comparative to that found with the previous experiment.

When treating MSW adults with the registered dosage of fenthion and placing the weevils a distance from untreated mango flushes and fruit, it was recorded that less feeding occurred, with all the weevils found dead on Day 1after treatment, than was recorded when treating the weevils at double this dosage. This may indicate that the registered dosage of 100ml / 100ℓ is the effective lethal dosage, with higher dosages not enhancing efficacy. As with the previous study, the fact that some feeding had taken place indicated that death was not instantaneous.

When treating fruit and flushes with fipronil at 50ml / 100ℓ water and placing untreated MSW adults a distance from the treated substances, 100% mortalities were again obtained within Day 1 after application. However, contrary to what was found with the higher dosage of 100ml / 100ℓ water, more feeding took place and 5 eggs were laid prior to death. When treating MSW adults with fipronil at 100ml product / 100ℓ water and placing the weevils a distance from untreated fruit and flushes, mortalities only occurred on Day 2. Only 4 weevils died and the remaining weevil remained alive and active up to Day 7 after treatment. Prominent feeding damage was observed on the foliage, with 21 eggs laid prior to death, indicating that direct contact with fipronil at this dosage was less effective than at the higher dosage of 100ml / 100ℓ water.

Table 8. Effect of fenthion (Lebaycid®), at the registered dosage rate and half the registered dosage rate, and fipronil (Regent®), at comparative dosage rates, on captive adult mango seed weevil activity and mortality.

Date / Time[1]	**Container**	**Treatment[2] (product / 100ℓ water)**	**Observation[3]**
07.11.06 16h00	**1[4]**	fenthion @ 50ml fruit + flushes treated	2 adult weevils inactive under foliage, 2 active, 1 among flush
	2[4]	fenthion @ 100ml fruit + flushes treated	2 adult weevils inactive under foliage, 3 active (2 among foliage)
	3[4]	fenthion @ 100ml weevils treated	4 adult weevils inactive and single under foliage, 1 very active
	4[5]	fipronil @ 50ml fruit + flushes treated	All adult weevils inactive under foliage
	5[4]	fipronil @ 100ml fruit + flushes treated	3 adult weevils inactive under foliage, 2 active and among flush
	6[5]	fipronil @ 100ml weevils treated	All adult weevils inactive under foliage

Date / Time[1]	**Container**	**Treatment[2] (product / 100ℓ water)**	**Observation[3]**
08.11.06 09h00	**1[4]**	fenthion @ 50ml fruit + flushes treated	**4 weevils dead**, 1 very active, **3 eggs**, relative feeding marks on flushes, fruit clean
	2[4]	fenthion @ 100ml fruit + flushes treated	**All weevils dead**, some feeding marks on stems of flushes, **2 eggs**, fruit clean
	3[4]	fenthion @ 100ml weevils treated	**All weevils dead**, 1 feeding / penetration mark on main stem of a flush, fruit clean
	4[5]	fipronil @ 50ml fruit + flushes treated	**All weevils dead**, some feeding marks on stem of a flush and along main vein of lamina, **5 eggs**
	5[4]	fipronil @ 100ml product / 100ℓ, fruit + flushes treated	**All weevils dead**, some feeding marks along main vein, some penetration marks on stem
	6[5]	fipronil @ 100ml weevils treated	All weevils alive but movement disorientated, many feeding scars on flushes, **21 eggs**

1 Date and time of observations (assessments) after treatment

2 Treatments done on 07.11.2006 at 13h30

3 Untreated / treated weevils placed a distance from treated / untreated fruit and flushes

4 Indirect contact (treating substances)

[5] Direct contact (treating adult weevils)

From these results it seemed evident that both products effectively controlled MSW, either through direct contact (treating the weevils), or when adult weevils were feeding on treated substances (indirect contact). The knock-down effect, however, was more prominent with the higher dosages.

7.3.4. Efficacy of various insecticides for mango seed weevil control

Figures 16 and 17 respectively summarize percentage egg infested and percentage weevil infested fruit. Figure 18 graphically depicts the total number of MSW adults, irrespective whether the weevils were alive or dead, collected under treated trees.

Since fenthion was applied on 31 October 2006, a time corresponding to peak oviposition found in another orchard on the organic farm, Moriah (Chapter 4; Fig. 17), and more than 1 month after the first MSW eggs were recorded (Chapter 4; 4.3.4. Oviposition in the field), ineffective MSW control was obtained. Since oviposition (Fig. 16) was comparative to that found for untreated fruit, this indicated that fenthion, at this late stage, did not affect MSW adults sufficiently to reduce oviposition. Since the percentage of infested seeds (Fig. 17) was also comparative to the untreated control, this indicated that fenthion had no effect on the MSW larvae present within the seeds at the time of application.

Fenvalerate initially reduced egg laying and thereby the number of weevil infested fruit. However, control did not extend for the duration of the season. The initial application was probably applied too early in the season, with the product not effectively making contact with hibernating weevils and, with the MSW adults were not feeding at this early stage in the season, the indirect effect of the product would also have been minimal. The second application of fenvalerate coincided with the fipronil application but, contrary to the fipronil application, weevil infestation in the fruit were not reduced to the same extent, despite the fact that slightly more dead weevils were found on the nets under trees treated with fenvalerate (Fig. 18). The reason for this probably being that fenvalerate did not have the same residual action as fipronil.

Fipronil, applied slightly later than the stipulated specifications for thrips control, when the majority of fruit were already golf boll size, effectively reduced the incidence of MSW in the fruit (Fig. 17), probably since oviposition in these plots was considerably reduced (Fig. 16). The incidence of reduced oviposition was probably due to weevil mortalities, even though few dead weevils were observed on the nets under the data trees (Fig. 18). The low incidence of dead weevils could be attributed to strong winds removing the dead weevils from the nets before evaluations could be conducted.

For the duration of the study, fruit from thiamethoxam treated trees, irrespective of the date of application, yielded the best results (Fig. 17). The fact that some eggs were found on fruit from thiamethoxam treated trees indicated that adult mortalities did not occur instantaneously (Fig. 16). The fact that fewer eggs were found on fruit from thiamethoxam treated trees indicated that the chemical did have an effect on the MSW adult. This was confirmed by the presence of MSW adults on the nets placed underneath 1 tree per plot. The MSW adults that were found under thiamethoxam treated trees were not dead, but the lethargic and uncoordinated movements of the weevils did indicate that the chemical had an effect. This effect was also observed under artificial conditions (Chapter 7; 7.3.2. Effect of thiamethoxam on mango seed weevil adults feeding). These weevils eventually died. The majority of weevils were found on nets placed underneath trees treated with thiamethoxam (Fig. 18). The fact that very low incidences of MSW infestations were recorded, irrespective of the fact that some fruit did have eggs on the fruit skin, indicated that thiamethoxam effectively prevented larval development.

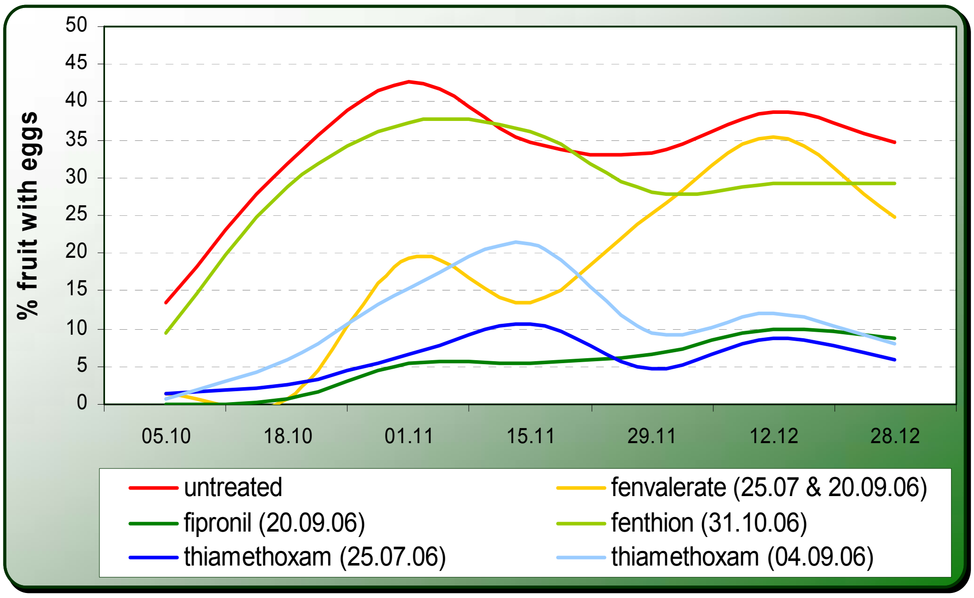

Fig. 16. Percentage of mango seed weevil egg infested fruit for each of the

treatments against different assessment dates (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

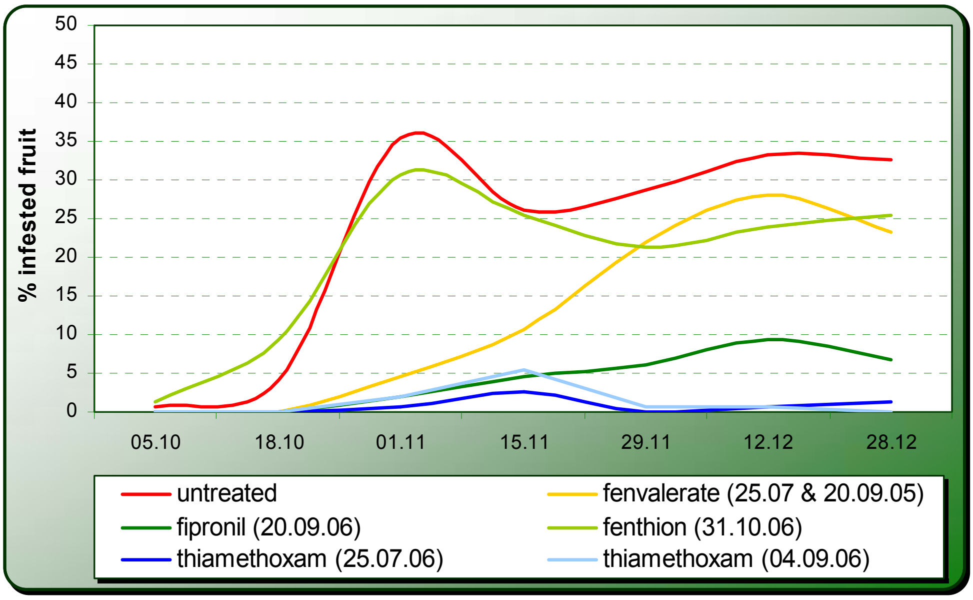

Fig. 17. Percentage mango seed weevil infested fruit for each of the treatments against different assessment dates (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

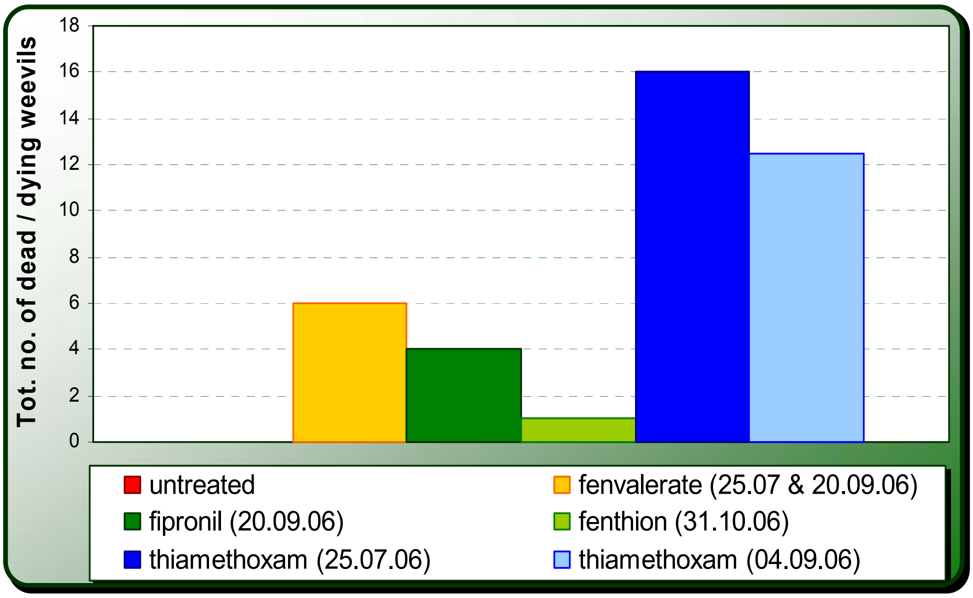

Fig. 18. Total number of dead and / or dying mango seed weevils recorded under one data tree per plot (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

No mealybug was recorded in the trial orchard, but mango scale infestations started to increase steadily just prior to the commercial harvest. Figure 19 graphically depicts the percentage of fruit with mango scale, for each of the treatments and for each assessment date, for the duration of the study. The only insecticide leading to an increase of scale, with more scale insects found on treated fruit than on untreated control fruit, was fipronil. Both treatments of thiamethoxam resulted in scale infestation levels noticeably lower than that for the untreated control fruit.

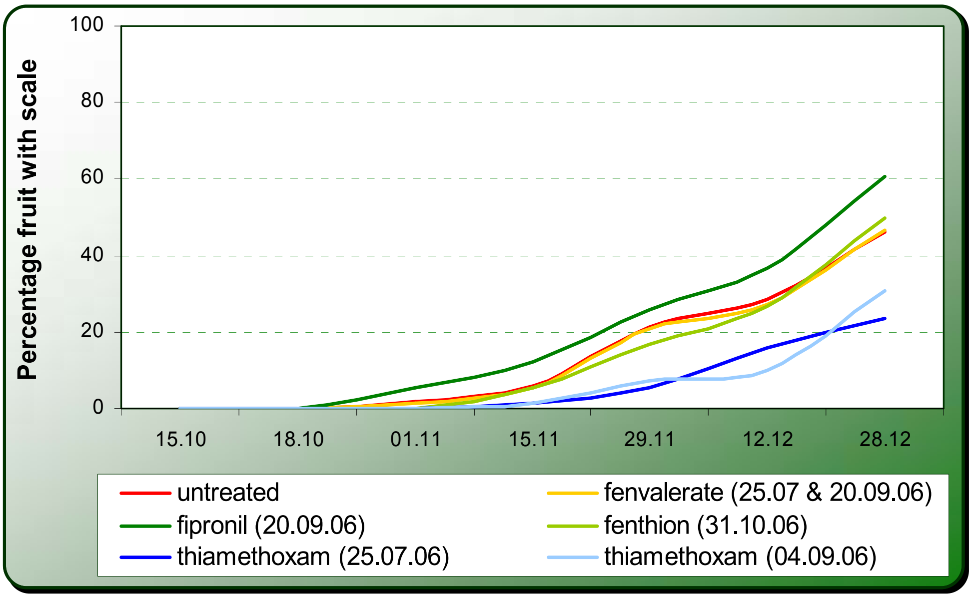

Fig. 19. Percentage fruit with mango scale (cv. 'Tommy Atkins', Block GD6, Bavaria Fruit Estates), 2006 / 2007.

7.3.5. Effect of different application times of thiamethoxam on mango seed weevil

In the 2006 / 2007 mango growing season, the number of induced MSW eggs on each of the data fruit, for each time sequence or induction period, which lasted one week, was noted when removing the bags to subsequent fruit clusters. The severity or intensity of MSW oviposition, for each of the treatments, was expressed as the average number of eggs per egg infested fruit for each time sequence or induction period. The intensity and duration of MSW oviposition for each treatment is graphically presented in Fig. 20.

The average number of eggs per treatment, for most of the trial period, was comparative between the different treatments, making comparisons between the treatments regarding infestation levels possible. For the majority of the induction periods the untreated control fruit contained only slightly more eggs than thiamethoxam treated fruit. Both the foliage and fruit that was placed inside the bags to provide shelter and a feeding medium was collected from chemically untreated mango trees.

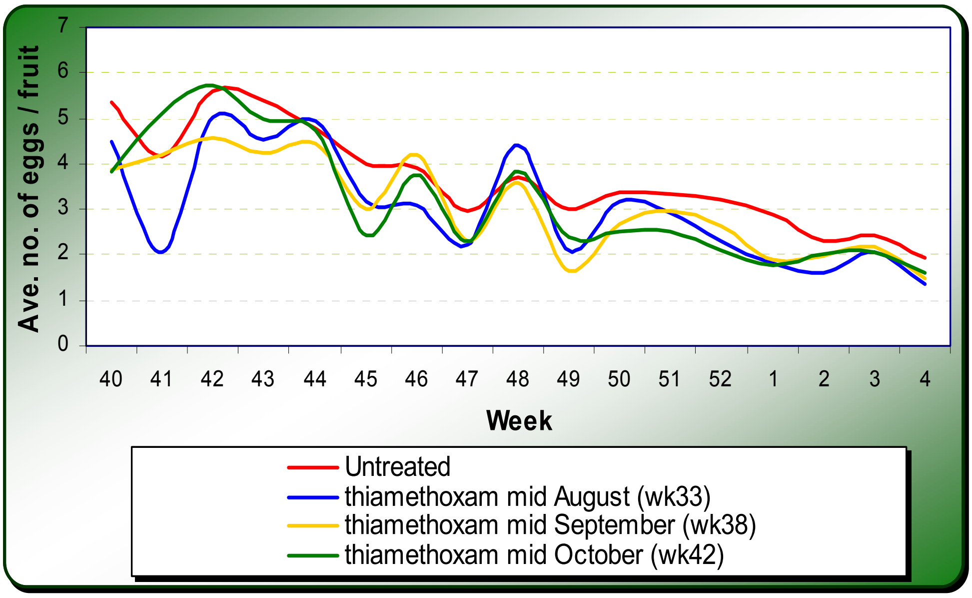

Fig. 20. Intensity (average number of mango seed weevil eggs per induction period) and duration of artificially induced oviposition via bagging (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

Figure 21 graphically depicts the efficacy curve, expressed as the percentage of weevil infested fruit over time, for each of the thiamethoxam treatments, compared to the infestation levels of untreated fruit.

Induced MSW infestation levels in fruit from trees treated with thiamethoxam during either mid August or mid September were comparative throughout the trial period, and remained low from the onset of oviposition up to the time that the last eggs were laid. The fact that only egg infested fruit were evaluated to guarantee fruit infestations, with induction occurring up to the end of January 2007, indicated that either a mid August, or a mid September application of thiamethoxam effectively controlled the mango seed weevil larvae from the onset of oviposition up to the time that the last eggs were laid.

Weevil infestation levels in fruit treated with thiamethoxam during mid October were initially high, indicating the time frame where egg laying was induced (weeks 40 to 42), but with the mango trees in these plots yet untreated. Infestation levels from this treatment were comparative to the other two thiamethoxam treatments at about 3 weeks after application (week 45), and remained low up to the end of the oviposition period.

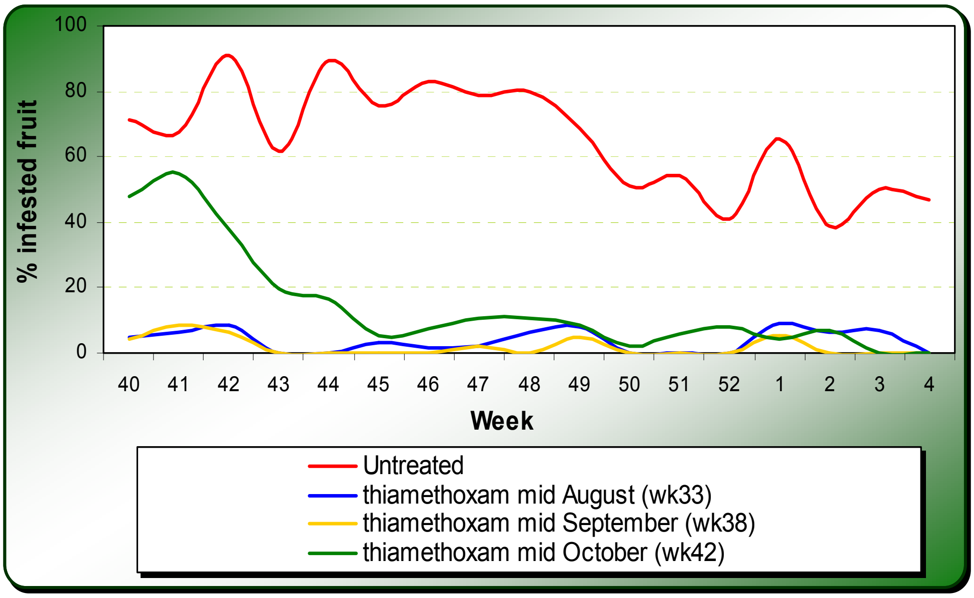

Fig. 21. Percentage of mango seed weevil infested fruit obtained after enclosing fruit clusters with captive MSW adults to induce oviposition (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007. Only egg infested fruit were used as data fruit.

The results from the statistical analysis, calculated for the percentage control obtained with each of the thiamethoxam treatments, i.e. thiamethoxam applied at various time throughout the mango growing season, is summarized in Table 9. For each of the treatments, the percentage infested MSW infested fruit was calculated as the total number of MSW infested fruit, divided by the total number of fruit evaluated and multiplied by 100. From these values the percentage MSW control that was obtained with each of the thiamethoxam treatments was calculated using Abbott's formula:

$$\left(\frac{Value_{Control} - . \ Value_{Treatment}}{Value_{Control}}\right) \times 100.$$

Variations in the percentage control between consecutive evaluations could probably be attributed to ineffective product uptake by different data trees, or by different fruit from the same tree. LeLagadec (2005b) found that the efficacy of the product depended greatly on the efficacy of uptake and this, in turn, depended on the efficacy of the irrigation system. It may also be due to inherent experimental variations due to the sample size.

Table 9. Percentage mango seed weevil control obtained with thiamethoxam (6ml product applied as a soil drench in the irrigation zone) applied at different throughout the mango growing season (cv. 'Keitt', Block G94, Grovedale), 2006 / 2007.

	Induction period (week):																
Treatment:	**40[1]**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**1**	**2**	**3**	**4**
Mid Aug	94	91	91	100	100	96	98	97	92	88	100	100	100	86	84	86	100
Mid Sept	94	88	93	100	100	100	100	98	100	93	100	100	100	92	100	100	100
Mid Oct	33[2]	19[2]	58[3]	69	82	93	91	87	86	88	96	90	81	94	82	100	100

[1] Week 40 = Onset of bagging

[2] Trees untreated

[3] Mid October application = Week 42 (Application dates for mid August in Week 33 and mid September in Week 38)

With natural MSW infestations recorded in the 2006 / 2007 mango growing season in Block G94, Grovedale, 150 fruit per treatment was sampled and sliced open to determine the incidence of MSW in the seed. Together with MSW incidences, incidences of mango scale and mealybug were recorded to determine the effect of thiamethoxam when applied at various times throughout the mango growing season. Figures 22 - 23 graphically summarize the various pest incidences as recorded on 08 February and 22 February 2007 respectively. For each parameter, pest incidence was expressed as the percentage fruit, of the total number of fruit evaluated, that was infested.

In the 2007 / 2008 season, the incidence of thrips was included to determine the efficacy of thiamethoxam for thrips control, since severe infestations were noted at the beginning of fruit set. Figures 24 - 25 summarize pest incidences in block G91, Grovedale, as evaluated on 24 January and 13 March 2008. For each parameter, pest incidence was expressed as the percentage fruit, of the total number of fruit evaluated, that was infested.

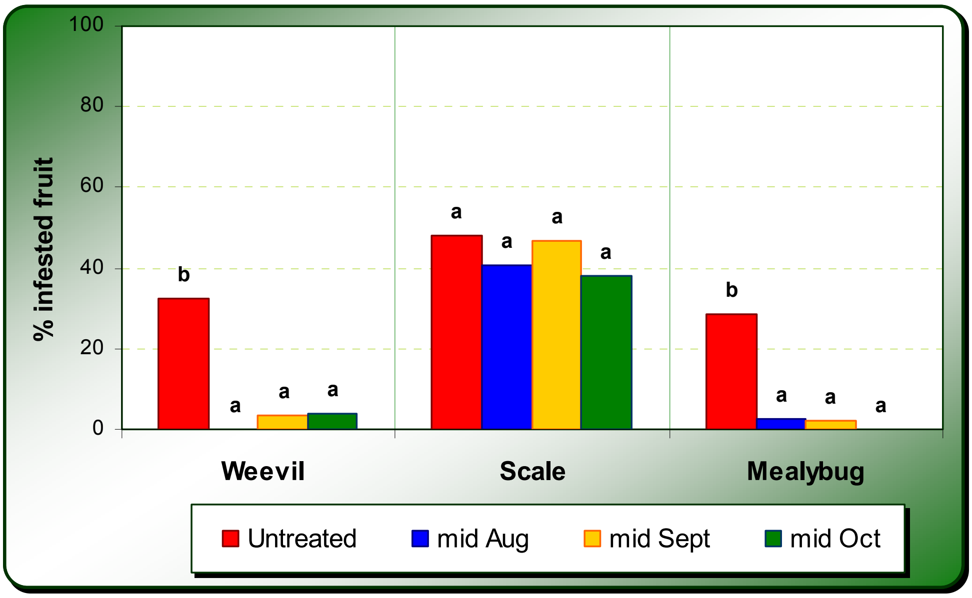

Fig. 22. Natural fruit infestation levels (150 fruit per treatment) for mango seed weevil (F (3, 596) = 47.464, p = 0.000), mango scale (F (3, 596) = 0.837, p = 0.474) and mealybug (F (3, 596) = 32.127, p = 0.000). Assessment date 08 February 2007 (cv. ‘Keitt’, Block G94, Grovedale), 2006 / 2007.

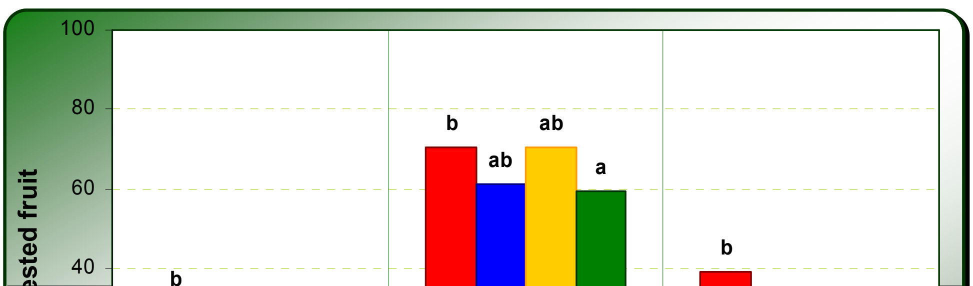

Fig. 23. Natural fruit infestation levels (150 fruit per treatment) for mango seed weevil (F (3, 596) = 36.304, p = 0.000), mango scale (F (3, 596) = 3.636, p = 0.127) and mealybug (F (3, 596) = 23.000, p = 0.000). Assessment date 22 February 2007 (cv. ‘Keitt’, Block G94, Grovedale), 2006 / 2007.

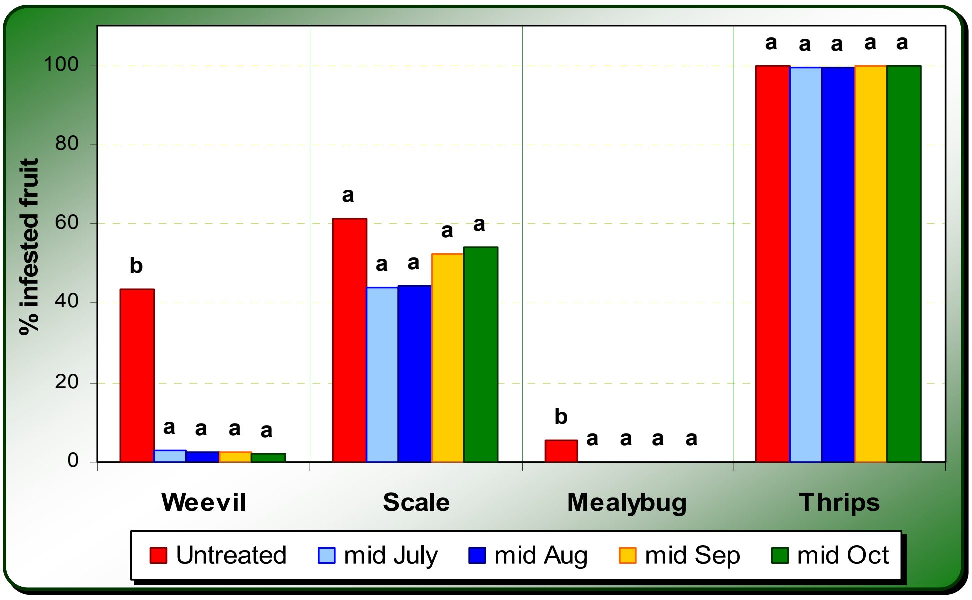

Fig. 24. Natural fruit infestation levels (240 fruit per treatment) for mango seed weevil (F (4, 15) = 15.636, p = 0.000), mango scale (F (4, 15) = 1.715, p = 1.991), mealybug (F (4, 15) = 46.091, p = 0.000) and thrips (F (4, 15) = 0.750, p = 0.573)). Assessment date 24 January 2008 (cv. ‘Keitt’, Block G91, Grovedale), 2007 / 2008.

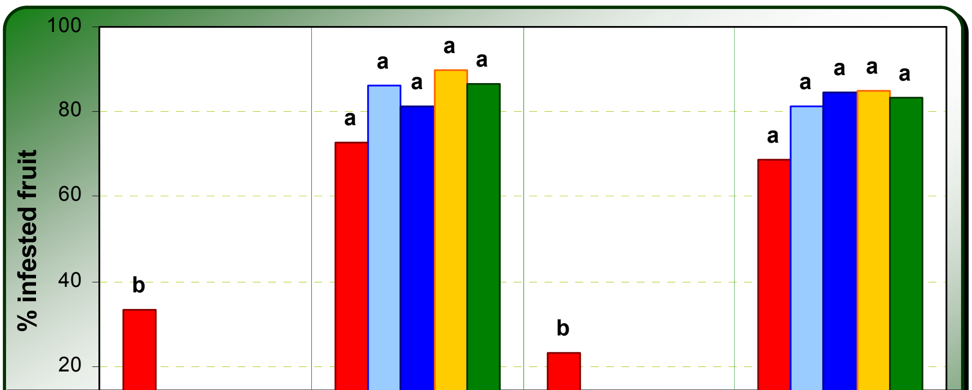

Fig. 25. Natural fruit infestation levels (600 fruit per treatment) for mango seed weevil ($F_{(4, 15)} = 24.502$, $p = 0.000$), mango scale ($F_{(4, 15)} = 1.890$, $p = 0.165$), mealybug ($F_{(4, 15)} = 16.343$, $p = 0.000$) and thrips ($F_{(4, 15)}$ 2.408, $p = 0.094$)). Assessment date 13 March 2008 (cv. 'Keitt', Block G91, Grovedale), 2007 / 2008.

For both assessments, in both the 2006 / 2007 and the 2007 / 2008 mango growing seasons, natural seed weevil infestation levels in fruit from thiamethoxam treated trees were significantly lower than in fruit from the untreated control trees. The timing of application did not have an influence on the efficacy of seasonal control, since no significant differences were found between the thiamethoxam treatments.

For both the assessments, in both the 2006 / 2007 and 2007 / 2008 seasons, thiamethoxam did not significantly reduce scale numbers, with no significant differences between values obtained for fruit from trees treated at different times during the season. This data contradicts the previous results that showed that thiamethoxam noticeably reduced mango scale infestations. This data also contradicts results obtained when investigating thiamethoxam for mango scale and mealybug control (LeLagadec, *et al.*, 2005b).

Thiamethoxam effectively controlled mealybug, with all the treatments differing significantly from the untreated control. The time of application did not have an influence on the efficacy of seasonal control, with no significant differences between the thiamethoxam treatments (various application times).

Thiamethoxam had no impact on thrips, since no significant differences were found between the treatments and the untreated control. The reduction in the percentage of fruit showing thrip damage between the two assessment periods in the 2007 / 2008 season can be attributed to fruit growth, with the severity of fruit damage being reduced as the fruit became larger and matured, making it more difficult to see.

Table 10 provides a summary of the percentage seasonal control that was achieved with each of the treatments, and for each of the assessment periods for both the 2006 / 2007 and 2007 / 2008 mango growing seasons. The percentage control that was obtained with thiamethoxam was calculated according to Abbott's formula.

Table 10. Percentage mango seed weevil, mango scale and mealybug control obtained with thiamethoxam applied at different times during the 2006 / 2007 (Block G94, Grovedale) and 2007 / 2008 seasons (Block G91, Grovedale), cv. 'Keitt'.

Treatment:	Assessment date:	Pest:			
		Mango weevil	**Mango scale**	**Mealybug**	**Thrips**
Thiamethoxam (Mid July)	24.01.2008	93.3	27.9	100.0	0.4
	13.03.2008	97.5	0	96.4	0
thiamethoxam (Mid Aug)	08.02.2007	100.0	15.3	90.7	
	22.02.2007	91.5	13.2	76.3	
	24.01.2008	94.3	27.2	100.0	0.4
	13.03.2008	97.5	0	97.8	0
thiamethoxam (Mid Sept)	08.02.2007	89.8	2.8	93.0	
	22.02.2007	89.4	0.0	83.0	
	24.01.2008	94.3	14.3	100.0	0
	13.03.2008	96.0	0	97.8	0
thiamethoxam (Mid October)	08.02.2007	87.8	20.8	100.0	
	22.02.2007	85.1	16.0	89.8	
	24.01.2008	95.2	11.6	100.0	0
	13.03.2008	98.0	0	97.1	0

The variations in MSW control, as well as the lower values obtained when compared to the registration trial conducted in G81 (Chapter 7; 7.3.1. Efficacy of thiamethoxam for mango seed weevil control), could probably be attributed to insufficient irrigation for some of the data trees, preventing sufficient uptake of the product. This phenomenon would be more prominent in small trial plots consisting of only a couple of trees, since a single data tree with insufficient product uptake will have a noticeable impact on the results obtained. Other studies, making use of larger trial plots, showed better mango seed weevil control (De Graaf, 2008).

The reason why comparative MSW seasonal control was obtained, irrespective of whether thiamethoxam was applied in July, August or September, is most probably due to two aspects. Indirectly the chemical had an effect on MSW adults feeding on treated substances, thereby reducing or eradicating the adult population and, in effect, reducing or preventing oviposition. Directly the chemical had an impact on MSW larvae developing in the seed, with larval mortalities ensuing due to consumption of the chemical while feeding in the seeds.

The notion of the indirect effect of thiamethoxam is supported by the results recorded when exposing captive MSW adults to thiamethoxam treated flushes and fruit in a laboratory study (Chapter 7; 7.3.2. Effect of thiamethoxam on mango seed weevil adults feeding). Observations in the 2006 / 2007 mango growing season, where live adult weevils were collected underneath thiamethoxam treated trees, but with these weevils acting lethargic and exhibiting uncoordinated movement, also support this theory (Chapter 7; 7.3.4. Efficacy of various insecticides for mango seed weevil control).

MSW infestation levels in fruit sampled from trees that were treated during the middle of October, after the bulk of natural oviposition had already taken place, were comparative to those in fruit treated at earlier times in the season. An initial conclusion would tend to favor the effect of fruit weaning to explain the comparative fruit infestation levels, since some eggs were laid prior to chemical treatment, with certain larvae already penetrated into the seed.

However, since fruit infestation levels in fruit sprayed with fenthion during the latter part of October were comparative to that of the untreated fruit (Chapter 7; 7.3.4. Efficacy of various insecticides for mango seed weevil control), this assumption would not hold true. For this reason the only explanation for the comparative fruit infestation levels would be due to the systemic nature of the chemical. The chemical is absorbed by the mango tree roots and translocated via the xylem to the mango seed. The chemical is therefore present within the seed, killing the MSW larvae as they feed.

With fenthion, a semi-penetrant insecticide, the product is sprayed onto the outside of the fruit, with the chemical moving only a short distance into the fruit pulp. Since the chemical is ultimately unable to penetrate into the mango seed, where the majority of MSW larvae reside at this stage in the season, the product would prove ineffective in killing MSW larvae present within the fruit seeds.

7.4. Conclusion

The laboratory study, investigating the effect of fenthion and fipronil on adult seed weevils, yielded very promising results for both products. Both products affected MSW adults through direct (when treating the adult seed weevils) and indirect contact (ingestion of treated food substances), leading to mortalities within a day after treatment. The knock-down effect, when treating their food source, was more pronounced with the higher application dosages.

Fipronil also rendered effective control in the field, but usage of this product lead to secondary pest manifestations. With fipronil also applied outside the registration for thrip control, detectible residue levels may result in fruit rejections. Fenthion did not render very good MSW control in the field, indicating that this product needed to be applied at a time when the first MSW eggs are noted in order to be effective. This, however, may warrant a second application to be applied, which in turn may lead to secondary infestations of mango scale and mealybug.

Fenvalerate rendered good initial MSW control in the field, but the fact that seasonal control was not achieved could the result of the first application applied too early in the season, when the weevils are still hibernating and which effectively rendered this application ineffective. The second application did not have the residual efficacy to control MSW oviposition, and therefore fruit infestations, up to the end of the season. Applying the product at a later stage would mean application outside the registration guidelines, which may in turn lead to detectible residue levels in the fruit at the time of the commercial harvest. Later applications may also increase the incidence of secondary pest out-breaks.

From the results of the various studies investigating chemical control of the MSW, thiamethoxam rendered excellent MSW control, while preventing the manifestation of mealybug as a secondary infestation. Thiamethoxam is also registered for mango scale and mealybug and, although varying results were obtained regarding scale control, this aspect does render this insecticide effective when controlling pest complexes.

Despite exhibiting excellent larval control, thiamethoxam also had an effect on the adult weevils, dislodging them from the trees in which they sheltered, thereby reducing the incidence of oviposition. This effect was also observed in the laboratory study investigating the effect of thiamethoxam on MSW adults feeding on thiamethoxam treated substances. Due to a decline in activity, indicated by lethargic and uncoordinated movements, MSW oviposition declined significantly, with MSW mortalities significantly more when feeding on thiamethoxam treated mango substances than when feeding on untreated substances.

The timing of application of thiamethoxam did not seem to affect the efficacy of thiamethoxam regarding MSW or mealybug control. The date of harvest and the maximum residue levels allowed would probably dictate the latest possible date for application.

The method of application of thiamethoxam, i.e. as a soil drench directly in the irrigation zone, makes this product ideal for integration into integrated pest management programmes, since above-ground parasitoids and predators are not affected. This systemic insecticide is readily taken up by the trees and has a very long residual action. This, together with the fact that thiamethoxam is applied during the flowering period, negates the necessity of fruit inspections to determine the onset or peak of weevil oviposition, and ascertains that no extensive knowledge is required regarding oviposition and weevil development.

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CHAPTER 8

General discussion and conclusion

During investigations on mango seed weevil (MSW) activity patterns, it became apparent that MSW were crepuscular – nocturnal insects, moving about and feeding mainly at dusk. This behaviour impacts on decision-making regarding contact insecticide application for MSW control, with applications applied at dusk logically expected to be more efficacious.

From the various studies conducted investigating MSW feeding preferences, it was evident that the weevils preferred to feed, over and above all other substrates, on young, succulent mango foliage (flushes). They did, however, also readily feed on mango fruit when the fruit was sliced to expose the soft inner fruit pulp. Adult seed weevils were not attracted to alternative substances such as sugar or protein, making these substances obsolete for use as lures in the field. No apparent MSW feeding or oviposition preferences were found for any of the cultivars currently under commercial production in the Hoedspruit magisterial district of the Limpopo Province.

Contrary to literature sources, MSW oviposition commenced during the latter part of September and continued up to the latter part of January. Since oviposition occurs for a period considerably more extended than previously reported, the implication is that a single application with a contact or semi-penetrant insecticide would prove ineffective to render seasonal control. However, with additional applications the impact on the environment becomes more severe, with the danger of exceeding minimum residue levels becoming a greater reality.

The majority of MSW eggs took between 7 and 14 days to hatch, with the larger majority of the miniscule first instar larvae already having penetrated into the seeds within 7 days to 2 weeks after oviposition. The rate of penetration activity depends on whether eggs are laid early or late in the mango growing season. This implies that chemical control with contact and semi-penetrant chemicals, aimed at controlling the MSW larvae, should preferably not commence later than 7 days after observing the first eggs in the orchards. However, with oviposition commencing by the middle of September, and continuing up to January, more than one application would be warranted. With weevil development from eggs laid late in the season slightly more accelerated than from eggs laid early in the season, the first are adults present within the seeds between 6 (eggs laid in December) and 8 weeks (eggs laid in October) after oviposition. The first mature adult weevils in the field were recorded during the latter part of December. Although studies investigating MSW adult emergence under artificial conditions indicated that MSW adults had the ability to emerge within a month after fruit sampling, irrespective of the cultivar, natural adult emergence in the field was only recorded for late-hanging cultivars from February onwards. Since some adults remained inside infested seeds for considerable periods of time before emerging, it is believed that moisture content of the ripening fruit may probably be the trigger for adult emergence in the field. Results and observations in this regard indicate that orchard sanitation should commence during the latter part of December to remove infested seeds and fruit, but also that sanitation practices should be followed more diligently from February onwards, removing the tree-ripening and sanitation fruit immediately for disposal to prevent emerging adults from re-infesting the orchards. However, since MSW do have the ability to continue to develop inside weaned or sanitation fruit, provided that the seeds are intact and that sufficient fruit pulp exists around the seed to prevent desiccation, the most efficacious way to apply sanitation measures would be to constantly remove weaned fruit from of the orchard.

No known biological control measures have proved to be effective in controlling MSW infestations thus far, with MSW control in organic orchards remaining problematic. Sanitation practices are labour intensive and tend to be discarded or poorly managed as the season progresses and more fruit ripen simultaneously. Kaolin does appear to impact on weevil mobility and therefore oviposition, but efficacy of control does depend on the time of application, with earlier applications proving to be more efficacious, than when applied after the onset of oviposition. The application of kaolin for MSW control, however, leads to secondary pest outbreaks of specifically mango scale and mealybug. With climatic conditions in the Hoedspruit area not conducive to the development and growth of organisms such as entomopathogenic nematodes and entomopathogenic fungi such as *Beauveria bassiana*, and with alternative organic products such as neem and garlic not rendering effective control comparative to that of chemical control measures, a solution for mango seed weevil in organic orchards still remains elusive. However, preliminary results with the entomopathogenic fungus, *Beauveria bassiana*, as well as with the product, InsectCover®, which both garlic and neem extracts, resulted in a reduction in MSW infestations. An increase in the number of applications, together with shortened intervals between applications, may improve control, although this may increase costs.

From the laboratory study investigating the direct and indirect impact of fenthion and fipronil on MSW adults, it seemed evident that both products effectively control the insect. Fipronil also rendered effective control in the field, but usage of this product lead to secondary pest manifestations. With fipronil also applied outside the registration for thrip control, detectible residue levels may result in fruit rejections. Fenthion did not render very good MSW control in the field when applied after the onset of MSW oviposition, indicating that this product should be applied the moment the first MSW eggs are sighted in order to be effective. However, when considering the time frame over which MSW oviposition extends, a second application may be warranted, which may increase the incidence of secondary infestations, most noticeably mango scale and mealybug.

Fenvalerate rendered good initial MSW control in the field, but the fact that seasonal control was not achieved indicated that the first application was probably applied too early in the season, when the weevils were still hibernating. Further to this, the second application either did not provide 100% mortality of adult weevils, or did not possess the residual capacity to control MSW oviposition for the duration of oviposition. Applying the product at a later stage would mean application outside the registration guidelines, which may in turn lead to detectible residue levels in the fruit at the time of commercial harvest. Later applications may also increase the incidence of secondary pest out-breaks.

Thiamethoxam rendered effective MSW and mealybug control, while suppressing and / or controlling mango scale. Since this product also meets IPM requirements, a solution for the MSW dilemma in conventional mango orchards in South Africa seems to have been discovered. A full cover foliar application with either fenthion (with the onset of oviposition) or fipronil (during fruit-set when the majority of fruit have reached golf ball size) could further reduce the number of adult weevils present within an orchard or area. With sanitation practices in place, especially from the end of December, when the first adult weevils are present within the seeds, and more specifically from February onwards, when MSW adult emergence occurs naturally in the field, MSW can be eradicated from specific production areas. Weevil-free areas can then be maintained by monitoring possible sources of infestation from adjacent areas, i.e. pack houses, drying units, compost sites and infested orchards or residential areas, in order to prevent adult weevils from re-entering these areas.