Key biotic components of the indigenous Tortricidae and Heteroptera complexes occurring on macadamia in South Africa.

By

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Abstract

In South Africa macadamia nuts are attacked by a variety of mostly indigenous pests which can be divided into two basic complexes, namely a nut borer complex (consisting of 3 tortricid moths.) and a stink bug (Heteroptera) complex consisting of approximately 35 insect species. The Heteroptera complex causes approximately 60% damage in unsprayed orchards and the estimated annual heteropteran induced crop loss could be as high as R24 million. Gravid female tortricid moths could discriminate between various cultivars and significant differences regarding oviposition on the 17 macadamia cultivars that were evaluated became apparent. Incidence of larval damage early in the season was negligible and this complex may therefore largely be regarded as pests of large (mature) nuts. Kernel distance (combined husk and shell thickness) and early maturing cultivars were probably not the primary determinants of resistance and the presence of toxic cyanogenic secondary metabolic compounds in the nuts should be investigated as a future research priority. Hybrid cultivars as well as cultivar 800 appeared to be more prone to tortricid damage while cultivars 788, 294 and 741 were significantly less damaged. There were also significant differences amongst immature nuts regarding susceptibility of various cultivars towards the Heteroptera complex. It was speculated that kernel distance is not the primary determinant of resistance because the kernel distance in immature nuts is not large enough to offer protection for any cultivar. Stink bug induced damage to immature nuts was the highest for the cultivars 800 and 863 while cultivars 741, 816 and 788 suffered the lowest incidence of damage. When the adult nuts were evaluated, cultivar 600 and 741 suffered the lowest Heteroptera induced kernel damage. The resistance mechanism is unclear at the moment but involve more than one parameter. When the effects of various control strategies (fixed interval spraying and IPM) were compared, IPM compliant farms (farms that monitored and sprayed according to threshold levels) did considerably better. These results were hardly surprising as fixed interval spraying entails spraying trees irrespective of the economic threshold level. Because damaged nuts generally do not drop early and cannot be distinguished from undamaged nuts, any damage resulting from a mistimed spray (spray after economic threshold level has been reached) must therefore be regarded as additive and will be reflected in the unsound kernel reports of processors. Increasing tree density had a important positive effect on tortricid ($r^2 = 0.821$) and Heteroptera ($r^2 = 0.922$) damage. An effective pruning programme is therefore an important prerequisite for high density macadamia orchards. Populations of both pest complexes were heterogeneously distributed throughout the orchard and will adversely affect the accuracy of scouting procedures based on knockdown sprays if the quantity of data trees during weekly sampling is insufficient. Two theories for the formation of hot spots exist and are briefly discussed. Tortricids cause an estimated crop loss of approximately R3 million annually in South Africa alone. Although a number of larvae can be found inside the nuts relatively soon after anthesis, the majority of early larval damage occurs from ± 14 weeks post anthesis onwards. Eggs and recently eclosed first instar larvae should therefore be more numerous during the ninth week post anthesis. This would also be the most important period when an insecticide with a contact action has to be applied (late November). Oviposition occurred when nuts reached a mean medial diameter of ± 20mm but this relationship is coincidental and is more related to the phenology of macadamia trees (end of premature nut drop). Control strategy (IPM vs. fixed interval spraying) had inconclusive results as the IPM compliant farms suffered severe infestations when compared to fixed interval sprayed farms, as well as the organic and unsprayed farms. The success of tortricid control probably pivots around the November insecticide application. Tortricid larvae feeding on the insides of the pericarp may contribute significantly towards immaturity because feeding damage invariably severs the vascular tissue connecting the developing nut to the plant. The relative seasonal occurrence of heteropteran damage indicates that levels gradually increase in spring and taper off during mid January. Exclusion trials in an unsprayed orchard confirmed this observation and the apparent reduction in damage during January could probably be ascribed to the hardening of the shell at the same time. The damage profile of *Bathycoelia natalicola* was calculated and indicated that mouthpart lengths of fourth and fifth instar nymphs are probably sufficient to penetrate kernels of the Beaumont cultivar up to harvest. Compensation for early crop damage was studied and where Heteroptera damage was artificially simulated by flower removal, the trees were able to compensate for early crop damage. Compensation for Heteroptera damage was confirmed when early sprays were withheld on a semi commercial field trial. Withholding early sprays had no effect on tortricids as the initial spray of this pest complex has to be applied during late November which coincided with spray applications on all three spraying regimes that were tested. Due to asynchronous flowering the first Heteroptera spray should probably be applied before the end of October each year.

CHAPTER 1

Introduction

1.1 Background on macadamia production in South Africa

1.1.1 History of macadamia production

The earliest record of macadamias (*Macadamia integrifolia* Maiden & Betche & *Macadamia tetraphylla* Johnson: Proteaceae) dates back to 1828 in Australia when it was observed that the nuts make good food for pigs (Anonymous 1998). The tree was taxonomically described by the botanist: Baron Ferdinand von Mueller in 1857and the name macadamia was given to the plant in honour of his friend Dr. John Macadam. Macadamia nuts were domesticated for the fist time in 1858 in Australia and according to Rosengarten (1984) it is the only native Australian plant ever developed as a commercial food crop. Rosengarten (1984) also mentioned that the first commercial plantation in Australia was established in 1888. The trees are still alive today and are still productive. Before the common name macadamia was adopted by the general public, it was also known as: Australian nuts, Queensland nuts, Bauple nuts, Bush nuts or the Australian hazelnut.

Seed were exported for the first time to Hawaii in 1882 and approximately 18 000 seeds were planted in 1918 (Rosengarten 1984). During the next few years many top yielding macadamia cultivars were selected from these seedlings which formed the backbone of the present day macadamia industry. Fifty years after introduction into Hawaii, macadamia nuts were the third biggest crop on the island. The macadamia industry then also expanded in Australia as well from virtually nothing to the biggest producer globally in only 40 years (Rosengarten 1984).

It is not clear when macadamias were introduced into South Africa for the first time but according to De Villiers (2003) the Durban botanical garden already had a tree by 1915. The tree was possibly established at least 8 years earlier (Joubert 1986). First seedling trees were established by the Agricultural Research Council's Institute for Tropical and Subtropical Crops (ARC-ITSC) in 1931 (Joubert & Thomas 1963).

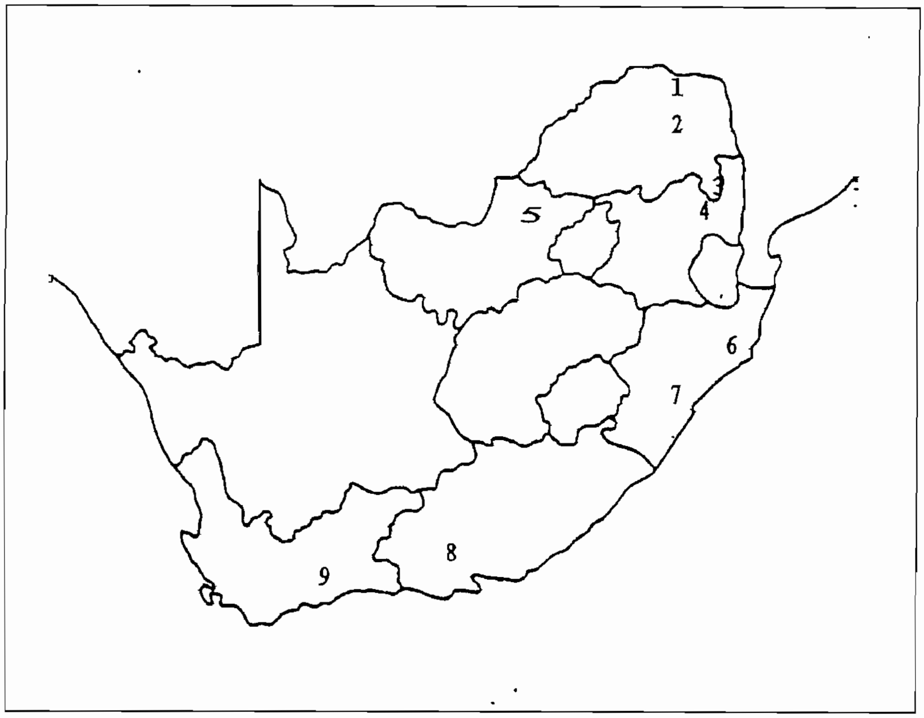
Subsequently seedlings were planted at Soekmekaar during 1957 which aroused great interest (De Villiers 2003). Reims nursery in KwaZulu Natal sold over 60 000 seedlings by 1960. First research by the ARC-ITSC was done in 1963 (Joubert 1986) and the meeting of the first macadamia society was held three years later. Vegetative propagation of good cultivars was initiated during the 1970's. The locally selected cultivars, Nelmak 1, 2 and 26 were released during 1973. The first macadamia and pecan nut symposium was held during 1979 at Politsi in the Limpopo province. The interest generated during this symposium led to the formation of the South African Macadamia Growers Association (SAMAC) (Anonymous 1998). The first grower handbook was published in 1993 and is currently in its second revision (De Villiers 2003).

1.1.2 Scope of the macadamia industry

According to Hargreaves (2003) Australia produces approximately 10 000 tonnes of kernel per annum which is equal to 40 % of the world total. Although modellers have predicted an annual growth of ± 15%, actual growth has been somewhat slower.
The total African production during 2002 was 5141 tonnes of kernel, of which 2878 t was produced in South Africa Lee (2003). The African industry has expanded by ± 10% per annum and is predicted to reach 14 000t kernel by 2010 of which 8 000t kernel will be produced locally. Statistics released in 2003 indicated that there were ± 3.1 million trees on ± 15 000ha in South Africa (Lee 2003). Approximately 46% of the trees were young (1-5 years old) indicating that this industry was expanding.

Other major macadamia producing countries in Africa include Zimbabwe, Malawi and Kenya. In South Africa the biggest production area (Fig. 1.1) is Levubu, closely followed by Nelspruit, Tzaneen and the South Coast of KwaZulu/Natal. Other minor production areas include George, Knysna, Magaliesberg and Rustenburg.

In Hawaii pressure on land due to tourism as well as the historical strength of the United States Dollar linked with high costs of production has slowed down growth considerably according to Vidgen (2003). Currently the industry peaked at 5500 tonnes of kernel and production is expected to gradually decrease. South America must be regarded as a wild card as the potential for growth is immense. According to Camargo (2003), production in Brazil in 1998 was 373t of kernel and was forecasted to reach 730t of kernel by 2005. Paraguay is a relative newcomer to the industry and according to Burt (2003) it only has about 300 ha under production. Major macadamia producing countries are indicated by Fig. 1.2.



1. *Levubu, Machado (Louis Trichardt)*
2. *Modjadjiskloof (Duiwelskloof), Tzaneen & Letaba*
3. *Hazyview, Burgershall*
4. *White River, Nelspruit & Barberton*
5. *Rustenburg*
6. *Stanger, Durban & Pietermaritzburg*
7. *Port Shepstone*
8. *Patensie*
9. *George*

Fig. 1.1 Major macadamia production areas in South Africa (De Villiers, 2003)

1.1.3 Origin and botanical aspects

Macadamias are evergreen trees of the family Proteaceae. It is indigenous to coastal subtropical rain forests of northern New South Wales and Southeast Queensland (Rosengarten 1984). Aboriginal tribes gathered the nuts during autumn as bush food but did not cultivate the plant. Macadamias were also used as a base for medicines and cosmetics for facial decoration (Anonymous 1998).

According to Joubert (1986) only two species namely *Macadamia integrifolia* and *Macadamia tetraphylla* are commercially used. Eight other species exist but the nuts are small, inedible, bitter and contain potentially poisonous cyanogenic glycosides. Macadamias are capable of producing self-pollinated fruit but in practice yields are much higher when two or more varieties are grown in close proximity. This explains why most orchards consist of a combination of varieties.

Table 1.1 Key stages in the phenological development of macadamia nuts in South Africa (Anonymous 1998)

Phenological stage	Month											
	J	A	S	O	N	D	J	F	M	A	M	J
Flower initiation	■	■										
Full bloom (anthesis)			■									
Early thinning				■	■							
Shell hardening							■					
Oil formation							■	■	■	■		
Harvesting									■	■	■	■
Nut diameter (mm)			2.5	6-10.5	17-23	28-30	30+	30+	30+	30+	30+	30+

1	*Australia*	8	*Kenya*
2	*Brazil*	9	*Malawi*
3	*California*	10	*South Africa*
4	*Costa Rica*	11	*Taiwan*
5	*Guatamala*	12	*Tanzania*
6	*Hawaii*	13	*Thailand*
7	*Israel*	14	*Zimbabwe*

Fig. 1.2 Major world wide production areas of macadamias (De Villiers 2003).

1.1.4 Phenological stages of macadamias

To gain a better understanding of the various sections in this dissertation dealing with plant responses to insect attack, an understanding is necessary of the basic phenological development of macadamia nuts (Table 1.1).

1.1.5 Damage profiles and insect control

Despite current optimism regarding the future of macadamias in South Africa, there are also a number of serious constraints. Macadamias are attacked by a variety of mostly indigenous pests which can be divided into three basic complexes namely a nut borer complex (consisting of 3 tortricid moth species), a stink bug (Heteroptera) complex consisting of approximately 35 stink bug species and a thrip complex consisting of two species. Fortunately not all are serious economic pests. The most important species are listed in Table 1.2.

According to Bruwer (1999) the pentatomids contribute 93.1% of the Hemipteran numbers, the coreids 4.3% and all the other families only 2.6%. The two spotted bug *Bathycoelia natalicola* is the most abundant species and contributes approximately 50.2% of the total numbers. The false codling moth *Thaumatotibia leucotreta* (Lepidoptera: Tortricidae) and the macadamia nut borer *Thaumatotibia batracopa* contribute approximately 90% of the tortricid complex.

According to Le Roux (2004) the total unsound kernel recovery percentage recorded by processors during 2003 was 3.5%, which equals 482.7 t of kernel. Insect damage amounted to ± 270.5 t of kernel which is nominally valued at approximately R 11.6 million.

Although it is well known that feeding activity of stink bugs induce abortion of newly formed nuts and flowers (Bruwer 1992), little is presently known regarding premature drop of immature nuts. Nuts damaged by tortricids after shell hardening but before physiological maturity (Table 1.1) would very likely be harvested and recorded as immature nuts by the processors. Nuts damaged by stink bugs after early thinning would very likely not be recorded because most farmers only start clearing the leaf litter towards the end of January in preparation of harvest.

Bruwer (2002) mentioned that stink bugs and tortricids are able to damage up to 75% of mature nuts if left uncontrolled.

Table 1.2 Selected IPM components of important macadamia insect pests in South Africa.

Pest spp.	Pest factors		Integrated control components					
	Pest status	Plant part affected	Bio-monitoring	Damage threshold	Predictive models	Biological control	Pheromones	Selective chemicals
Heteroptera (Pentatomidae) *Bathycoelia natalicola* Schouteden Two-spotted stink bug	1	N	(+)	(+)	(++)	(+)	(++)	(++)
Bathycoelia rodhaini Yellow-spotted stinkbug	3	N	(++)	(++)	(++)	(++)	(++)	(++)
Nezara viridula (L) Green vegetable bug	2	N	(+)	(+)	(++)	(+)	(++)	(++)
Nezara pallidoconspersa *Yellow-edged stink bug*	2	N	(+)	(+)	(++)	(++)	(++)	(++)
Farnya sp Variegated stink bug	2	N	(++)	(++)	(++)	(++)	(++)	(++)
(Coreidae) *Pseudotheraptus wayi* Brown Coconut bug	1	N	(+)	(+)	(++)	(+)	(++)	(++)
Lepidoptera (Tortricidae) *Thaumatotibia leucotreta* (Meyrick) False codling moth	1	N	+	(+)	++	+	+	+
Thaumatotibia batrachopa (Meyrick) Macadamia nut borer	1	N	+	(+)	++	+	+	+
Cryptoplebia peltastica (Meyrick) Litchi moth	2	N	++	(+)	++	(+)	+	+
Ectomyelois ceratoniae (Zeller) Carob moth	4	N	(++)	(+)	++	(+)	+	+
Thysanoptera (Thysanoptera) *Scirtothrips aurantii* Faure Citrus thrips	2	I, N, F	+	(++)	(++)	(+)	(++)	(++)
Heliotrips haemorrhoidalis (Bouche') Greenhouse thrips	2	I, N, F	+	(++)	(++)	(+)	(++)	(++)

Pest status *1 - Key pest, requiring management every year, but not in every locality*
2 - Sporadic pest, occasionally requiring management
3 - Induced pest seldom observed in unmanaged situations
4 - Potential pest, rarely if ever requiring management on bearing trees but may occasionally require management on young trees.
Plant part affected: F - Foliage, I – Inflorescence, N - Nuts
IPM Components *+ - available*
(+) - Preliminary study but needs refinement or further research.
++ - Currently under research
(++) - Little or nothing is known in this area

1.2. Types of damage

1.2.1. Heteroptera complex

This group of insects has piercing/sucking mouthparts and is able to feed directly on the kernel. According to Bruwer (1992) the coconut bug, *Pseudotheraptus wayi* (Fig. 1.3A) secretes toxic saliva, possibly a pre-digestive enzyme and may cause sunken necrotic lesions in the kernel (Fig. 1.4A) and often in the shell of the nut as well (Fig. 1.4B). The pentatomids and especially *B. natalicola* (Fig. 1.3B) also cause sunken lesions of a lesser magnitude in the kernels. Although slightly infested kernels can be reworked by the processors, most affected kernels are unfit for export and are usually only used for oil extraction.

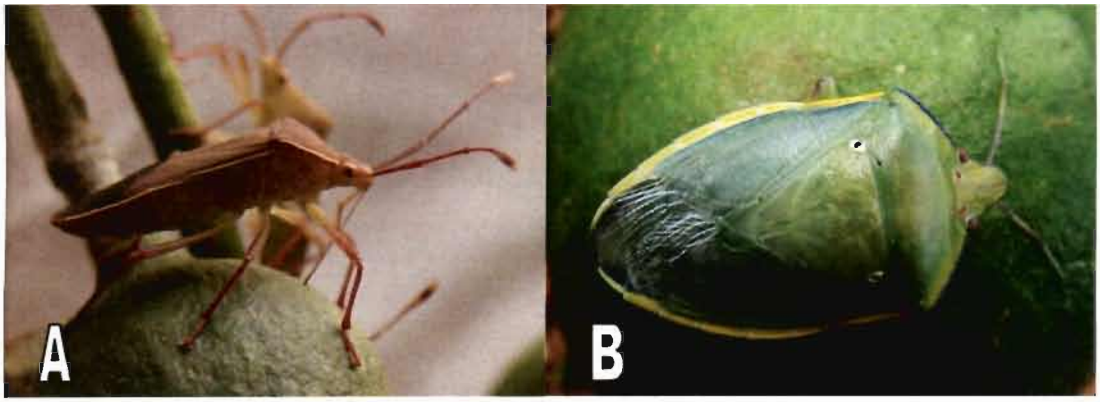


Fig. 1.3A: Adult coconut bug *Pseudotheraptus wayi* (Hemiptera: Coreidae); B: Adult two spotted bug *Bathycoelia natalicola* (Hemiptera: Pentatomidae).

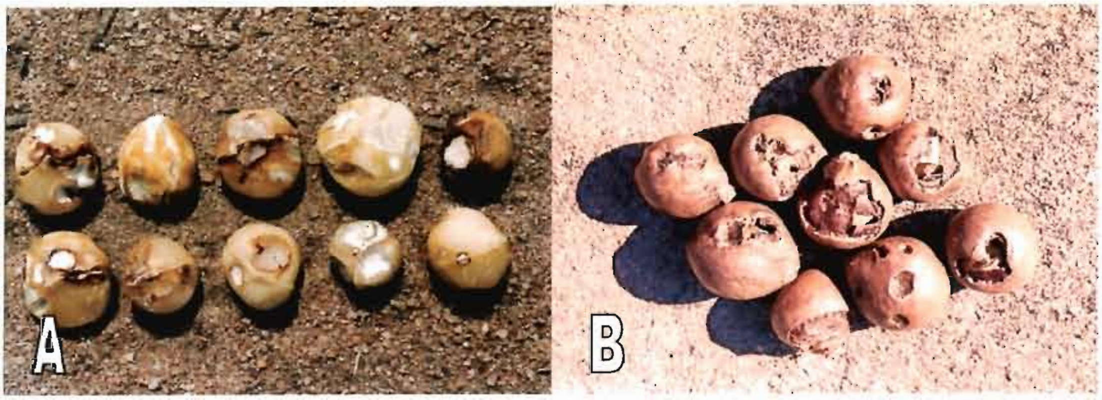


Fig. 1.4A: Macadamia kernels badly damaged by coconut bugs B: Damage to the brown nutshells caused by coconut bugs (De Villiers 2003).

1.2.2 Tortricid complex

Larvae generally feed on the inside of the green husk (Fig. 1.5A) and sometimes penetrate the hard brown shell. In small nuts, the entire contents are devoured, but in more mature nuts a portion of the kernel may remain (Fig. 1.5B). Externally, infested nuts can be distinguished by a small hole(s) in the green husk (Fig.1.6).

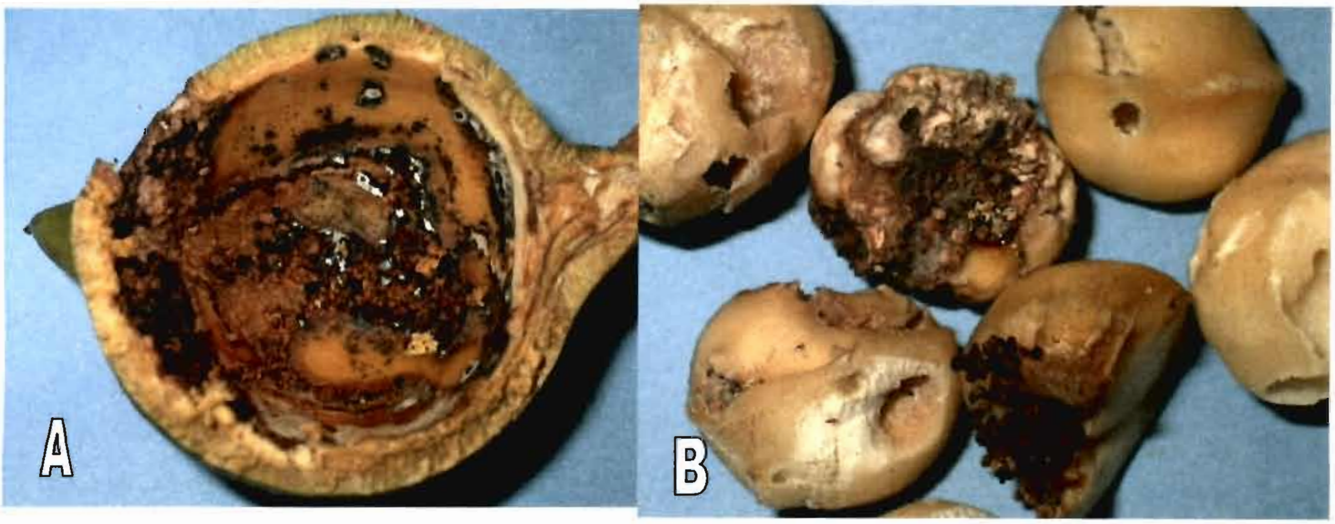


Fig. 1.5A: Tortricid damage on the inside of the husk of a mature nut showing feeding damage and larval excreta, B: Tortricid damage on mature kernels.

Fig. 1.6 Macadamia husk showing an exit hole made by a tortricid larva.

1.2.3 Thrip complex

Until recently thrips were regarded as a minor pest and in most cases this supposition is still valid. However, in some areas (Levubu and Southern

KwaZulu/Natal) reports of severe infestation are becoming more frequent. Symptoms of infestation include scarification of young nuts and some degree of leaf curl. In cases of severe infestation, damage to lateral growing tips, shortened internodes and rosetting has been observed.

1.3 Monitoring and economic injury levels

1.3.1 Heteroptera complex

According to Todd (1989) pentatomids are K selected and inflict damage at relatively low population levels. The only method to monitor for these insects is to select a number of trees (±10) randomly in a ± 5 ha block. These trees are then sprayed with an insecticide with a high vapour pressure deficit such as dichlorvos 1000g/L at 150ml/100L water. If more than 1.2 pentatomids/tree are collected beneath the sprayed trees/hour a full cover spray has to be applied. Alternatively the lower branches of 10 randomly selected trees should be shaken early in the morning before the temperature rises above 18°C. If more than 0.7 heteropterans/tree are recorded insecticides have to be applied (De Villiers *et al.* 2003).

Although fairly accurate, the above mentioned methods are cumbersome and due to the volatile nature of dichlorvos, chronic exposure has in the past led to unacceptably high levels of choline esterase in the blood of some insect scouts (A. Shaw. personal communication)

In Australia a sequential sampling plan was designed by Ironside (1988) to assist with decision making. Approximately 320 nuts from 32 trees in a block of up to 5 ha should be monitored for stink bug feeding marks on the inside of the pericarp. This should ideally consist of 10 nuts per tree from 4 trees selected from 8 representative areas in a block. Generally sprays should commence if stink bug infestation levels reaches 4%.

1.3.2 Tortricid complex

A significant amount of research is being carried out at the moment regarding pheromones, alone or in combination with various "attract and kill" matrixes. The active ingredients of the pheromones of economically important tortricids have been identified and are currently available in different formulations (see www.insectscience.co.za). Last Call Macadamia Nut Borer, Macadamia Nut Borer Ferolure and False Codling Moth Ferolure have recently been registered in South Africa and standards for monitoring are available (G. Booysen, Insectscience, personal communication). However, according to Jones (1995a) pheromone traps have a limited use for determining population dynamics in macadamia orchards. In various field trials conducted in Hawaii increases in trap catches did not always correspond with increases in husk damage and *vice versa.* The presence of eggs on the outsides of husks was a similarly unreliable indicator of tortricid larval damage (Jones 1995a).

It is easiest to monitor for the presence of tortricids on fallen nuts but the decision to spray or not should only be taken if nuts on the trees are also sampled for eggs (Ironside 1988). Jones (1995a) and Ironside (1988) designed sequential sampling techniques to facilitate spray decisions. Ironside (1988) included the susceptibility of various cultivars in his equations.

1.4 Control strategies

1.4.1 Cultural control

This aspect has received little or no attention in the past. There are however, a few practical options available to the industry.

1.4.1.1 Trap crops

Although agricultural crops included in the host range of all macadamia pests are well-known, relatively little is known regarding natural host plants of especially the Heteroptera complex. It is known that *Nezara viridula* is generally attracted to a large variety of seed bearing weeds, and has been recorded on various *Crotalaria* spp, *Amaranthus* spp. as well as *Bidens pilosa* (Jones *et al.* 2001). However, in South Africa no concerted attempt has yet been made by industry to use trap crops as a means to control stink bugs. Although it is unlikely that a trap crop will lure heteropterans away from a macadamia orchard and reduce stink bug numbers below the economic threshold level, it could possibly be used as a monitoring tool provided that:

i) Stink bug populations in the trap crop are representative of those in the macadamia orchard.

ii) It is easier and more accurate to monitor heteropterans in the trap crop.

It could be a good strategy to cultivate alternative host plants that fruit in the winter near macadamia orchards (Waite 2003). The heteropterans could then be controlled with discrete sprays to reduce the severity of incursions in spring. Jones *et al.* (2001) adopted a more cautious stance and recommended that a better alternative would be to encourage non-host grasses throughout the orchard as stink bugs could possibly damage macadamias if the fruiting bodies of alternative hosts became unsuitable or unavailable.

1.4.1.2 Host plant resistance

The use of resistant and/or tolerant plants must be regarded as a cost-effective first line of defence in any crop protection programme. Macadamia is no exception, however, according to Bruwer (1992) resistance is largely a function of the thickness of the combined husk and shell (kernel distance). Factors such as possible varietal differences regarding the production of allelochemicals, the ability of varieties to compensate for early stink bug related crop loss as well as different abilities of varieties to cope with varying degrees of plant stress will undoubtedly add new levels of complexity to this important facet of crop protection. Compensation for early crop damage, as was reported by Waite *et al.* (2000), must also be regarded as a promising aspect of plant resistance that still warrants further investigation as it hasn't yet been studied under South African conditions.

1.4.1.3 Tree size manipulation

Some macadamia varieties are very tall (up to 10 m) and it has been observed that most commercial air assisted sprayers effectively reaches up to only 4 – 4.8 m (Le Roux, personal communication). Spray recovery in a mature macadamia tree is insufficient at heights higher than 6m (Drew 2003). It is thus safe to assume that poorly sprayed nuts in the tops of mature trees will act as a refuge for important pests. It has also been observed that high density, overgrown orchards are more prone to stink bug damage than orchards with an open canopy (P. S. Schoeman unpublished data).

1.4.2 Biological control

All the major pests listed in Table 1.2 are indigenous to Southern Africa with the exception of *N. viridula,* consequently most major natural enemies listed in Table 1.3 are also indigenous. Despite this Van den Berg (1995) and De Villiers *et al.* (1980) imported the tachinids: *Trichopoda giacomellii* and *Trichopoda pennipes* respectively. Although both species established successfully, levels of biological control did not increase significantly. This leaves us with three options to consider:

i) Artificially augmenting populations of natural enemies early in the season when numbers of natural enemies and their respective host complexes are low.

Table 1.3 Checklist of recorded natural enemies of major insect pests of macadamia in South Africa.

Order and Family	Species	Host	Reference
Hymenoptera			
Scelionidae	*Trissolcus* sp A	P, B, Y & V	Bruwer (1992)
	Trissolcus sp B	P & B	Bruwer (1992)
	Trissolcus basalis (Wollaston)	N	Froneman & De Villiers (1991)
	Undetermined sp.	P & B	Bruwer (1992)
Eulophidae	*Pediobius* sp.	P & B	Bruwer (1992)
Pteromalidae	*Pachyneuron* sp.	P, B & V	Bruwer (1992)
Eupelmidae	*Anastatus* sp.	P	Bruwer (1992)
Formicidae	*Oecophylla longinoda* (Latreille)	P	Way (1953) & Tait (1954)
	Pheidole megacephala (F.)	P	Vanderplank (1958)
	Anoplolepis custodiens Smith	P & CL	Gunn (1921)
Trichogrammatidae			
	Trichogrammatoidea cryptophlebiae Nagaraja	CL	Newton & Crause (1990)
	Trichogrammatoidea sp.	CP	Searle (1964)
	Chelonus curvimaculatus Cameron	CL	Ford (1934)
Braconidae			
	Agathis bishopi (Nixon)	CL	Ford (1934)
	Agathis leucotretae (Nixon)	CL	Ford (1934)
	Bassus sp.	CL	Ford (1934)
	Phanerotoma curvicarinata Cameron	CL	La Croix & Thindwa (1986)
	Ascogaster sp.	CB	La Croix & Thindwa (1986)
	Bracon hancocki (Wilkinson)	CB	La Croix & Thindwa (1986)
	Phaenerotoma sp.	CB	Ford (1934)
Chalcididae	*Oxycoryphe edax* Waterson	CL	La Croix & Thindwa (1986)
	Antrocephalus sp	CB	Ford (1934)
Ichneumonidae	*Apophua leucotreta* (Wilinson)	CL	La Croix & Thindwa (1986)
	Trathala sp.	CB	La Croix & Thindwa (1986)
	Apophua sp.	CB	La Croix & Thindwa (1986)
	Diadegma sp.	CB	La Croix & Thindwa (1986)
Diptera			
Tachinidae			
	Bogosia antinorii Rodhaini	Y & N	Van den Berg (1997)
	Bogosia taeniata (Wiedeman)	Y	Van den Berg (1997)
	Bogosia helva/bequartii	Y	Van den Berg (1998)
	Bogosia bequaerti Curran	B & N	Bruwer (1992)
	Cylindromyia eronis (Villeneuve)	B	Bruwer (1992)
	Trichopoda pennipes (F.)	N	De Villiers *et al* (1980)
	Trichopoda giacomellii (Blanchard)	P	Van den Berg (1995)

P – *Pseudotheraptus wayi*
N – *Nezara viridula*
Y- *Nezara pallidoconspersa*
CB – *Thaumatotibia batracopa*
B – *Bathycoelia natalicola*
CP – *Cryptophlebia peltastica*
V – *Farnya sp*
CL – *Thaumatotibia leucotreta*

ii) Augmenting natural control by conserving indigenous natural enemy complexes by designing chemical control programmes which are less disruptive than the current 4 – 6 week calendar based sprays.

iii) Using aspects of macadamia phenology such as the ability of host plants to compensate for early season insect damage and natural host plant resistance to reduce unnecessary spray applications.

According to Waite (2003), increasing egg parasitism rates by artificial rearing and subsequent mass releases of parasitoids has little hope of providing economic control of heteropterans because of the massive breeding area that needs to be covered with successive releases throughout the production season. If breeding within the orchard was the major source of damaging bugs then augmentation might have been feasible, but the reality is that most damage is inflicted by the highly mobile adults which migrate into macadamia orchards from the surrounding natural bush (Waite 2003).

According to Joubert (1997) microbial control is a relative recent facet of IPM in macadamias in South Africa. Exploratory work by the ARC-ITSC indicated that this trend is well worth investigating. The well-known entomopathogenic fungus *Beauveria bassiana* has occasionally been recorded on *T. leucotreta* in citrus orchards (Begeman, personal communication). An isolate of this parasitic fungus has recently been found on a specimen of *B. natalicola* at Nelspruit and is currently being mass reared for trial purposes. Two commercial products containing granulo viruses are also manufactured by two local bio-pesticide companies for the control of *T. leucotreta* on citrus.

1.4.3 Mechanical and physical control methods

Presently very little or no mechanical and/or physical methods are used to control any of the pests on macadamia. Some producers collect and destroy unparasitised stink bug eggs in an effort to reduce stink bug numbers. The efficacy of this practice is dubious because heteropterans are very mobile and can easily re-infest a macadamia plantation when they fly in from the surrounding bush. Additionally, egg rafts can only effectively be collected from the bottom 2 – 3m of a macadamia tree. Possibly the greater significance of this approach is that it sensitises producers to the value of biological control.

1.4.4 Chemical control

De Villiers & Du Toit (1984) did the first registration work with Cypermethrin 200g/L EC and Deltamethrin 250g/L EC. Both these chemicals were effective in controlling heteropterans, but three successive applications gave rise to secondary pest population outbreaks of the long tailed mealy bug *Pseudococcus longispinus*. Haaksma (1993) mentioned that during the early 1990's, Integrated Pest Management (IPM) in Australia hadn't practically materialised. He also emphasised that synthetic pyrethroid applications should be limited to a maximum of three because of possible secondary pest outbreaks and resistance.

De Villiers & Viljoen (1987) found that soil applications of Aldicarb GR 150 g/kg were able to limit kernel lesions economically with the added advantage of being relatively safe for beneficial insects. However, according to Froneman & De Villiers (1990), producers soon experienced problems due to this chemical's long residual activity and concomitant long withholding period. Injudicious usage of Aldicarb also led to unacceptably high residue levels and subsequent rejection of nuts by processors in the Limpopo province.

Two formulations of Endosulfan were also tested by Froneman & De Villiers (1990) and both were found to be effective against heteropterans although they had significantly shorter residual periods compared to synthetic pyrethroids.

Australian researchers considered the use of systemic insecticides such as Fipronil and Thiamethoxam mainly because of their relative low impact on beneficial insects (Waite 2003). Daneel *et al.* (1995), Van der Meulen & Van der Meulen (1988) and Snyman (1997) evaluated various systemic insecticides (Aldicarb GR 150 g/kg, Monocrotophos SL 400g/L, Imidacloprid SC 350g/L and Methamidophos AL 500g/L). Although some of these chemicals did limit heteropteran damage, registration was never attempted, probably due to problems similar to those highlighted by Froneman & De Villiers (1990). Additionally the undiluted chemical has to be handled and this poses a considerable health risk (Joubert 1997).

Bruwer (2004) evaluated a range of chemicals from synthetic pyrethroids to organic pesticides as well as a range of fixed spraying programmes. Application of synthetic pyrethroids ± every six weeks gave the best results. Although Bruwer (2004) reported no problems regarding secondary pests, De Villiers & Du Toit (1984), Haaksma (1993) and Joubert (1997) warn that excessive usage of pyrethroids could induce problems regarding resistance and/or secondary pest outbreaks. Bruwer's (2004) research will probably lead to the registration of Acephate SP 750g/kg which will provide producers with a wider selection of insecticide groups to choose from, which in turn would facilitate an insect resistance management strategy.

Current insecticides registered against macadamia pests are summarised in Table 1.4. Many farmers and consultants believe that registered synthetic pyrethroids are effective against the tortricid complex as well (Bruwer 1988).

Some producers are currently applying up to eight insecticide applications consisting of six pyrethroids, one chlorinated hydrocarbon and one organophosphate during the production season. The macadamia production season lasts ± 8 months which means that the orchards are sprayed at least once a month.

Table 1.4. Pesticides registered on macadamias in South Africa (Anonymous 2007)

Pesticide	**Formulation**	**Dosage (per 100 l of water)**	**Post harvest interval (days)**
Alpha-cypermethrin	100g/l EC	10ml	30
Alpha-cypermethrin	100g/l SC	10ml	30
Beta-cyfluthrin	50g/l EC	15ml	14
Beta-cyfluthrin	125g/lSC	6ml	-
Beta-cypermethrin	100g/l EC	25ml 10ml	30
Carbaryl	480g/l SC	450ml	-
Carbaryl	850g/kg WP	250g	-
Chlorpyrifos	750 g/kg WG	64g	83
Cypermethrin	200g/l EC	20ml	30
Dichlorvos	1000g/l EC	150ml	-
Endosulfan	475g/l SC	120ml	10
Gamma-cyhalothrin	60g/l CS	4.2ml	82
Lambda-cyhalothrin	50g/l CS	10ml	82
Lambda-cyhalothrin	50g/l EC	10ml	82

Permethrin/z-8-dodecen-1-ol	60/1.6g/kg VP	150g/ha (3000 droplets/ha)	-
Zeta-cypermethrin	100g/l EW	20ml	30
Tau-fluvalinate*	240g/l EW	-	-

*This prodct was only recently registered against the Heteroptera complex and was therefore not listed by Anonymous (2007). Information was supplied by the Subtropical Growers Association (SUBTROP).

While resistance is not yet a problem as far as the heteropterans are concerned, *T. leucotreta* has already exhibited resistance against certain pyrethroids which were applied to citrus in South African (S. Moore, personal communication).

1.5 Problem statement and suggested solutions

The macadamia industry in South Africa is presently confronted by the following problems:

i) The crop is valuable and the potential risk regarding unproven alternative biological control strategies is simply too big. Producers cannot afford to take chances and have settled on a prophylactic chemical approach as a form of insurance.

ii) Because macadamias is such a new crop in South Africa, very little detailed information regarding the various IPM components of important pest insects is available.

iii) Importing nations are placing stricter environmental and social regulations on the production of various crops.

iv) Current pest monitoring techniques are cumbersome and few producers spray according to scouting results.

The magnitude of the heteropteran and tortricid complexes is such that it will not be economically feasible to produce macadamias without some form of chemical intervention. It is evident that although new pesticides would be advantageous especially in terms of resistance management and market acceptance, it will not solve the fundamental problem regarding macadamia pest management in South Africa. Synthetic pyrethroids are effective because of their long residual activity periods and indiscriminate mode of action. Most modern insecticides are much more specific and would require a more intimate knowledge regarding population dynamics of pest insects as well as phenological development of macadamias, if current efficacy standards regarding insect control and kernel quality are to be maintained.

Decision support regarding insecticide applications will thus be important regarding effective IPM in the future.

To deal with these matters, the following specific research question and objectives was addressed by this study: How can specific IPM components be developed and strengthened with the objective of minimizing insecticide dependence? The following specific objectives will be investigated:

a) Macadamia cultivars differ significantly in terms of various botanical aspects such as flowering, yield potential, husk and shell thickness. A logical departure point for prospective studies regarding alternative insect control will therefore be to first evaluate commercially important varieties in terms of resistance/tolerance towards the two main insect complexes.

b) The damage profiles of both pest complexes will be studied under diverse growing conditions. Although aspects of the economic impact of the heteroptera complex have been studied in the past, detailed knowledge regarding the economic impact of the South African tortricid complex is still vague.

c) Because monitoring techniques are cumbersome (Refer to section 1.3 page 9) many producers simply rely on a fixed interval spraying regime. The consequences of adopting an IPM approach over fixed interval spraying will have to be practically demonstrated.

d) The distribution patterns of heteropteran and tortricid damage in an orchard will have to be studied as it could increase the accuracy of scouting procedures.

e) Many growers begin their spraying programmes before flowering and this could have a detrimental effect on beneficial insect populations. The effect of tree compensation for early heteropteran damage will have to be studied to determine if these early sprays are really needed.

It is evident that to reduce pesticide usage while maintaining or improving the quality of macadamia nuts, a good understanding of the crop and pest environment is required, as well as the possible interactions between these processes.

CHAPTER 2

Materials and Methods

2.1 Factors contributing towards tortricid and heteropteran resistance /tolerance of macadamia cultivars

The following series of trials were designed to quantify differences in susceptibility of macadamias towards tortricids and heteropterans. This was regarded as an important research priority because the quantification of resistant/susceptible status of commercial cultivars and the subsequent management thereof could possibly facilitate integrated control of both pest complexes as it might decrease the current over-dependence on synthetic pyrethroids.

2.1.1 Description of trial sites

The study was conducted at two localities with differing levels of management.

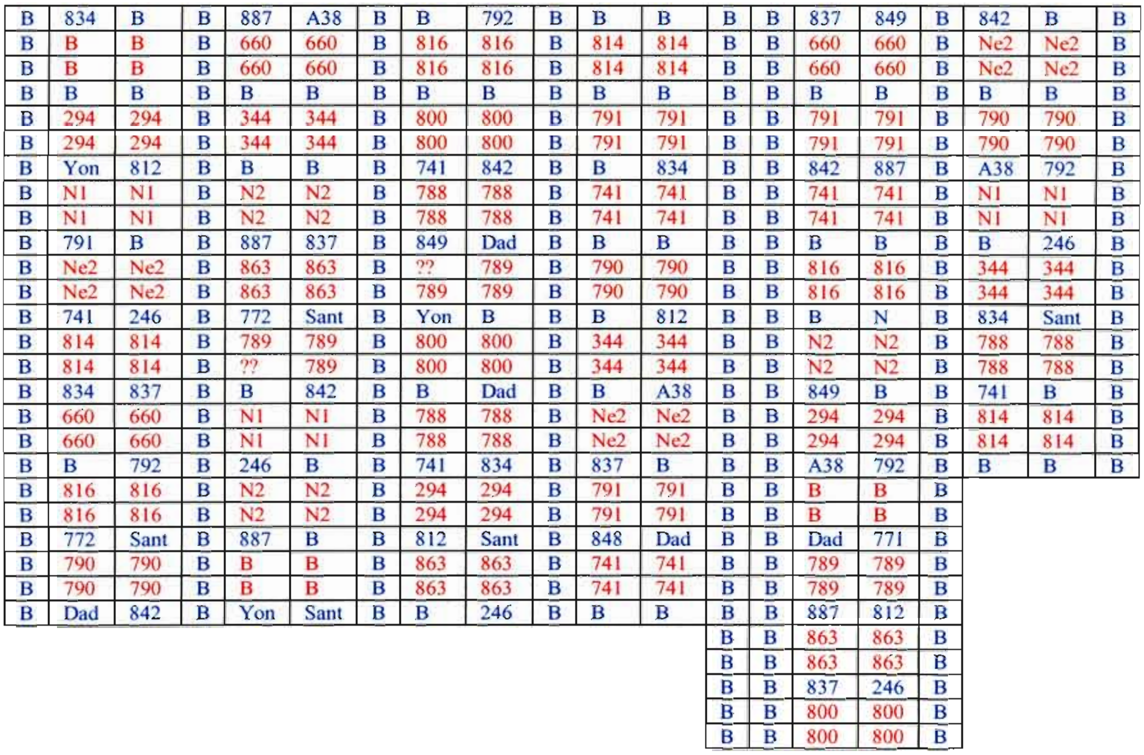
2.1.1.1 Burgershall trial site

This site (±2 ha) was situated at the Burgershall Research Station of the Agricultural Research Council's Institute for Tropical and Subtropical Crops (ARC-ITSC) near Hazyview in Mpumalanga (Annexure 2.1). The site was situated in the centre of a major macadamia production area and as such was representative of rainfall, pest complex and elevation.

Each macadamia cultivar used during this trial (Annexure 2.2) was planted in 3 randomly distributed plots consisting of four trees each. Guard rows of the cultivar Beaumont (695) were predominantly planted between all cultivar plots (Fig. 2.1). The orchard was established in November 1993 at a spacing of 8 x 4 m (313 trees/ha = medium dense orchard). The orchard borders banana plantations on two sides and litchis and avocado orchards on the remainder (Fig. 2.2). The trees formed part of a commercial orchard and were therefore sprayed on a commercial basis and as such the orchard ecology would therefore not reflect the natural situation regarding population dynamics of tortricids and heteropterans.

2.1.1.2 Nelspruit trial site

Permission to use the second site (0.3ha) was only obtained in January 2003 and as such data will not reflect results from the natural thinning period of the 2002/03 season. The site is situated on the research farm of the ARC-ITSC in Nelspruit



B	834	B	B	887	A38	B	B	792	B	B	B	B	B	837	849	B	842	B	B
B	B	B	B	660	660	B	816	816	B	814	814	B	B	660	660	B	Ne2	Ne2	B
B	B	B	B	660	660	B	816	816	B	814	814	B	B	660	660	B	Ne2	Ne2	B
B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
B	294	294	B	344	344	B	800	800	B	791	791	B	B	791	791	B	790	790	B
B	294	294	B	344	344	B	800	800	B	791	791	B	B	791	791	B	790	790	B
B	Yon	812	B	B	B	B	741	842	B	B	834	B	B	842	887	B	A38	792	B
B	N1	N1	B	N2	N2	B	788	788	B	741	741	B	B	741	741	B	N1	N1	B
B	N1	N1	B	N2	N2	B	788	788	B	741	741	B	B	741	741	B	N1	N1	B
B	791	B	B	887	837	B	849	Dad	B	B	B	B	B	B	B	B	B	246	B
B	Ne2	Ne2	B	863	863	B	??	789	B	790	790	B	B	816	816	B	344	344	B
B	Ne2	Ne2	B	863	863	B	789	789	B	790	790	B	B	816	816	B	344	344	B
B	741	246	B	772	Sant	B	Yon	B	B	B	812	B	B	B	N	B	834	Sant	B
B	814	814	B	789	789	B	800	800	B	344	344	B	B	N2	N2	B	788	788	B
B	814	814	B	??	789	B	800	800	B	344	344	B	B	N2	N2	B	788	788	B
B	834	837	B	B	842	B	B	Dad	B	B	A38	B	B	849	B	B	741	B	B
B	660	660	B	N1	N1	B	788	788	B	Ne2	Ne2	B	B	294	294	B	814	814	B
B	660	660	B	N1	N1	B	788	788	B	Ne2	Ne2	B	B	294	294	B	814	814	B
B	B	792	B	246	B	B	741	834	B	837	B	B	B	A38	792	B	B	B	B
B	816	816	B	N2	N2	B	294	294	B	791	791	B	B	B	B	B			
B	816	816	B	N2	N2	B	294	294	B	791	791	B	B	B	B	B			
B	772	Sant	B	887	B	B	812	Sant	B	848	Dad	B	B	Dad	771	B			
B	790	790	B	B	B	B	863	863	B	741	741	B	B	789	789	B			
B	790	790	B	B	B	B	863	863	B	741	741	B	B	789	789	B			
B	Dad	842	B	Yon	Sant	B	B	246	B	B	B	B	B	887	812	B			
												B	B	863	863	B			
												B	B	863	863	B			
												B	B	837	246	B			
												B	B	800	800	B			
												B	B	800	800	B			

Fig. 2.1 Layout of the macadamia cultivar trial at Burgershall. For ease of interpretation all guard rows were coloured blue while all data blocks were coloured red. For background information on these cultivars refer to Annexure 2.2. (B = Beaumont)

(Annexure 2.1) and was planted in 1999 at a plant spacing of 2 x 4m (1250 trees/ha = very dense orchard hence significant insect damage is expected). The orchard was initially planted as a high density pruning trial and not as a cultivar trial therefore the respective cultivars were not planted in a randomised configuration. Instead Fig 2.3 indicates that the nine cultivars were planted alongside each other in single rows. Although the orchard was optimally fertilised and irrigated, it received no insecticidal or fungicidal sprays during and/or preceding the study period. The site was also situated in the centre of a major macadamia production area and was also representative of rainfall, pest complex and elevation. According to Fig 2.4 the orchard borders guava and mango orchards on two sides and natural bush on the remainder.

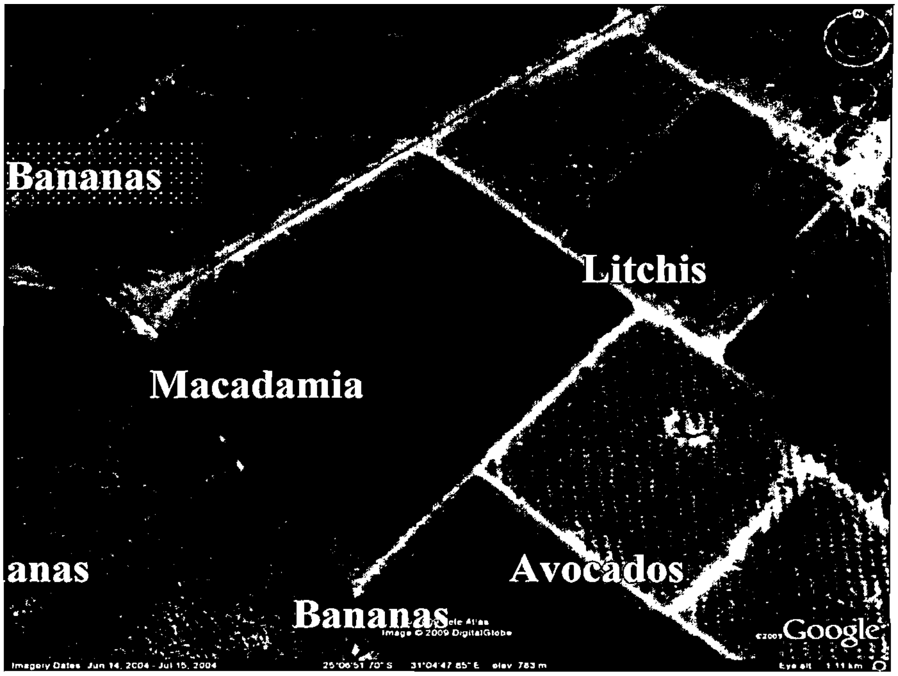


Fig. 2.2 General layout of the macadamia orchard at Burgershall in relation to surrounding orchards which could have influenced the distribution of important macadamia pest insects.

695	695	695	695	695	695	695	695	695	695	695	695	695	695	695	695
N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2	N2
344	344	344	344	788	788	788	788	788	788	788	788	788	788	788	788
A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4	A4
816	816	816	816	816	816	816	816	816	816	816	816	816	816	816	816
A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16	A16
741	741	741	741	741	741	741	741	741	741	791	791	791	791	791	791

Fig. 2.3 Layout of the macadamia cultivar trial at Nelspruit.

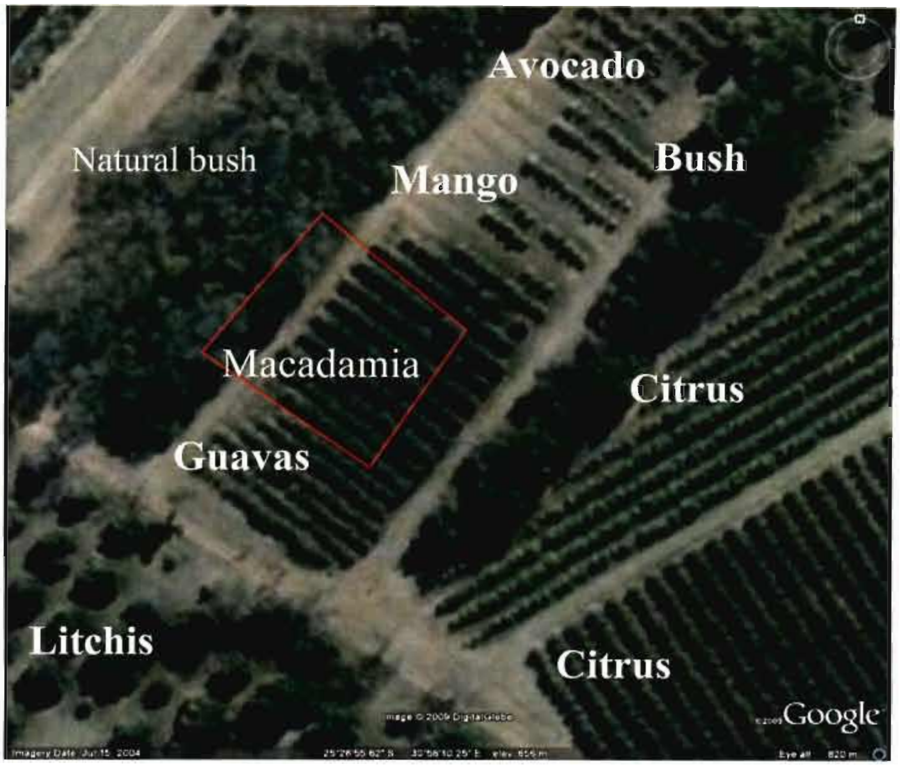


Fig. 2.4 General layout of the macadamia orchard at Nelspruit in relation to surrounding orchards which could have influenced the distribution of important macadamia pest insects.

2.1.2 Data collection

2.1.2.1 Burgershall

Ten nuts were randomly collected every week under the trees of the four tree plots. The survey started during August 2002 and was concluded during July 2004. Because of limited commercial viability, the cultivar 790 as well as cultivars making up the respective guard rows, was omitted from this study. Most of the surrounding commercial crops were poor hosts of the dominant heteropteran (*B. natalicola*), (Table 2.1) but subsequent unpublished research actually indicates a gradient of *P. wayi* damage in avocados along the avocado/macadamia interface depicted in Fig. 2.2. *P. wayi* damage in macadamias is comparatively scarce and the effect of this gradient is therefore difficult to quantify within this orchard. It was assumed that the layout of this trial would mitigate the effects of heterogeneous dispersion patterns, as well as gradients of infestation due to the proximity of alternative host plants.

Approximately 20 000 nuts were sampled over the two year period which was considered as sufficient to be representative of the natural situation regarding cultivar preferences of the two insect complexes on both trial sites.

2.1.2.2 Nelspruit

The survey started during August 2002 and was concluded during July 2004 and approximately 10 nuts were collected from five randomly selected trees of each cultivar within the orchard. Although most cultivars were represented by 16 trees a limited number of trees were available for cultivars 344 (4 trees), 788 (12 trees), 741 (10 trees) and 791 (6 trees) (Fig 2.3).

Towards the end of the natural nut drop period (beginning of December) and prior to senescence of mature nuts (February/March), the trees shed very few nuts. During this period nuts were collected from a larger number of trees in order to collect sufficient nuts for analysis. During the natural harvest cycle (March/June) the data collection procedure described for the early thinning period was used.

Table 2.1 Host status of various commercial subtropical crops grown in close proximity to macadamia orchards in Mpumalanga according to Van den Berg *et al.* (2001) and Bedford *et al.* (1998).

Commercial crop	**Host status**				
	Pseudotheraptus wayi	***Bathycoelia natalicola***	***Thaumatotibia leucotreta***	***Thaumatotibia batrachopa***	***Cryptophlebia peltastica***
Banana	+	+	+	+	+
Litchi	+++	+	++	++	+++
Citrus	+	+	+++	+	+
Guava	+++	+	++	+	+
Mango	+++	+	+	+	+
Avocado	+++	++	++	+	+

Legend

Non host -	+
Poor host -	++
Good host -	+++

Since this block had never been sprayed it was assumed that insect populations were relatively stable. Macadamias appear to be the preferred host for most of the economically important insects listed in Table 2.1 and as such may act as a source of infestation for the surrounding orchards portrayed in Figs 2.2 & 2.4. This is currently also the viewpoint of a number of subtropical fruit farmers with orchards in close proximity to macadamias.

2.1.3 Assessment methods

During the natural thinning period, all nuts were dissected and examined for heteropteran puncture marks on the inside of the husk (Fig 2.7 A & B) as well as for tortricid incidence.

2.1.3.1 Heteroptera

Heteropteran damage assessments according to puncture marks on the insides of the husks were done and were only effective during the early season (September - early December). Thereafter the inside of the husks of many cultivars turned dark brown upon approaching physiological maturity, effectively obscuring the puncture marks. From December to February nuts were manually dehusked and the partially hardened shell was also removed by hand. The presence/absence of heteropteran induced kernel lesions were then recorded for each nut.

All mature nuts were then dried at ambient temperature and humidity for three weeks whereupon they were cracked by hand and assessed for the absence/presence of heteropteran induced kernel damage.

2.1.3.2 Tortricidae

Tortricid damage was easy to identify during all three stages of the development of macadamias (early thinning period, prior to shell hardening and after shell hardening) by simply dissecting each nut. Damage was categorized as: larvae burrowing into the small developing nuts, damage only to the inside of the husk and damage (holes) in the shells (kernel damage).

An index value ranging from 1 (least affected) to 4 (most affected) was assigned to each cultivar. The tortricid and heteropteran complexes were analyzed separately. The sum of each cultivar's individual index value was then divided by the number of observations to facilitate comparison of the different cultivars on both trial sites.

2.1.4 The effect of kernel distance on resistance/tolerance

To determine the effect of the combined husk and shell thickness (kernel distance) on resistance, the husks and shells of 15 cultivars at Burgershall and nine cultivars at Nelspruit were measured with a digital micrometer. Fifty nuts of each cultivar were measured at both localities. Kernel distances were determined at three positions ie: distally, medially and proximally. To ensure that results were comparable due to dehydration of the husk and concomitant shrinkage, all husk measurements were done within 24 hours after collection. Care was also taken to select nuts without blemishes as the presence of these would indicate that the nuts had already spent some time on the ground.

Additionally the position of heteropteran induced kernel lesions were also noted to determine if thinner parts of the shell could be associated with higher levels of heteropteran damage.

2.1.5 Statistical analyses

Data was analysed using the statistical program Genstat (2003). Differences between cultivars were determined with Fisher's protected least significant difference test while normal linear regression curves were drawn to quantify the relationship between kernel distance and infestation incidence.

2.2 An analysis of integrated pest management versus fixed interval spraying of macadamia for the Heteroptera complex.

In order to promote Integrated Pest Management (IPM) it was important to demonstrate that farmers actually benefit financially if they comply with the basic principles of IPM (monitoring and spraying according to predetermined threshold levels). This is especially important for macadamias because monitoring is cumbersome and requires a significant commitment from growers in terms of time and effort (see section 1.3.1).

Six farms, ranging from unsprayed to various levels of chemical control were selected in the Nelspruit region during 2006/07. Approximately 27 842 nuts were randomly harvested throughout the season. From October to December, naturally aborted nuts were collected, dissected and the presence of heteropteran damage was subsequently recorded. Mature nuts were harvested at the end of the season, dehusked, dried at ambient temperature and humidity, cracked and rated for heteropteran damage.

This study was expanded during 2007/08 and insect damage on a further 12 farms was studied. Farms were selected because of their diverse approach to IPM and were broadly categorized into five groups ranging from no chemical sprays to complete adoption of IPM principles. These farms were situated in all the major macadamia production regions ranging from the south coast of KwaZulu-Natal to Limpopo. All nuts were dehusked, dried at ambient temperature and humidity, hand cracked and subsequently rated for the presence/absence of heteropteran kernel damage. 2 300 nuts were analysed during this survey.

Kernel quality data from a further 5 farms were obtained from a macadamia processor near Nelspruit. The farms were divided into IPM compliant and fixed spray interval categories and kernel quality from both categories were compared to the industry mean (± 120 growers).

Many factors such as cultivars and combinations of cultivars, climate and the compliment of natural host plants may determine the incidence of stink bugs on macadamias. However, apart from cultivar choices, the effects of other factors are very difficult to quantify and were therefore not included in this analysis. Cultivar choices do have an effect on insect populations (see section 3.1) but again the effects of combinations of cultivars are probably also important and are also very difficult to quantify. Additionally the choice of most growers regarding cultivar selection is similar. As a result more than 45% of the trees currently planted consist of the Beaumont cultivar. For these reasons it was decided that kernel quality is probably a reliable indicator of insect activity in commercial macadamia orchards.

2.3 Distribution of the tortricid and heteropteran complexes affecting macadamias

2.3.1 The effect of tree density on the incidence of the tortricid and heteropteran complexes

This trial was conducted during May 2006 on a commercially managed orchard on the research farm of the ARC-ITSC in Nelspruit (Annexure 2.1) and consisted only of the South African bred hybrid cultivar Nelmak 2. The 2.5 ha orchard was planted in 1970 at densities ranging from 39, 51, 83, 156, 278 and 400 trees per hectare (Fig.

2.5). Approximately 20 mature nuts were randomly selected beneath five replicate trees at each density (ie: 20 nuts/tree x 5 replicates/density x 6 densities = 600 nuts). All nuts were dissected and were examined for the presence of tortricid damage in the inside of the pericarp. The nuts were then dried for ± 6 weeks at ambient temperature and relative humidity. All nuts were individually cracked with a hand cracker and rated for heteropteran induced kernel damage. Approximately 635 nuts were examined which was estimated as sufficient to be a representative sample of insect damage in a commercial orchard of similar size.

Fig. 2.5 Aerial view of the Nelmak 2 density trial at the research farm of the ARC-ITSC in Nelspruit.

Additionally the number of egg packets of the two spotted bug *Bathycoelia natalicola* on the basal 2.5 meters of the main stems of five trees was determined for each density and 123 egg packets containing ± 1 722 eggs were recorded.

Because of the size of these trees, the cryptic nature of heteropterans as well as the ability of these insects to fly away from perceived sources of danger such as sprayer rigs used to monitor stink bugs, it was decided to rather use indirect methods such as egg deposition and incidence of crop damage.

The relationship between increased tree density and insect damage as well as the abundance of egg packets were quantified with standard linear regression curves. The data was log transformed to ensure a better fit.

2.3.2 Distribution patterns of *Bathycoelia natalicola, Pseudotherapthus wayi* and the tortricid complex

The aim of this study was to quantify the distribution of important macadamia pest insects in an orchard as it could have a profound effect on the accuracy of standard insect scouting procedures and subsequent spray decisions.

This trial was carried out in a ± 1ha organic orchard ± 25 km west of Nelspruit (Annexure 2.1). During November 2007 and 2008, five prematurely aborted nuts from each tree were removed and dissected under a stereo microscope. The orchard consisted of 130 trees therefore 650 nuts were dissected during November 2007 and 2008 respectively. Feeding damage of *B. natalicola*, *P. wayi* as well as the incidence of tortricid larvae were noted for each nut. Results were expressed as a percentage and were subsequently recorded on a colour coded map of the orchard. Since a

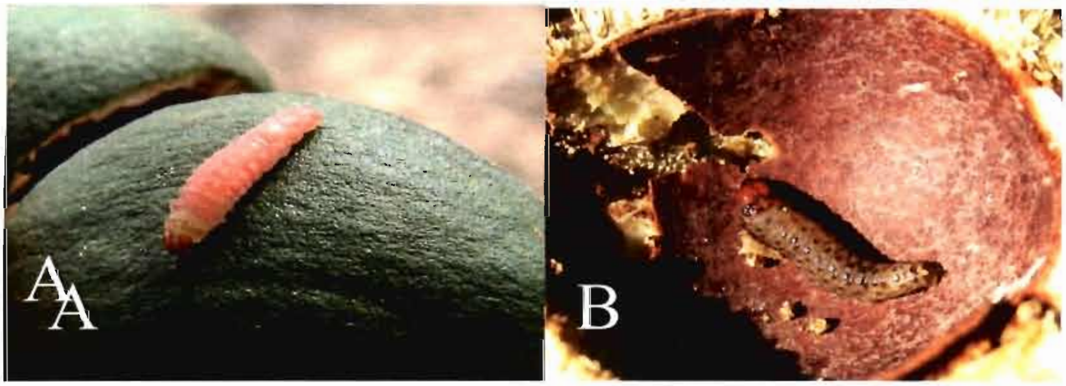


Fig. 2.6 Fully developed tortricid larvae commonly found on the inside of the macadamia pericarp during February. A: *Thaumatotibia batracopa,* B: *Thaumatotibia leucotreta.*

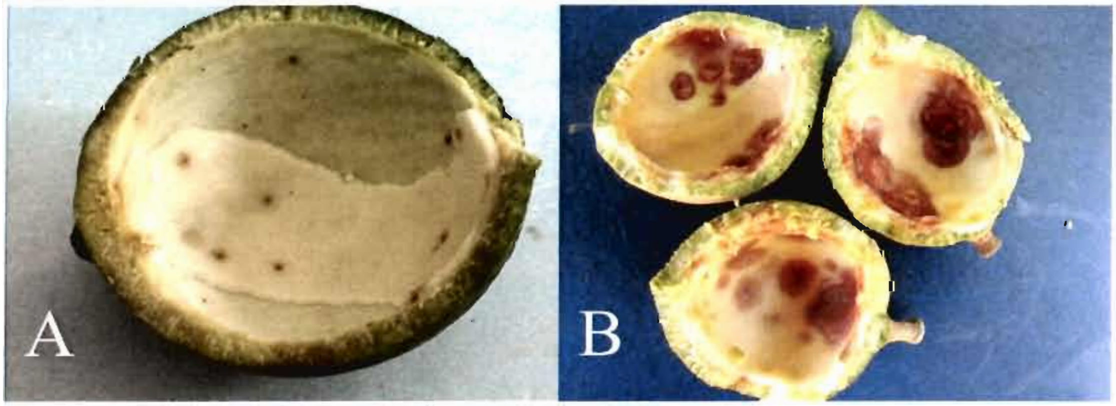


Fig. 2.7 Heteropteran feeding lesions on the inside of the pericarp of mature macadamia nuts. A: *Bathycoelia natalicola,* B: *Pseudotheraptus wayi.*

single heteropteran feeding event is sufficient to render a nut unmarketable, any nut with one or more tortricid larvae (Figs. 2.6 A & 2.6B) or heteropteran feeding lesions (Figs. 2.7A & 2.7B) were therefore regarded as destroyed. During February 2008 the basal 2.5m of all main stems of each tree were examined for the presence of *B. natalicola* egg packets. Egg numbers were divided into five damage classes which were graphically depicted on a colour coded orchard map. Approximately 127 egg packets consisting of 1778 individual eggs were sampled from 130 trees. From these maps, areas of increased insect activity (hot spots) were arbitrarily identified as well as areas of decreased activity (cool spots).

The orchard is bordered on three sides by natural bush and roadways and on the remainder with another macadamia orchard. The perimeter (outermost two tree rows) of the three non-macadamia facing sides of the orchard were rated for Heteroptera and tortricid damage to determine the presence/absence of an infestation gradient.

Hot spots were quantified by three or more trees in close proximity that had damage ratings of more than 60%.

2.4 Damage estimates and population trends of the tortricid nut borer complex occurring on macadamia

2.4.1 Description of trial sites

The study was conducted at eight localities with different levels of insect management (ranging from unsprayed, haphazardly sprayed with poor levels of general orchard husbandry to well managed orchards adhering to IPM principles and excellent levels of general orchard husbandry) within the Mpumalanga Province of South Africa. Farms were selected in the major macadamia production centres of Nelspruit, Burgershall, Karino, Organic, Kiepersol/Hazyview and Barberton (Annexure 2.1). Care was taken to select orchards that were representative of typical commercial orchards in the region.

Except for the organic orchard and the one at Nelspruit, the pests in all other orchards were controlled with commercial insecticides (consisting largely of synthetic pyrethroids and endosulfan) and would therefore not reflect the natural situation regarding population dynamics of important pest species.

2.4.2 Procedures regarding population monitoring

Approximately 10 naturally aborted nuts from five randomly selected trees were collected every week from the localities listed in Annexure 2.1. Because it was expected that these insects are heterogeneously distributed, nuts were collected from at least five localities within each orchard. Towards the end of the natural nut drop period (beginning of December) and prior to the senescence of mature nuts (February/March) the trees shed very few nuts. Aborted nuts were therefore collected from a larger number of trees (± 25) in order to collect sufficient nuts (50 nuts/farm/week) for analysis.

The young prematurely aborted nuts were microscopically examined for tortricid eggs and measured with a digital micrometer. All the nuts were then dissected to determine the presence of active tortricid larvae. After hardening of the seed coat (testa), all nuts were de-husked by hand and examined for tortricid damage. The nuts were then dried at ambient temperature and humidity whereupon they were cracked by hand and scored for tortricid induced kernel damage.

The survey commenced in August 2002 and was concluded in May 2006. Approximately 41 200 nuts were examined over four seasons. Because of the narrow window of opportunity for effective chemical control and because growers report mediocre results with various contact insecticides, the timings as well as the type of insecticide applications are listed in Annexure 2.3. An estimate of spray efficacy at farm level was made by comparing percentage pest incidence in orchards that were sprayed in November (n= 4) with orchards that were not sprayed in November (n = 11).

2.4.3 Possible effect of tortricid larvae on aborted nuts

To determine if tortricid larvae caused damage after nuts had dropped, approximately 500 nuts were collected from three cultivars; A16, A4 and Beaumont at the Nelspruit locality (Annexure 2.1). Nuts were harvested from five randomly selected trees of each cultivar during April – June when most nuts are physiologically mature (Table 1.1). All nuts were harvested from the basal 2.5 m and were subsequently manually de-husked to quantify husk damage. The nuts were dried for three weeks at ambient temperature and humidity whereupon they were manually cracked to assess incidence of tortricid induced kernel damage. Damage assessments obtained were then compared to tortricid damage on nuts that were collected on the ground during the same time using a Student's t-test.

2.4.4 The effect of husk feeding tortricid larvae on immaturity of kernels

This trial was designed to quantify the effect of tortricids in the husks as immature nuts make up a large portion of the unsound kernel percentage annually (Nunes 2007).

Ten prematurely aborted nuts were picked up from each of 5 randomly selected trees at an unsprayed orchard during the second part of the season before the onset of the normal harvest cycle (January – April 2005 and January – April 2006). Shells of nuts that contained live tortricid larvae in the husk were marked with a black felt tip marker. After drying, all nuts were cracked by hand whereupon the kernels were immersed in water at room temperature to determine maturity (mature kernels float due to high oil content while immature nuts sink). The first part of this survey was conducted during the January - April 2005 production season and data was pooled from all eight localities that were surveyed at the time. The survey was conducted across a broad range of commercially available cultivars (788, 741, 341, Beaumont, 791, 816 and Nelmak 2). During the second part of the survey in 2006, only Beaumont (695) trees were used. Since this cultivar matures very late in the season it is therefore expected to be more prone to tortricid induced immaturity than any of the other cultivars.

2.5 Damage estimates and population trends of the Heteroptera complex occurring on macadamia

2.5.1 Description of trial sites

Refer to Annexure 2.1 for a description of the trial sites where this survey was conducted.

Except for the organic orchard and the one at Nelspruit, all other orchards were sprayed on a commercial basis and would thus not reflect natural population dynamics of heteropterans.

2.5.2 Procedures regarding population monitoring

Refer to section 2.4.2 for the design of the trial. Approximately 30 200 nuts were examined over four seasons. The relative large numbers of nuts which were examined was considered to be sufficient to represent the nature and scope of damage inflicted by heteropterans at all trial sites.

2.5.3 The effect of Heteroptera feeding activity on nut drop

To ascertain if the Heteroptera complex caused damage after nuts had dropped, nuts (n = 160) were sampled underneath five randomly selected trees from each of the following three cultivars: A16, A4 and Beaumont. The nuts were harvested from April – June during the natural harvest cycle of macadamias (Table 1.1). These nuts were then compared to an equal number of physiologically mature nuts that were randomly picked approximately 2,5m above soil level. All the nuts were immediately de-husked by hand, dried for three weeks at ambient temperature and humidity whereupon they were manually cracked to assess incidence of heteropteran induced kernel damage. The data was then subjected to an Student's t test to determine if there were differences between the two localities.

To best quantify the possible effect of heteropterans on fallen nuts, it was decided to conduct this trial in Nelspruit on the only unsprayed farm listed in Annexure 2.1. Fallen nuts were therefore exposed to very high levels of heteropterans. On most commercial farms where the nuts are routinely sprayed, prohibitively large numbers of nuts will have to be cracked for a reliable comparison.

2.5.4 Quantification of seasonal heteropteran damage

In an effort to quantify possible seasonal variation in Heteroptera damage which could be exploited to reduce the frequency of insecticide application and/or increase kernel quality the following trial was conducted in the unsprayed orchard of the ARC-ITSC in Nelspruit (Annexure 2.1):

2.5.4.1 The effect of selective exposure of macadamia nuts throughout the production season to natural populations of heteropterans in an unsprayed orchard

The cultivar Beaumont (HAES 695) was selected for this part of the trial because it has a tendency to retain mature nuts on the tree unlike most other cultivars which shed nuts when approaching maturity. 130 racemes containing 439 nuts were randomly selected on 25 trees. These racemes were selected from the basal 2.5m and although care was taken to select nut clusters on all the trees, those near the edges of the orchard invariably had more suitable nut clusters. Beaumont nut clusters containing three or more nuts are relatively scarce but for the purpose of this trial, clusters containing three - five nuts were selected as it would optimise the number of bags used during this trial. All suitable nut clusters were covered with birdspun, (Cape Agricultural Products (Pty) Ltd.) cages (300mm x 150mm) immediately after premature nut drop came to an end towards the end of November 2004. Because this trial was conducted in an unsprayed orchard it would probably reflect the natural situation regarding Heteroptera damage as close as possible.

Starting on the 15th of December ± 10 cages containing 30 – 40 nuts (3 – 4 nuts/cage) were removed every fortnight and exposed to natural populations of heteropterans. The clusters were marked with flagging tape and cages were replaced after each 14 day exposure. The final 20 cages containing 54 nuts were removed on the 3rd of May 2005 and all the nuts were subsequently harvested within 2 weeks. Additionally one adult and one 5th instar nymph of *B. natalicola* were placed into each of 7 cages and 33 nuts were exposed to *B. natalicola* in this way. The heteropterans were confined to the nut clusters for a period of one month during April 2005 when all the nuts were mature and ready for harvest. An additional 40 nuts that were not caged for the duration of the trial were also harvested from 10 localities to serve as a control.

2.5.4.2 The effect of selective protection of macadamia nuts throughout the production season from natural populations of heteropterans in an unsprayed orchard

A second trial was conducted concurrently on 25 A4 trees in the same unsprayed orchard. The A4 cultivar was selected because it is very precocious and contained large numbers of nuts/cluster (± 6). 72 Racemes containing 390 nuts were randomly selected on 25 trees. Suitable racemes were selected from the basal 2.5 m of a tree.

The cages that were removed from the Beaumont trees every fortnight were placed around nut clusters of the A4 cultivar. Each nut cluster was only protected from populations of naturally occurring heteropterans for a period of two weeks whereupon the cages were again removed. All nut clusters were marked with flagging tape indicating the date that the respective clusters were protected by the cages. This trial was initiated simultaneously with the Beaumont trial but was harvested one week later during 9 – 13 May 2005.

After harvesting, all the nuts were manually de-husked, dried at ambient temperature and relative humidity, hand cracked and rated for Heteroptera damage. The kernels were subsequently divided into five classes ranging from uninfested (no visible lesions) to more than 90% destruction of kernel surface area. Damage was expressed as a damage index according to the equation of Wheeler (1963):

$$\text{Stinkbug damage index} = \frac{\text{Sum of all numerical ratings}}{\text{Total number of nuts}} \text{ X } \frac{100}{\text{Maximum damage category}}$$

Abbots formula (Abbot 1925) was then used to calculate the % undamaged nuts in each trial. The following equation was used:

$$\%\text{ undamaged nuts} = \left(1 - \frac{\text{n in T after treatment}}{\text{n in Co after treatment}}\right) \times 100$$

Where n = natural population of heteropterans

T = Treated (exposed/protected to/from natural populations of heteropterans for a fortnight)

Co = Control (nuts exposed to natural populations of heteropterans for the entire duration of the trial).

2.5.5 Risk profile of heteropterans with specific reference to *B. natalicola*

Trials were conducted in order to calculate the seasonal risk profile of *B. natalicola* and were based only on kernel distance versus the rostrum length of the respective nymphal stages.

The combined husk and shell thicknesses (kernel distance) of the following medially measured nut size cohorts were determined with a digital micrometer:7.5 – 9.99, 10.0 -12.49, 12.5 – 14.99, 15.0 - 17.49, 17.5 – 19.99, 20.0 – 22.49, 22.5 – 25.99 & 26.0 – 27.5mm. The shell and husk thickness (kernel distance) of each nut was measured and a regression line was fitted to the data to demonstrate the relationship between the mean medial diameter and kernel distance.

This survey was conducted during the 2006/07 production season on a commercial farm at Karino approximately 20km east of Nelspruit (Annexure 2.1). Data collection commenced in October 2005 just after flowering and lasted until nuts reached a maximum diameter of approximately 30mm during December 2006. Approximately 50 randomly selected nuts were picked from the trees and measured each week to quantify the incremental seasonal increases in mean medial diameter and kernel distance. It was decided to measure only the medial kernel distance of the nuts as this area is the thinnest and therefore the most vulnerable to heteropteran attack. All measurements were done on the Beaumont cultivar since it currently comprises approximately 45% of all macadamia trees planted in South Africa.

Various developmental stages of *B. natalicola* and *P. wayi* were also collected in macadamia orchards at the ARC-ITSC in Nelspruit. All the various stages were photographed because producers and insect scouts are currently confusing immature insects with less damaging species or even with other insects.

To determine if Dyar's law is indeed applicable to inter instar growth ratios of mouth part lengths of the respective nymphal stages of *B. natalicola*, the rostrum length of each instar was determined using a stereomicroscope fitted with an ocular eyepiece and a stage micrometer. The mouthparts were measured from where the four stylets (two mandibular and two maxillary) enter the labrum to the point where they end in the labium.

2.6 Compensatory ability of macadamias to flower removal and early crop damage: Implications for managing the Heteroptera and tortricid insect complexes

2.6.1 Natural abortion rate of two major macadamia cultivars in South Africa

This trial was conducted in an unsprayed orchard at the experimental station of the ARC-ITSC at Nelspruit (Annexure 2.1). One hundred nut clusters each of the Beaumont and 816 cultivars respectively were marked just after anthesis. The nuts remaining per raceme were counted weekly until 36 weeks post anthesis whereupon the trial was terminated.

2.6.2 Effect of heteropteran feeding on nut abortion

2.6.2.1 Exposure to heteropterans during October (4 weeks post anthesis)

To quantify the effect of heteropteran feeding on nut abortion the following trial was initiated on an unsprayed orchard at Nelspruit (Annexure 2.1) during October 2003 and October 2004 (± 4 weeks after anthesis) when endosperm development and cell division were actively taking place (Joubert 1986). Nut clusters containing at least five nuts each, were randomly selected in the bottom 2.5m of the trees. Ten clusters (cv. Beaumont) were exposed to both *P. wayi* and *B. natalicola* by placing two heteropterans in a cage (20mm x 15mm in diameter) which was tied around each nut cluster. Each exposure lasted three days whereupon the cages containing bugs were removed. Because of the difficulty of obtaining sufficient insect material for trials during the early season, these trials were unfortunately not replicated.

The exposure period was restricted to only three days to minimise the mechanical effect of trampling by the insects on the small nuts. Additionally, to obtain sufficient nourishment from the small nuts, heteropterans may feed a number of times per day on each nut which may result in the rapid abortion of affected nuts. Restricting the exposure period to only three days was therefore regarded as a more natural situation.

2.6.2.2 Exposure to heteropterans during November (8 weeks post anthesis)

During 2004 an additional 10 nut clusters were selected and subsequently exposed to *B. natalicola* during November (just before premature nut drop came to an end). The same procedure as in section 2.6.2.1 was then followed for the remainder of the trial.

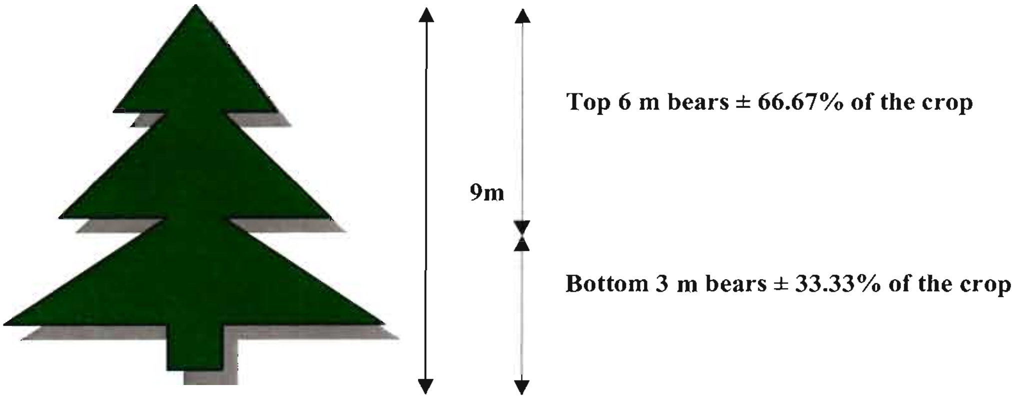
2.6.2.3 The effect of infestation time after anthesis on nut abortion

Feeding marks on the inside of the husk are increasingly used by some farmers to determine the presence of heteropterans in an orchard. Since infested nuts remain on the trees for longer towards the end of premature nut drop, it is suspected that this monitoring method will gradually become more unreliable as the season progresses. The aim of this trial was to quantify the period when feeding marks on the inside of the husk (Fig. 2.7) can reliably be used to determine the abundance of heteropterans in an orchard.

Twenty nuts were harvested from a minimum of five unsprayed A16 trees at Nelspruit every week from approximately 2 weeks after anthesis (mid October) up until the end of premature nut drop during December 2004. Nuts were dissected and all heteropteran feeding lesions were recorded. Heteropteran damage on these nuts was then compared to heteropteran damage on an equal number of naturally aborted nuts that were collected from the same trees. Only nuts that were recently aborted (green husk without any fungal growth or discoloration on the epidermis) were used for this trial. On the nuts harvested from the trees, it is expected that the initial incidence of heteropteran feeding lesions will be low just after flowering but should increase to levels equal to that of the nuts collected from the ground when insect induced abortion no longer occurs (early December).

2.6.3 Artificially simulating early season damage

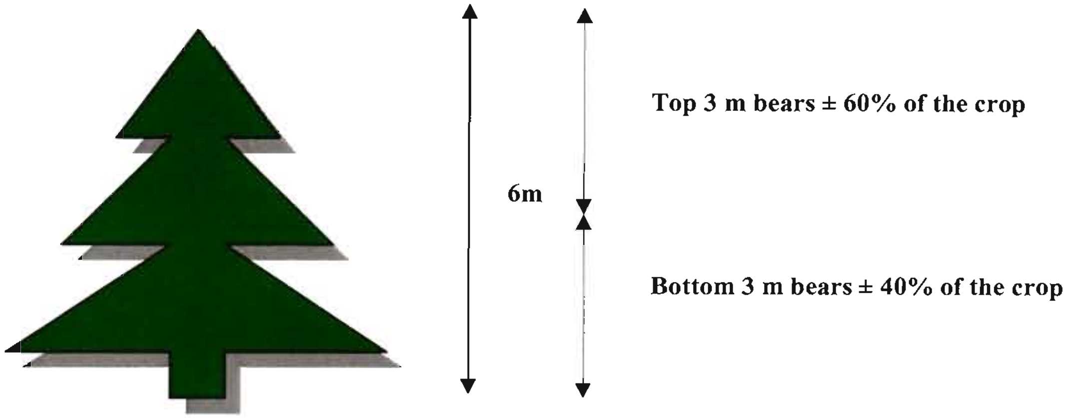
This trial was conducted on the unsprayed orchard at Nelspruit and on a commercial orchard at Burgershall (Annexure 2.1). To simulate heteropteran damage, racemes containing flowers were removed at peak flowering (approximately mid September). The trees at Burgershall were nine metres tall and approximately 10 years old while the trees at Nelspruit were only six metes tall and four years old. Two treatments were applied namely a severe removal of flowers (75% from the bottom three metres) and a more mild removal (40% from the bottom three metres). Ladders were used for the removal of the higher racemes but because macadamias are generally very tall and dense trees, racemes occurring in the tops of the trees were impossible to reach. Consequently removal of racemes only took place in the bottom 2.5m – three metres of the trees. The percentage total flower removal at Burgershall and Nelspruit was indicated by Figs. 2.8 and 2.9 respectively.



75% flower removal from bottom 3 m = 75 x 33.33/100 = 25% of total flowers removed

40% flower removal from bottom 3 m = 40 x 33.33/100 = 13.33% of total flowers removed

Fig. 2.8 Method used for estimating the total percentage flower removal at Burgershall experimental station.



75% flower removal from bottom 3 m = 75 x 40/100 = 30% of total flowers removed
40% flower removal from bottom 3 m = 40 x 40/100 = 16% of total flowers removed

Fig. 2.9 Method used for estimating the total percentage flower removal at Nelspruit experimental station.

Beaumont nuts were picked from the trees during June which coincides with the normal harvest period.
At Burgershall each treatment was replicated five times and each replicate tree was randomly selected within a 2 ha mixed cultivar orchard. Due to the shortage of suitable trees at Nelspruit each treatment could only be replicated three times. All the nuts were counted and weighed and yield was therefore expressed as "wet nuts in shell" (WIS).

Data was analysed using the statistical program Genstat (2003). Fisher's protected least significant difference test was done to quantify differences between the various treatments.

2.6.4 Commercial field trials quantifying the effect of withholding early season sprays.

To determine if macadamia trees can compensate for early crop loss the following trials were done on the Burgershall experimental station. The orchard consisted of a mix of the cultivars 344, 791, 741 and Beaumont. During 2003/04, the following treatments were applied:

1) 50 % of the orchard received the first insecticidal spray consisting of a synthetic pyrethroid (Beta cyfluthrin 50g/L ECl @ 15 ml/100L water) on 13 October.

Hereafter, normal spraying intervals (refer to point 3 below) were followed for the rest of the season.

2) The remainder of the orchard received the initial insecticidal spray consisting of endosulfan on 9 December. Hereafter, normal spraying intervals (refer to point 3 below) were followed for the remainder of the season.
3) These two trial blocks (1 & 2) were compared to an adjoining commercially managed orchard that received the following sprays: Endosulfan 475 g/L SC @ 120 ml/100L water (Nov, Dec, Feb, March) and a synthetic pyrethroid (Beta cyfluthrin 50g/L ECl @ 15 ml/100L water) (Aug & Oct).

The trial was refined during 2004/05 and the following treatments were applied:

1) The trial orchard received initial spray applications on 2 November 2004, followed by spray applications consisting of a synthetic pyrethroid (Beta cyfluthrin 50g/L ECl @ 15 ml/100L water) on 26 November 2004 and endosulfan (Endosulfan 475 g/L SC @ 120 ml/100L water) during January en February 2005.
2) Incidence of insect induced nut damage on above-mentioned treatment was then compared to an adjoining commercially managed orchard that received two synthetic pyrethroids sprays (Beta cyfluthrin 50g/L ECl @ 15 ml/100L water) prior to 2 November as well.

Approximately 2 800 and 1 700 naturally aborted nuts were collected underneath these trees during the period February – May 2004 and January – May 2005 respectively. Due to the nature of this trial (demonstration trial and a limited number of trees), a fully randomised trial design could not be done.

Ten nuts from each of five randomly selected trees per cultivar were collected periodically throughout the study period from each of the four cultivars. All the nuts were manually de-husked and rated for tortricid damage. The nuts were then dried at ambient temperatures and humidity for ± 3 weeks whereupon they were hand cracked and rated for the absence/presence of heteropteran induced kernel lesions.

Data was analyzed using the statistical program Genstat (2003). Fisher's protected least significant difference test was done to quantify differences among the various treatments. Because the data was heterogeneously distributed, 2003/04 data was transformed using the formula: $\sqrt{(x + 0.5)}$.

Annexure 2.1 Description and geographical location of trial sites at which population dynamics of the tortricid and Heteroptera pest complexes of macadamia were monitored in South Africa.

Trial site	Grid reference	Elevation	Farm size	Remarks
Nelspruit	25° 26' 55.73"S 30°58' 09.77"E	657m	Part of 80 ha research farm	The orchard consisted of nine cultivars, which were not planted in a randomized configuration. Although the orchard was optimally fertilized and irrigated, it received no insecticidal or fungicidal sprays during and/or preceding the study period. The orchard was bordered by guava and mango orchards on two sides and natural bush on the remainder (in close proximity to potential host plants of both pest complexes).
Hermansburg	25°32'22.48"S 30°56'04.35"E	946m	25ha	Orchard consisted of a mix of largely Hawaiian varieties on ± 25 ha and was bordered by natural bush. General management was suboptimal mainly because the trees were grown under dry land conditions.
Kaapschehoop	25°31'13.11"S 30°52' 12.21"E	961m	40ha	Orchard was bordered by natural bush and timber plantations consisting largely of *Pinus* sp. and *Eucalyptus* sp. Although many macadamia cultivars have been planted on the farm, nuts were only collected from a ± 9 year old orchard consisting of the cultivar 788.
Burgershall	25°07'01.94"S 31°05'04.15E	765m	Trial sites form part of 100 ha research farm	The orchards were established in November 1993 and were bordered by banana plantations on two sides and litchis and avocado orchards on the remainder.
Kiepersol	25°06'28.46"S 31°01'05.56"E	988m	100ha	This locality was chosen because it is currently one of the biggest macadamia producing farms in the region. It is well managed and is surrounded either by other macadamia farms or timber plantations. The trees were also ± 9 years old and consisted largely of the Beaumont and

				816 cultivars.
Barberton	25°40'07.35"S 30°51'19.21"E	892m	25ha	This well managed orchard consisted of 5 year old trees consisting only of the Beaumont and 816 cultivars. The orchard was bordered by avocado and macadamia orchards on two sides and natural grasslands on the remainder. The farmer expressed interest in adopting IPM principles.
Karino	25°29'41.08"S 31°06'49.53"E	578m	35ha	This well managed 9 year old orchard consisted mostly of the Beaumont cultivar, but a number of Nelmak 2 trees were interplanted among these as pollen donors for optimal cross pollination. Because this farm is situated in a predominantly citrus region, it has a history of severe infestations of the false codling moth (*T. leucotreta*).
Organic farm	25°20'26.85"S 30°52'24.87"E	866m	10ha	The trees were very old (± 30 years) and consisted largely of the old 246 cultivar. The trees were well managed but did not receive any inorganic pesticides or fertilizer during the past three seasons. The orchard was largely surrounded by natural bush, but was planted in close proximity to large conventionally managed macadamia orchards.

Annexure 2.2 Origin and characteristics of macadamia cultivars used during resistance assessment trials of the Heteroptera and Tortricidae complexes according to Allan (2006).

Cultivar (name)	Origin	Country of origin	Growth form	Special characteristics
294 (Purvis)	*M. integrifolia*	Hawaii (1981)	Spreading	Good kernel appearance. Adapted to low elevations.
344 (Kau)	*M. integrifolia*	Hawaii (1971)	Upright	Precocious bearer – coastal growers report high tortricid damage.
660 (Keaau)	*M. integrifolia*	Hawaii (1966)	Upright	Nuts drop early, small kernels of excellent appearance.
695 (Beaumont)	Hybrid between *M. integrifolia* and *M. tetraphylla*	Australia	Intermediate	Most planted macadamia cultivar in South Africa. Precocious bearer and roasting characteristics of kernel resembles *M. integrifolia* derived cultivars.
741 (Mauka)	*M. integrifolia*	Hawaii (1977)	Upright	Graft-wood of 741 and 800 got mixed in South Africa and caused confusion. Adapted to high elevations.
788 (Pahala)	*M. integrifolia*	Hawaii (1981)	Spreading	Very thick husk and shell thicknesses, excellent kernel appearance and quality.
789	*M. integrifolia*	Hawaii	Spreading	Good kernel appearance and good crack out percentages.
791 (Fuji)	Hybrid between *M. integrifolia* (50%), *M. tetraphylla* (5%) *and M. ternifolia* (45%)	Hawaii	Open upright tree with long branches	Precocious bearer prone to an unidentified kernel condition – so called 791 spot which downgrades these kernels significantly.
800 (Makai)	*M. integrifolia*	Hawaii (1977)	Round shape; very	Excellent kernel appearance used as standard of quality in

			dense canopy	Hawaii. Adapted to lower elevations.
814	*M. integrifolia*	Hawaii	Round canopy	Very precocious bearer – small but excellent kernels – popular cultivar.
816	*M. integrifolia*	Hawaii	Upright – open	Excellent kernel very high crack out percentages up to ± 48% trees normally have a yellow sheen; leaves without spines.
863	*M. integrifolia*	Hawaii	Spreading	Poor kernel appearance but good crack out percentage.
Hidden Valley A4	Hybrid between *M. integrifolia* (70%), and *M. tetraphylla* (30%)	Australia (1989)	Spreading	Precocious bearer – very large kernels of good appearance; susceptible to thrip damage.
Hidden Valley A16	Hybrid between *M. integrifolia* (70%), and *M. tetraphylla* (30%)	Australia (1989)	Upright	Precocious bearer – very large kernels of good appearance; susceptible to thrip damage.
Nelmak 1	Hybrid between *M. integrifolia* (50%), and *M. tetraphylla* (50%)	South Africa (1973)	Upright/spreading	Inflorescence pink and very long. Very large kernels of good appearance.
Nelmak 2	Hybrid between *M. integrifolia* (50%), and *M. tetraphylla* (50%)	South Africa (1973)	Spreading, open tree	Precocious bearer. Very large kernels of good appearance.
NE2	This cultivar also got mixed in transit and was never commercially released.			

Annexure 2. 3. Timing and number of insecticide treatments applied against macadamia insect pests during the main fruiting period over three seasons (2003/04 – 2005/06).

Location	Approximate spray application dates				
Burgershall (2003/04)	Aug (SP)	Oct (SP)	Dec (E)	Jan (E)	Feb (E)	March (E)
Burgershall (2004/05)	Oct (SP)	Oct (SP)	Nov (SP)	Nov (SP)	Jan (E)	Feb (E)
Burgershall (2005/06)	Oct (SP)	Dec (SP)	Jan (SP)	Feb (E)	March (E)	
Kaapschehoop (2004/05)	July (SP)	Aug (SP)	Oct (SP)	Dec (SP & E)	Feb (SP)	March (SP)
Kaapschehoop (2004/05)	Aug(SP)	Oct (SP)	Dec (SP)	Feb (SP)	March (SP)	
Kiepersol (2004/05)	Oct (SP)	Dec (SP)	March (SP)	June (SP)		
Hermansburg (2004/05)	July (SP)	Sept (SP)	Oct (SP)	Nov (SP)	Jan (SP)	
Hermansburg (2005/06)	Oct (SP)	Nov (SP)	Dec (SP)	Feb (SP)	March (SP)	
Karino (2005/06)	Nov (SP)	Dec (A)	Feb (E)	March (E)		
Barberton (2005/06)	Oct (SP)	Nov (SP)	Dec (SP)	Feb (SP)	March (SP)	
Organic (2005/06)	Sept (FPE)	Sept (CO)	Oct (NO)	Nov (NP)	Dec (FPE, NO & CO)	Feb & March (FPE)

Legend

SP – Synthetic pyrethroid

A – Acephate SP 750 g/kg

CO – Canola oil

NP – Natural pyrethrum

E - Endosulfan SC 475g/L

FPE – Fermented plant extract

NO – Neem oil

The mean spray turn around times for the respective locations was: Burgershall (3 days), Kiepersol (2 weeks), Karino (3 days), Barberton (4 days), Organic farm (1day), Kaapschehoop (5 days) and Hermansburg (12 days).

CHAPTER 3

Results and Discussion

3.1 Factors contributing towards tortricid and heteropteran resistance/tolerance of macadamia cultivars

3.1.1 Introduction

The aims of this study were to strengthen knowledge regarding plant insect interactions in order to design more environmentally sensitive control programmes and to facilitate decision support regarding cultivar choices for small, organic, as well as commercial farmers.

3.1.2 Results

Due to the heterogeneous nature of the distribution of tortricids and heteropterans, relative incidence of insects on a particular cultivar is probably not directly linked to the resistance/susceptible status of a particular cultivar against a specific pest. The terms relatively damaged or relatively undamaged are more descriptive and will be used for this section. Relatively damaged nuts therefore indicates susceptibility and *vice versa*.

3.1.2.1 Tortricid complex

3.1.2.1.1 Natural thinning period (premature drop of immature nuts)

Because the damage profiles and morphology of all major nut boring pests are similar, no distinction was made between various tortricid species and therefore all results in this section refer to the tortricid complex in general. Due to very low numbers of tortricid larvae recorded in the nuts during this phase (1.22%, n = 9 199 at Burgershall and 0.39%, n = 2 541 at Nelspruit), statistical analysis revealed no significant differences amongst the various cultivars (Nelspruit, F value = 1.18, P = 0.322; Burgershall F value = 2.17, P = 0.014). However, Figures 3.1 and 3.2 were included as it highlights certain important trends.

The mean level of infestation during the natural thinning period did not vary much between the seasons in the commercial orchard at Burgershall (2002 = 1.24%; 2003 = 1.38%), but was considerably lower in the unsprayed orchard at Nelspruit during

2002 (0.39%, n = 2 541). Natural control in the unsprayed area probably accounted for this observation.

At Burgershall, cultivars 863, 800 and 294 were more damaged by tortricid larvae followed closely by cultivars 741, 344 and 789. In the unsprayed orchard at Nelspruit all the hybrid cultivars (Annexure 2.2), as well as 788 were damaged by tortricid larvae, while in all the *M. integrifolia* derived cultivars no damage was recorded. Damage during this period was too slight to draw any meaningful conclusions, but the trends that became apparent during this period are important and will be highlighted during subsequent sections of this chapter.

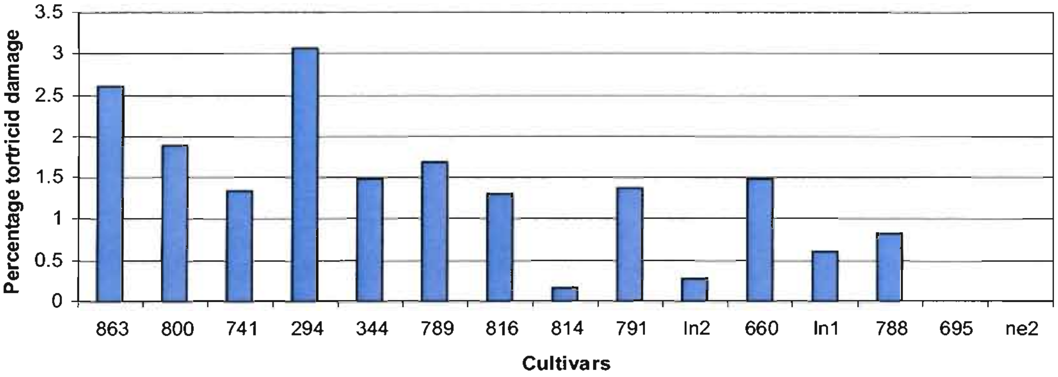


Fig. 3.1 Pooled percentage damage incurred by tortricid larvae on small developing nuts (Aug – Dec 2002 and Aug – Dec 2003) for 15 macadamia cultivars in a commercially managed orchard at Burgershall. Average infestation = 1.22%, n = 9199.

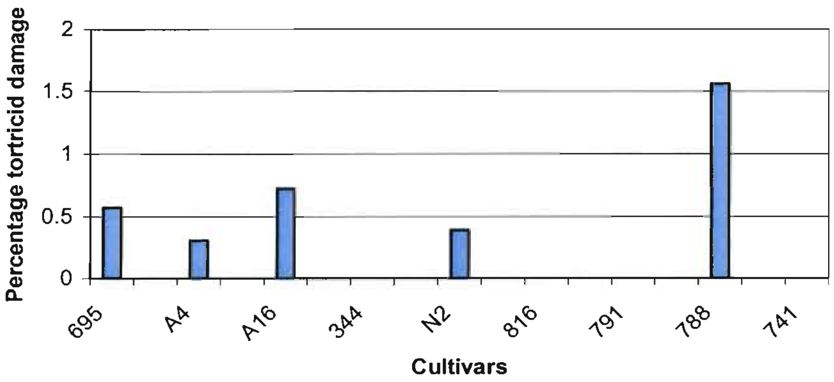


Fig. 3.2. Tortricid relative susceptibility of 9 macadamia cultivars based on damaged nuts during premature drop of immature nuts, recorded from 13 October 2003 to 5 January 2004 in an unsprayed orchard at Nelspruit. Average infestation = 0.38%, n = 2541.

Although a number of aborted nuts smaller than 15 mm containing tortricid larvae were recorded, they were only recorded during the early part of the monitoring period (August - October) when all the nuts were small and still immature.

According to Fig 3.21 tortricids may largely be regarded as pests of larger older nuts and when the average size of aborted nuts containing tortricids was compared to the average size of uninfested nuts (Figs 3.3 & 3.4), this assumption was confirmed.

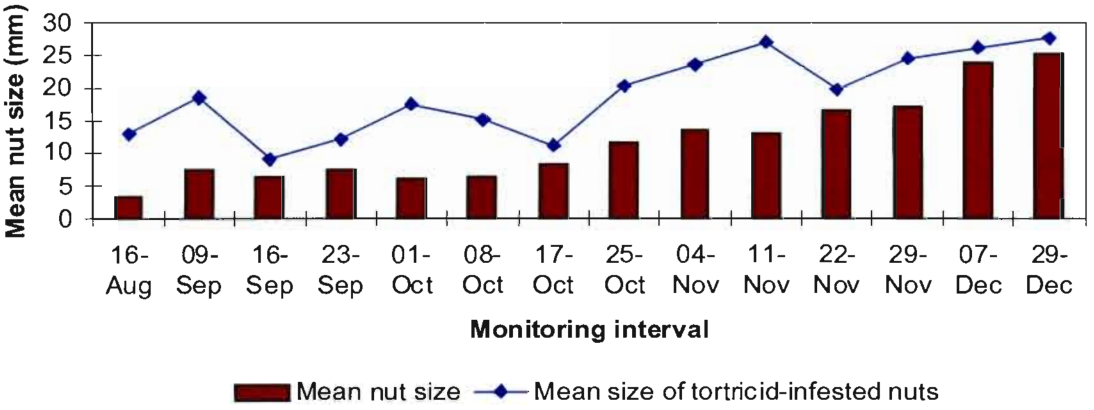


Fig. 3.3 Nut size preference of tortricids based on larval damage of aborted nuts during the natural thinning period at the Burgershall research station during the 2003 season.

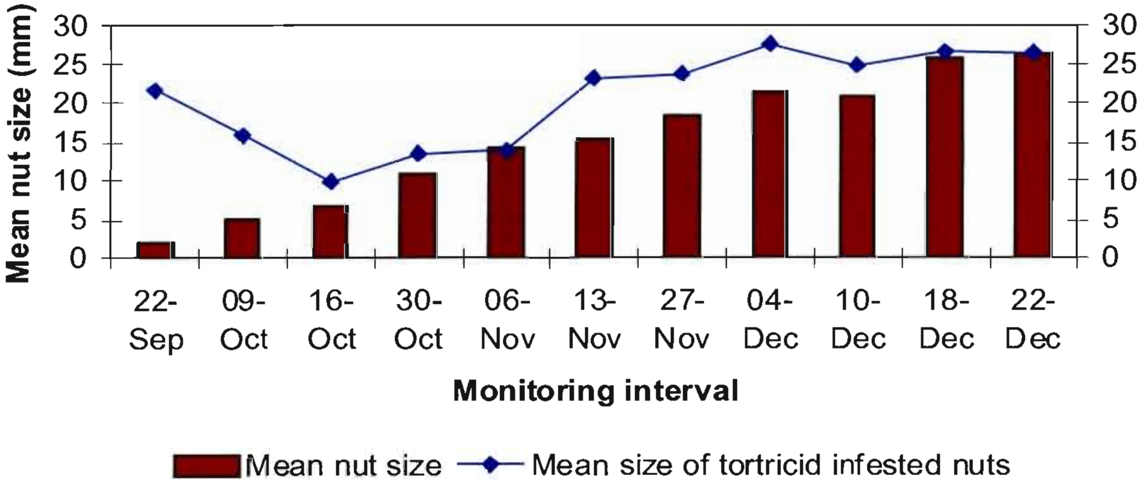


Fig. 3.4 Nut size preference of tortricids based on larval damage of aborted nuts during the natural thinning period at the Burgershall research station during the 2004 season.

Peak flowering normally occurs during mid September (week 28 of the Julian calendar). Although a small number of out of season nuts were recorded early in the season, the most severely damaged cultivars (863, 800 and 294) were slightly more numerous immediately after flowering (Compare Table 1.1 with Annexure 3.1).

According to Table 3.4 hybrid cultivars appear to be particularly susceptible to this group of insects, but according to Annexure 3.1 the relative seasonal occurrence of hybrid nuts with a medial diameter of more 10 mm reveals the exact opposite of what was expected. These cultivars mature much later which points to the possibility that resistance is more complicated than the mere availability of suitably sized nuts early in the season.

According to Annexure 3.2 tortricid larvae did not considerably exploit nuts of the susceptible *Macadamia integrifolia* derived group early in the season during both seasons of monitoring, while hybrid cultivars infested with tortricid larvae only became significantly numerous later in the season which indicates that nut maturity do not have an important influence on resistance.

3.1.2.1.2 Natural nut drop (mature nuts)

- **Nelspruit assessment**

Although an appreciable variation in data was expected from this locality due to high insect incidence (Annexure 3.7) and the expected heterogeneous distribution of tortricids (Fig. 3.20), hybrid cultivars were consistently more damaged by the tortricid complex (Table 3.1). Although not all differences between the five most severely affected cultivars were significantly different, Table 3.1 indicates that during both monitoring periods nearly all the most severely infested cultivars were hybrids.

This pattern (more severely infested hybrid cultivars) remained relatively constant when kernel damage was subsequently evaluated. Although 791 is also a hybrid (Annexure 2.2) it was assumed that the addition of *M. ternifolia* (which contains cyanogenic compounds) probably correlated with some degree of resistance as this species is known to be hypertoxic (Smith & Meston 1914). As expected, this cultivar is genetically similar to other hybrids (Pearce *et al.* 2001).

Beaumont was in most cases considerably damaged, but this can possibly be ascribed to the method of data collection. Unlike most other cultivars Beaumont does not spontaneously abort nuts when approaching physiological maturity. During these assessments only aborted nuts were collected in order to standardise methodology which could have resulted in a significant overestimation of the susceptibility as only severely infested nuts are likely to abort.

The cultivars 741 and 788 were generally associated with low infestation levels in husks as well as inside the kernels during both seasons of monitoring. The host status of Nelmak 2, 791, 816 and 344 varied between seasons. Possible reasons for this conundrum are discussed in section 3.1.3.2.

Table 3.1 Mean number of husk and kernel feeding tortricid larvae collected from naturally aborted mature nuts in an unsprayed variety orchard at Nelspruit from 12/02/2002 – 28/05/2003 and from 22/12/2003 – 07/07/2004.

Cultivar	Mean number of larvae								
	2002/03				2003/04				
	Kernel	Ranking [a]	Husk	Ranking [b]	Kernel	Ranking [c]	Husk	Ranking [d]	Overall ranking a+b+c+d/ number of observations
Beaumont	2.08a	1	6.36ab	2	7.26ab	3	24.16cd	3	2.25
A4	1.31ab	2	5.50bc	3	10.06b	2	26.2d	2	2.25
Nelmak 2	0.69bc	3	9.71a	1	3.26ab	5	15.8bc	6	3.75
A16	0.15c	5	3.36bcd	4	20.46b	1	43.32d	1	2.75
791	0.42bc	4	2.43cd	7	7.2ab	4	14.9bc	7	5.5
788	0.15c	6	2.5cd	6	0.72ab	8	10.48ab	8	5.6
344	0.08c	7	3.29bcd	5	1.31ab	7	18.81bcd	5	6
741	0.08c	8	0.07d	9	0a	9	18.70bcd	9	8.75
816	0.0c	9	0.71d	8	2.67ab	6	20.19bcd	4	6.75
F value	3.9		8.49		6.42		15.23		
LSD	1.01		3.44		9.39		10.88		
P	0.05		0.05		0.01		0.01		

Columns were analyzed separately

Means within columns followed by the same letter do not differ significantly

Susceptibility ranking: High values – more resistant, Low values – more susceptible

- **Burgershall assessment**

As expected all hybrids including 791 were susceptible to the tortricid complex (Table 3.2). The cultivar 741 had significant tortricid damage during 2003/04 while it was uninfested during the previous season (see section 3.1.3.2 for a general discussion regarding contradictory results). The smooth skinned *Macadamia integrifolia* derived cultivar, 800 had significantly more damage than any of the other cultivars and was severely affected.

The cultivars 816, 344 and 294 are commercially important and were therefore highlighted in subsequent decisions. These cultivars were significantly less damaged by the tortricid complex. Again the host status of 344 is dubious as significant variance occurred between the seasons. Growers in KwaZulu-Natal consider this cultivar as susceptible but this evidence must be regarded as anecdotal as no trials in this regard have been done in South Africa yet. It is expected that the compliment

Table 3.2 Mean number of infested nuts due to husk and kernel feeding by tortricid larvae collected from naturally aborted mature nuts in a commercial variety orchard at Burgershall during the 2002/03 and 2003/04 seasons respectively from December – March.

Cultivar	Mean number of infested nuts						
	2002/03		2003/04				
	Husk	Ranking a	Husk	Ranking b	Kernel	Ranking c	Overall ranking a+b+c/number of observations
800	32.5a	1	66.04e	1	27.39ef	2	1.33
Nelmak 2	22.5ab	2	15.83a	14	9.36abcd	10	8.66
695	21.71abc	3	18.27a	12	17.86abcdef	6	7
Nelmak 1	19.22abc	4	46.61cd	3	33.66f	1	2.66
NE2	13.75abc	5	26.18ab	9	4.52ab	13	9
814	11.67abc	6	13.18a	15	9.98abcd	9	10
789	11.67abc	7	43.32bcd	5	13.92abcde	7	6.33
294	4.96bc	8	19.87a	11	3.79a	14	11
816	4.00bc	9	16.26a	13	2.04a	15	12.33
863	1.67bc	10	45.99cd	4	21.9cdef	4	6
791	1.32bc	11	20.85a	10	11.9abcde	8	9.66

660	1.25bc	12	41.36bcd	6	20.58bcdef	5	7.66
788	1.19bc	13	31.58abc	7	6.7abc	12	10.66
344	0.00c	14	28.07abc	8	9.09abcd	11	11
741	0.00c	15	52.37de	2	25.05def	3	6.66
F value	1.8		5.76		4.38		
LSD	22.43		18.6		16.7		
P	0.05		0.01		0.01		

Columns were analyzed separately

Means within columns followed by the same letter do not differ significantly

Susceptibility ranking: High values – more resistant Low values – more susceptible

of natural host plants surrounding these macadamia orchards linked with mild subtropical conditions could lead to more severe tortricid infestations in the coastal areas. Additionally the majority of trees planted initially in the South Coast of KwaZulu-Natal consisted only of cultivar 344 (A. Shaw personal communication), these trees are now mature and probably provide tortricid moths with more nourishment and shelter when compared to younger orchards consisting of other cultivars.

No statistical analysis was carried out on kernel feeding tortricids at Burgershall during 2003/04 because only two out of 703 nuts were infested. When oviposition by tortricid moths was recorded during natural drop of mature nuts at Burgershall it became evident, according to Table 3.3 that discrimination between cultivars by gravid females occurs before oviposition. At Burgershall 814, 816 and NE2 were statistically significant less attractive to gravid female moths while 788, 791, 695, Nelmak 2 and 741 were less attractive to this complex in the unsprayed location at Nelspruit.

The cultivar 800 was most attractive to ovipositing tortricids at Burgershall while the hybrid cultivars A16 and A4 were particularly attractive at Nelspruit. The cultivar 816 which is normally relatively resistant was statistically significantly more preferred for oviposition than the other cultivars at Nelspruit. Possible reasons for these contradictions are discussed in section 3.1.3.2.

Table 3.3 Relative preference of tortricids for 17 macadamia cultivars based on oviposition during natural nut drop, recorded from 2 February to 17 June 2004 at Nelspruit and from 15 January to 18 March 2004 at Burgershall.

Cultivar	**Mean number of eggs per nut**	
	Burgershall	**Nelspruit**
814	3.86a	
NE2	4.09a	
816	4.22a	15.13c
789	5.99ab	
791	6.18ab	8.95a
695	6.21ab	11.33abc
294	6.61abc	
344	6.78abcd	13.34bc
Nelmak 2	6.99abcd	12.13abc
788	7.45abcd	9.85ab
863	7.63abcd	
660	9.29bcd	
Nelmak 1	10.76cde	
741	11.14de	12.68abc
800	14.74e	
A4		13.95bc
A16		20.99c
F value	6.18	9.13
LSD	4.40	4.23
P	0.01	0.01

Columns were analyzed separately

Means within columns followed by the same letter do not differ significantly

When the mean incidence of symptoms was compared between hybrids and *M. integrifolia* derived cultivars at Nelspruit and Burgershall during the 2002/03 season, a Mann-Whitney U (Willcoxon rank-sum) test revealed significant differences despite very large variation (Table 3.4).

Table 3.4 Comparison of mean husk and kernel tortricid damage between hybrids and *M. integrifolia* derived cultivars at Burgershall and Nelspruit during the 2002/03 season.

	Mean number of infested nuts		**P**
	M. integrifolia	**Hybrids**	
Nelspruit Kernel ± SE	0.1351a ± 0.38	0.95b ± 1.86	0.001
Burgershall Husk ± SE	0.463a ± 1.86	2.20b ± 0.88	0.001

Rows were calculated separately

Means within rows followed by the same letter do not differ significantly

3.1.2.2 Heteroptera complex

3.1.2.2.1 Natural thinning period (immature nuts)

From Table 3.5 it is evident that damage during the natural thinning period at Burgershall for both seasons was not homogenous. Cultivars 863, 800, 344, 294 and 789 had consistently more damage than the other cultivars in this survey. No consistent pattern was evident regarding the other cultivars although cultivars 816, Nelmak 2, & NE2 had high total damage rankings which would indicate resistance.
In the unsprayed orchard at Nelspruit cultivars 695, 344 and Nelmak 2 had the highest damage ratings, while cultivars 741, 816, 788 had lowest damage rankings.

Table 3.5 Relative susceptibility of 15 macadamia cultivars to the Heteroptera complex based on puncture marks on the insides of husks recorded during the natural thinning period at Burgershall during the 2002/03 and 2003/04 seasons and at Nelspruit during the 2003/04 season.

Cultivar	Mean number of infested nuts						
	Burgershall				Nelspruit		
	2002/03	Ranking a	2003/04	Ranking b	2003/04	Ranking c	Overall ranking a+b+c/number of observations
863	2.68c	1	2.58abcd	6			3.5
800	2.19bc	2	3.67cd	2			2
344	1.61abc	3	1.22a	15	3.82bcd	3	7
294	1.55abc	4	4.27d	1			2.5
789	1.53abc	5	2.73abcd	5			5
791	1.14ab	6	2.56abcd	7	2.48abc	6	6.3
Nelmak 1	1.13ab	7	1.24a	14			10.5

814	1.08ab	8	2.74abcd	4			6
741	1.08ab	8	3.41bcd	3	1.17a	9	6.67
660	1.03ab	9	2.02abc	8			8.5
788	1.03ab	9	1.65ab	10	1.75ab	8	9.0
NE2	0.96ab	10	1.31a	13			11.5
695	0.9a	11	1.80ab	9	5.94d	1	7
Nelmak 2	0.86a	12	1.56ab	12	4.63cd	2	8.67
816	0.77a	13	1.6ab	11	2.18ab	7	10.3
A16					3.09abc	5	5
A4					3.17abc	4	4
F value	2.36		3.54		5.71		
LSD	1.27		1.863		2.32		
P	0.01		0.01		0.01		

Columns were analyzed separately

Means within columns followed by the same letter do not differ significantly

Susceptibility ranking: High values – more resistant Low values – more susceptible

3.1.2.2.2 Natural nut drop (mature nuts)

When kernel damage amongst cultivars were compared during natural nut drop in the 2002/03 season at Nelspruit, cultivars 741 and 791 showed significant levels of low damage, while no statistical differences were observed between the remainder of the cultivars (Table 3.6).

Table 3.6 Relative susceptibility of 9 macadamia cultivars to the Heteroptera complex based on damaged kernels recorded for the duration of natural nut drop at Nelspruit during the 2002/03 season.

Cultivar	Average number of infested nuts
741	2.18a
791	3.27a
816	6.62b
788	7.14b
695	7.21b
A16	7.52b
344	8.05b
N2	8.10b

A4	8.61b
F value	11.3
LSD	2.48

P< 0.01, *Means within column followed by the same letter do not differ significantly*

Due to a large variation no statistically significant differences were observed amongst cultivars during 2003/04 at Burgershall (F-value = 1.2; P≤ 0.277). Figs 3.5 and 3.6 were nevertheless included as the trends observed during these monitoring periods support trends portrayed in Tables 3.5 and 3.6. At Burgershall the cultivars 816, 294 and 695 were severely damaged while Ln1, Ln2, 789, 660 and 741 had low damage ratings (Fig 3.5). According to Fig 3.6, A16 and 791 had low damage ratings in the Nelspruit trial, while 695 and 344 had the highest incidence of heteropteran damage.

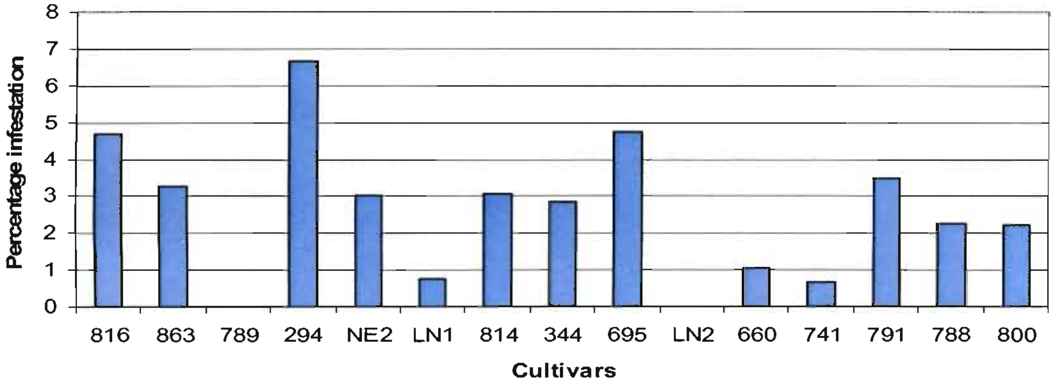


Fig 3.5. Percentage infestation of 15 macadamia cultivars to the Heteroptera complex based on damaged kernels recorded during natural fruit drop at Burgershall during the 2002/03 and 2003/04 seasons.

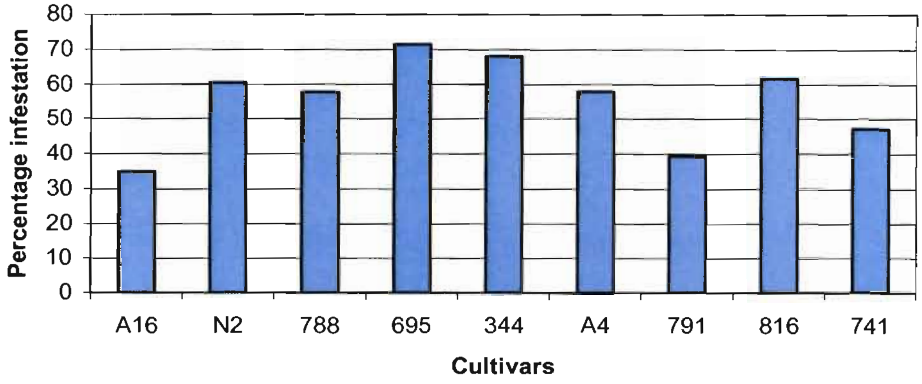


Fig 3.6 Percentage infestation of nine macadamia cultivars to the Heteroptera complex based on damaged kernels recorded during natural fruit drop at Nelspruit during the 2003/04 season.

3.1.2.3 The effect of the combined husk and shell thickness on cultivar resistance tolerance

According to Bruwer (1992) and Jones (1995b) cultivar susceptibility is largely a function of the combined thickness of the husk and shell (kernel distance). Although statistically significant differences were observed between various cultivars regarding kernel distances at the Nelspruit (Annexure 3.3) and the Burgershall (Annexure 3.4) trial sites, large kernel distances did not consistently correspond with lower damage and *vice versa* (Table 3.7). According to Fig 3.7 heteropteran damage was highest on the medial area of the nut, presumably because this is where the husk and shell are the thinnest. This was also the only area of the nut where *Nezara* spp. with relative short mouth parts (±6 mm) was able to penetrate the shell and husk of a fully developed macadamia nut (Fig 3.8).

According to Table 3.7 there was no clear relationship between medial kernel distance and the extent of insect damage of most cultivars.

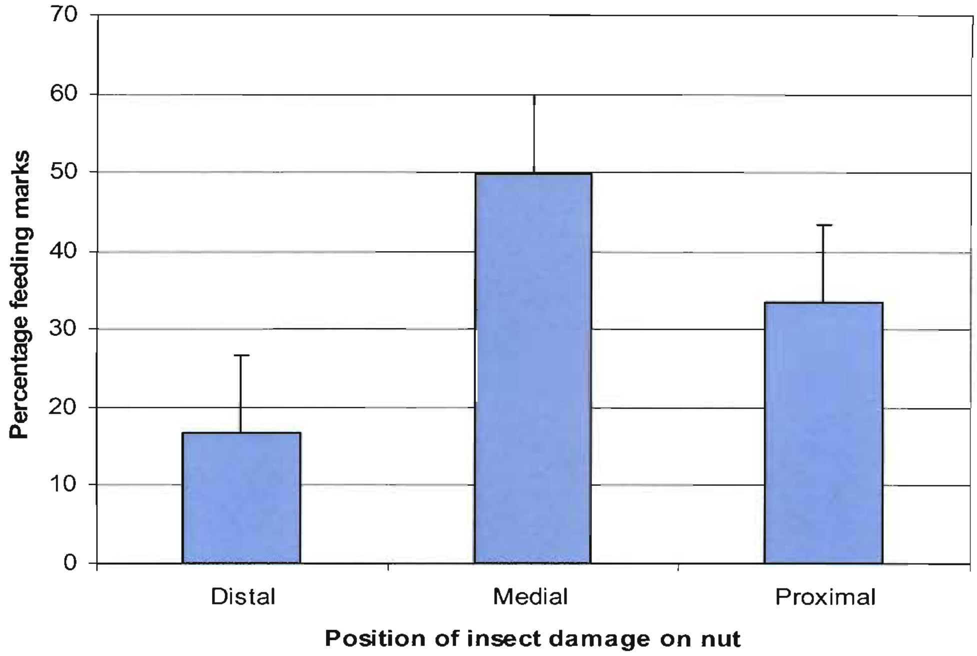


Fig 3.7. Location of Heteroptera induced lesions on unsprayed mature nuts at Nelspruit.

Fig. 3.8 The position of shallow pitting (possibly *Nezara* spp. damage) on a mature macadamia kernel. Note that most of the damage occurred in the medial area where the husk and shell are at their thinnest.

Table 3.7 The relationship between kernel distance (Annexures 3.3 & 3.4) and the resistance tolerance status of the tortricid and Heteroptera complexes (Annexures 3.5 & 3.6)

Cultivar	**Status of cultivar in terms of the combined medially measured husk and shell thickness**		**Status of pest complex according to Tables 3.5 and 3.6**	
	Burgershall	**Nelspruit**	**Tortricid larvae**	**Heteropterans**
863	Thin		Susceptible	Susceptible
789	Thin		Intermediate	Resistant
816	Intermediate	Intermediate	Resistant	Susceptible
294	Thick		Resistant	Susceptible
NE2	Thick		Resistant	Intermediate
LN1	Intermediate		Susceptible	Resistant
814	Thin		Intermediate	Susceptible
344	Intermediate	Thin	Resistant	Intermediate
LN2	Thin	Thick	Intermediate	Resistant
695	Intermediate	Thin	Susceptible	Susceptible
660	Thin		Intermediate	Resistant
791	Intermediate	Thin	Resistant	Resistant
741	Thick	Intermediate	Intermediate	Resistant
788	Thick	Intermediate	Resistant	Intermediate
800	Thick		Susceptible	Susceptible
A16		Thick	Susceptible	Intermediate
A4		Thick	Susceptible	Intermediate

According to Table 3.20 mouthpart length of the most dominant pentatomid, (*B. natalicola)* is 13.6 ± 0.21mm. If this is compared to the kernel distances measured in Annexures 3.3 & 3.4, it is obvious that kernel feeding can take place on all 17 cultivars listed in Table 3.7.

If it is assumed that the majority of kernel feeding occurs in the medial sector (Figs 3.7 & 3.8) then clearly no cultivar could offer any form of resistance if resistance is mainly based on kernel distance.

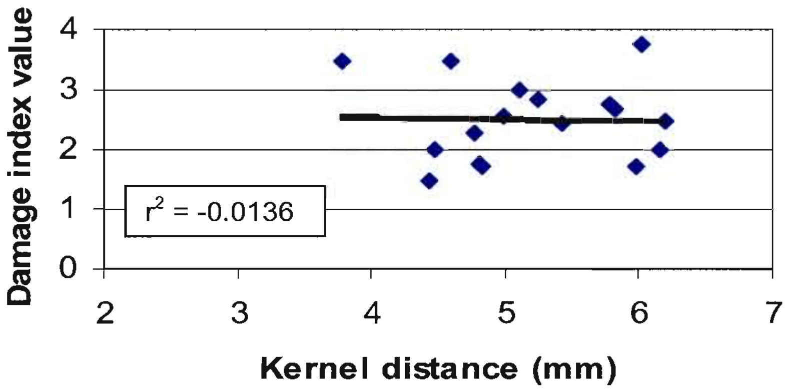


Fig. 3.9 The relationship between Heteroptera damage index value and kernel distance (mm) of 15 commercial macadamia cultivars at Burgershall research farm during 2003/04.

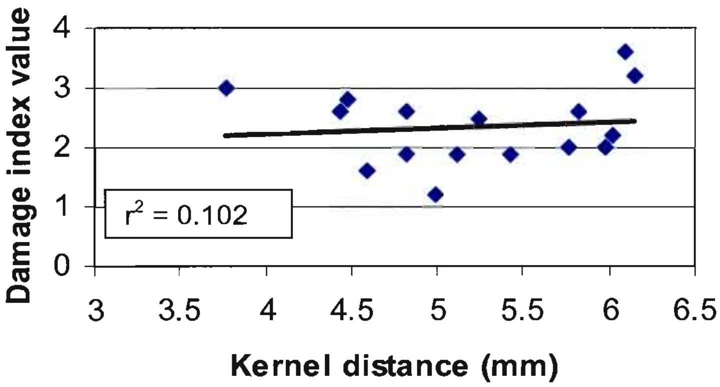


Fig. 3.10 Relationship between tortricid damage index value and kernel distance (mm) of 15 commercial macadamia cultivars at Burgershall research farm during 2003/04.

According to Figs. 3.9 and 3.10, regression analyses for the tortricid and Heteroptera complexes revealed no clear relationship between kernel distances (Annexures 3.3 & 3.4) and resistance index values (Annexures 3.5 & 3.6).

According to Jones (1995b), altitude has an important effect on shell thickness. Typically plants grown at high altitudes have relatively thick shells. This assumption was valid because macadamias grown at a higher altitude (± 300m higher) at Burgershall appeared to have larger mean medial kernel distances (5.19mm, n = 350) than Nelspruit (4.47 mm, n = 350) when kernel distances of cultivars 695, Ln2, 344, 788, 791, 816 and 741 were compared. Large kernel distances could also play an important role in minimizing damage inflicted by lesser important species with shorter mouth parts such as *Nezara viridula* (6.1mm) and *Nezara pallidoconspersa* (5.8mm). Certainly cultivar 788 with thick medial kernel distances is generally considered to be resistant while cultivars 800 and 294 with equally thick kernel distances are susceptible (Table 3.7). If kernel distance was the only factor preventing heteropterans from feeding on the kernels, then all small nuts during the early thinning period must be equally susceptible to these insects and according to Table 3.5 this was certainly not the case.

3.1.3 Discussion

Selection of varieties is usually an easy and cost effective method to minimize crop losses, provided information regarding resistance/tolerance status of cultivars is available prior to planting.

3.1.3.1 Alternative postulates regarding resistance

Cultivar resistance probably depends on more than one factor. Jones and Caprio (1992) indicated that resistance is more complex and although shell thickness could be an important factor, aspects such as shell hardness and the rate of shell formation could be important as well. Their views are supported by Follett *et al.* (2009) who regard shell and husk thickness as a secondary factor in the quantification of resistance/tolerance towards heteropterans in macadamias.

In South Africa where *B. natalicola* and *P. wayi* are dominant in terms of economic importance, clearly alternative resistance mechanisms such as the physical or chemical characteristics of cultivars must be important as well. Mouthparts of *B. natalicola* are long enough to penetrate and damage any of the nuts that were examined during this study. If alternative resistance factors did not play a role it is expected that all cultivars would have been equally damaged and according to section 3.1.2.2 there were significant differences.

During this study, cultivar 791 exhibited some degree of tolerance. Pearce *et al.* (2001) found that this cultivar contains 45% *Macadamia ternifolia* genetic material. According to Smith & Meston (1914) and O'Neill (1996) *Macadamia ternifolia* kernels has high cyanide content. The kernels of other inedible macadamias (*M. jansenii* and *M. claudiensis*) are also rich in cyanogenic compounds which act as a very effective deterrent for potential herbivores (Smith and Meston 1914). The evolutionary advantage of this adaptation must be considerable since the hyper toxic *M. claudiensis* only has a very thin shell protecting it from potential herbivores. In contrast commercial macadamia cultivars have comparatively thick, as well as very hard, shells.

Cyanide only accumulates in the shell and husk of edible varieties, but not in the kernel (O'Neill 1996). Furthermore cyanide is in many instances only released in the nut upon tissue disruption. This could possibly explain the resistance of macadamias against the tortricid complex, although further research will still have to be done to prove this conclusively. It is doubtful whether allelochemicals in the husk and shell will significantly affect heteropterans, as they disrupt a relatively small amount of husk and shell tissue when inserting their mouthparts into the nut. According to Pearce *et al.* (2001), some of the cultivars with lower damage ratings belong to a similar genetic subgroup which indicates towards a possible genetic basis for resistance determination. Further research should, however, be done to confirm this assumption.

3.1.3.2 Explanations for contradictory results observed during this study

The resistance/tolerance status of a number of cultivars during this study was often contradictory. A good example here was the status of cultivar 741 (Table 3.2). During the initial year of monitoring this cultivar appeared to be resistant, as no infected nuts were recorded. Despite this, this cultivar suffered severe tortricid damage during the subsequent season. Possible explanations for these contradictory results are:

1) **Heterogeneous distribution of tortricid and heteropteran pest complexes**

Both pest complexes on macadamias are heterogeneously distributed (see section 3.3.2.2) and with this in mind many nuts from a large number of trees were sampled. Unfortunately there was also an upper practical limit to the amount of nuts that were sampled every week. If the monitored tree(s) were located in an area of increased or decreased insect activity, the results in terms of insect damage were expected to be profoundly affected.

The effect of gradients of damage created by edge effects is also expected to influence data significantly. In subsequent unpublished research with the heteropteran complex on avocados prominent edge effects were discernible, especially where these orchards border natural bush or macadamia orchards. The consequences of edge effects are difficult to quantify because the compliment of natural as well as cultivated plants in the immediate surroundings of macadamia orchards are bound to vary significantly between farms.

2) Seasonal variability of macadamia cultivars

Parameters such as yield (Sippel *et al.* 2001; Sippel *et al.* 2002) and kernel quality (Table 3.8) varied significantly in other studies as well. Data in Table 3.8 was obtained from Golden Macadamias (Pty) Ltd. and constitute average figures for the industry (± 60 growers). Significant variation in heteropteran damage as well as other kernel disorders was prominent between various seasons. The results of Jones and Caprio (1992) were also highly variable with some cultivars fluctuating between significantly susceptible and significantly resistant during two subsequent seasons of monitoring. It is suggested that cognizance be taken of this inter cultivar variability and to rather use long term trends (Annexures 3.5 and 3.6) if the resistant/susceptible status of cultivars have to be quantified.

3.1.3.3 Resistance/susceptibility: status of the tortricid complex

3.1.3.3.1 Natural thinning period

According to Table 3.5 some degree of cultivar selection already to occur during oviposition. The suggestion by Waite *et al.* (1999) that tortricids are pests of larger more mature nuts is probably valid but severely damaged cultivars produced large mature nuts only marginally sooner than the less susceptible cultivars during the early thinning period (Annexure 3.1) which would contradict *Waite et al.*'s (1999) observation. Hybrid

Table 3.8 Industry average of kernel quality disorders at Golden Macadamias (Pty) Ltd (Nelspruit). (Alwyn du Preez personal communication)

Variety	Year	Mean mass of damaged nuts /400g sample					
		Heteroptera (Early)	Heteroptera (Late)	Tortricid	Early germination	Immature	Mould
695	2004	29.53	21.83	5.28	2.23	20.61	3.09
695	2005	58.23	12.88	1.10	3.65	23.47	2.66
695	2006	29.67	15.75	0.20	12.71	8.64	2.03
816	2005	69.86	123.29	0.29	0.00	49.43	5.00
816	2006	13.18	34.09	0.45	0.00	17.27	1.36
Nelmak	2004	6.94	17.97	1.92	5.50	35.81	6.94
Nelmak	2005	51.00	37.57	0.94	2.17	26.62	4.23
Nelmak	2006	8.04	13.51	2.65	21.63	36.12	9.71
344	2004	48.08	12.62	2.46	0.08	11.31	5.54
344	2005	47.50	37.31	0.13	0.25	8.81	1.31
344	2006	13.33	45.56	0.00	0.00	15.00	3.89
791	2004	21.36	8.10	1.14	0.05	14.98	3.45
791	2005	51.35	20.74	0.53	2.97	21.33	3.70
791	2006	11.21	5.56	0.00	2.06	19.25	2.22

cultivars generally produce large nuts and mature significantly later in the season, which indicates that resistance is more complicated and involve more processes than the presence of large physiologically mature nuts early in the season.

Implications of these findings are that kernel distances and early maturing cultivars would probably play a minor role in determining the resistance status of commercial macadamia cultivars.

3.1.3.3.2 Natural nut drop (mature nuts)

Cultivars derived from hybridization between *M. integrifolia* and *M. tetraphylla* are more prone to exploitation by the African tortricid complex, with Nelmak 2 being a possible exception. When the damage for both seasons and both localities were pooled, Annexure 3.5 indicated that the *M. integrifolia* derived cultivar 800 was also susceptible.

This cultivar was also susceptible in the study of Jones & Caprio (1992). Pearce *et al.* (2001) showed that two groups of cultivar 741 exist. The group with a more spreading growth form, such as the trees in Burgershall, was probably genetically identical to cultivar 800 while the more upright growth form such as those in Nelspruit were actually true cultivar 741's. This could probably explain why the cultivar 741's at Nelspruit had very little tortricid damage and the trees at Burgershall were severely damaged.

Drew (2004) mentioned that cultivarA16 was very prone to tortricid infestation and ascribed it to the density of the husk. He also mentioned that gravid females prefer to oviposit on nuts that had been damaged in some way. It had also been observed on various occasions in the field that females deposit a large number of eggs right next to the suture line where the husk would split when the nuts approach physiological maturity (Drew 2004). It would be easier for the young larvae to penetrate the husk here than to excavate a burrow through the hard and sometimes smooth epidermis.

From Annexure 3.5 it is evident that cultivars 788, 294 and 741(Nelspruit) generally had the lowest tortricid damage ratings. Blight (1989) mentioned that cultivar 791 might be resistant to *T. leucotreta* and according to Annexure 3.5 this cultivar generally had low damage levels.

Although hybrids are normally more genetically fit, Annexure 3.5 indicated that hybrid macadamia cultivars were more susceptible to tortricid larvae. According to Pearce *et al.* (2001) higher *M. integrifolia* content imparts some degree of susceptibility against tortricids. The following hybrids were listed by Pearce *et al.* (2001) in descending order of *M. integrifolia* content: A16. A4, Beaumont, Nelmak 1 and Nelmak 2.

3.1.3.4 Resistance/susceptibility: Status of the Heteroptera complex

3.1.3.4.1 Natural thinning period

If kernel distance was the only factor preventing heteropterans from feeding on the kernel then surely all cultivars would be equally affected as the nuts were still very small during this stage. The combined husk and shell thickness of all cultivars are expected to be considerably smaller than the mouthpart length of even heteropterans with relative short mouthparts such as *Nezara viridula*. Table 3.5 indicated that at Burgershall cultivars 800, 863,344, 294 and 789 had high damage ratings while no consistent pattern regarding the intensity of feeding preferences was discernible for the other cultivars. Based on damage ranking, cultivars 863, 800 and 294 were the worst affected. At Nelspruit cultivars Beaumont (695), Nelmak 2 and 344 were more severely attacked while; cultivars 741, 816 and 788 had low damage rankings.

3.1.3.4.2 Natural drop (mature nuts)

There were significant differences between commercial cultivars in terms of tolerance towards heteropterans (Table 3.5). The ability of damage suppression by resistant cultivars in absence of chemical control for pest complexes is highly questionable. Most growers select cultivars on the basis of quick income generation and factors such as pest and disease resistance play a secondary role on most macadamia farms in South Africa.

The option exists to plant susceptible cultivars in combination with resistant cultivars to manage especially the Heteroptera complex. Here again economic considerations will dictate which cultivars will be preferred by farmers. Although trees can be top worked (cut down and grafted on the new shoots), cultivar changes are normally difficult and expensive to make.

Although no conclusive evidence for typical resistance mechanisms such as antixenosis and antibiosis were found during this study, kernel distance could play an important role by mechanically preventing nymphal stages and/or lesser important heteropterans with shorter mouthparts to feed on the kernel. The copious amounts of resin exuded by cultivar Beaumont could be a form of antixenosis as it certainly appears to deter stinkbugs while the apparent resistance mechanism of cultivars with a high cyanide content such as 791 may be explained as a form of antibiosis (The association between two organisms where one organism secretes an antagonistic substance). Additional research is however required to define these aspects conclusively.

3.2 A comparison between integrated pest management *versus* fixed interval spraying of macadamia.

3.2.1 Introduction

Integrated Pest Management (IPM) is a sustainable approach to manage pests by combining the use of all practical methods of pest control including biological, cultural, physical and chemical methods, in a manner that attains the macadamia grower's goals while minimizing economic, health and environmental risks. Has this concept been used so widely in the past that the term IPM has lost its meaning? What is IPM and how do growers benefit if they adopt basic IPM principles? These are issues many growers of macadamias are currently faced with and these issues are even more pertinent now because after a significant amount of IPM related training in KwaZulu-Natal, growers still report excellent results with fixed interval spraying.

To justify the current emphasis of the macadamia industry on increased environmental awareness and concomitant reductions in insecticide usage, it is very important to demonstrate that the adoption of basic principles such as scouting and spraying according to predetermined threshold levels are financially and ecologically more rewarding than fixed interval spraying.

Fixed interval spraying has many advantages. Most notable is that this approach is significantly less management intensive. In a macadamia IPM program, scouting as well as the interpretation of these results account for significant amounts of time from both farm labour, as well as management.

Fixed interval spraying is also perceived as a low risk approach. To minimise this risk, growers simply increase the spray frequency but De Villiers & Du Toit (1984) found that even after two subsequent synthetic pyrethroid sprays, increases in secondary pests were already evident. The following trials were therefore primarily designed to quantify any economic advantages of IPM over fixed interval spraying.

3.2.2 Results

Insect damage on nuts harvested from a number of Nelspruit farms with different management levels were studied to determine if IPM has any advantage over fixed interval spraying in terms of kernel quality but even more importantly in terms of economic returns. These surveys were also important because the practical value of IPM had to be determined in order to justify the current research programme of the Southern African Macadamia Growers Association (SAMAC).

According to Table 3.9 there were considerable differences in heteropteran induced kernel lesions between the three spraying regimes during the early season of 2006/07. These differences were also evident during the subsequent phase of kernel damage and was also reflected when all damage ratings were pooled. Although all these farms were sprayed on average four times during the season, results in terms of heteropteran induced unsound kernels were considerably different (although not statistically).

Table 3.9 The effect of various insect control strategies, ranging from unsprayed to strict adherence to IPM principles on heteropteran induced damage over a range of cultivars in the Nelspruit region during the 2006/07 season.

Management strategy	**Early damage**		**Kernel damage**		**Total damage**		
	Infested kernels (%)	**N**	**Infested kernels (%)**	**N**	**Infested kernels (%)**	**N**	**Average number of sprays**
Calendar sprays	1151 (9.15)	12582	814 (14.45)	5632	1965 (10.79)	18214	4
IPM	17 (2.35)	724	7 (0.91)	772	14 (0.94)	1496	4
Unsprayed	860 (27.31)	3149	2952 (59.24)	4983	3812 (46.88)	8132	0
Total	2028 (12.32)	16455	3773 (33.13)	11387	5791 (20.8)	27842	4

When the cost benefit ratios were calculated for the three insect management approaches (Table 3.10) differences between treatments became even more obvious.

The farms that practiced IPM benefited between R 26.26 to R32.11 for each Rand spent on crop protection. In contrast the cost benefit ratios of the three farms that sprayed on a fixed interval basis were considerably more unfavourable (cost benefit range 1: 20.8 – 1:12.4).

Table 3.10 Economic analysis/tree of the effect IPM strategy on damage and concomitant profits during the 2006/07 season.

	Number of sprays	Insect damage (%) *a*	TKR (kg) b	USK (kg) *c*	SKR (kg) *d*	Payment (Rand) *E*	Advantage gained by spraying (Rand) *f*	Cost of Control (Rand) *g*	Profit/ tree (Rand) *h*	Cost Benefit Ratio *i*
Nelspruit (unsprayed)	0	64.8	3.84	2.49	1.35	81.00				
B/hall (calendar spray)	6	42.19	3.84	1.62	2.22	133.19	52.19	9.84	123.35	1:12.54
B/hall (IPM)	3	41.78	3.84	1.60	2.24	134.14	53.14	4.92	129.22	1:26.26
Kaapschehoop (calendar spray)	6	21.78	3.84	0.84	3.0	180.00	99.00	9.84	170.16	1:17.29
Kiepersol (IPM)	4	5.6	3.84	0.22	3.62	217.2	136.2	6.56	210.64	1:32.11
Glenwood (calendar spray)	5	16.46	3.84	0.63	3.21	192.6	111.6	8.2	184.4	1:22.49
Average	4.8	25.56	3.84	0.98	2.86	171.6	90.6	7.87	163.73	1:20.8

Legend

a Insect damage = totals of nut borer and stink bug infestation on mature nut kernels measured from January 2006 – harvest

b TKR (Total Kernel Recovery) = An average total kernel recovery percentage of 27.4% was assumed

c USK (Unsound Kernel) = ***a*** x ***b***/100

d SKR (Sound Kernel Recovery) = ***b* – *c***

e Payment = Assumed kernel value of R60.00/kg x ***d***

f Advantage gained by spraying = **e** value of estate – **e** value (81.00) of unsprayed standard reference (Nelspuit)

g Cost of control = cost of control/tree (R1.64) x number of spray applications

h Profit/tree = **e** – ***g***

i Cost benefit ratio = ***h*/*g***

Assumptions

i. To demonstrate the influence of the frequency of spray applications and concomitant insect damage and profit/tree it was decided to work with a TKR value of 27.4% as it represents an approximation of the industry mean.

ii. Tree age was assumed to be 10 years and the yield per tree of 15 kg NIS (nut in shell) was inferred according to Reilly *et al.* (1988).

iii. Spray cost using hand lances was calculated at R1.64/tree. This figure was calculated at a tree density of 417 trees/ha

iv. Approximately 15 labour units were required to spray a hectare/hour @ ±R40.00/day

v. Running cost for a 60kw tractor = R15.00/hour.

vi. Chemicals (pesticide & adjuvants) = R50.00/ha/application

vii. The unsprayed orchard at Nelspruit served as a standard reference. Values were obtained over four seasons from 3 972 nuts.

Table 3.11 The effect of various insect control regimes, ranging from unsprayed to strict adherence to IPM principles on Heteroptera-induced damage over a range of cultivars in major macadamia producing regions during the 2007/08 season

Locality	**IPM index**	**Number of sprays**	**Number of nuts examined**	**Number of stinkbug lesion on kernel**
Nelspruit1	0	3	62	52
Levubu 1	0	5	114	5
Total group 0			176	57 (32.38%)
Nelspruit 2	1		58	2
Burgershall	1		645	16
Total group 1			703	18 (2.56%)
KZN1	2	5	41	5
Nelspruit3	2	6	54	0
Total group 2			95	5 (5.26%)
Levubu 2	3		95	1
KZN 2	3	4	27	3
Barberton	3	6	500	1
Karino	3		56	0
Total group 3			678	5 (0.74%)
Nelspruit 4	4	0	500	483
White river	4	0	44	12
Brondal	4		120	41
Total Group 4			664	536 (80.72%)

IPM index

0 – fixed interval spraying

1 – Use pheromone traps but generally spray for stinkbugs on a fixed interval basis

2 – Use pheromone traps for tortricids and have a rudimentary scouting system

3 – Use pheromone traps for tortricids and have an efficient scouting system

4 – No chemical usage or organic macadamia production

Despite alternative farms that were selected during 2007/08, Table 3.11 again indicated that farms practicing IPM had considerably lower Heteroptera-induced kernel damage. When tables 3.9 and 3.11 were compared, it was evident that Heteroptera damage was higher in untreated orchards during 2007/08. Despite the higher incidence of heteropterans, kernel damage in IPM compliant farms was again less than one percent.

Although monitoring and spraying according to threshold levels appear to be important in reducing Heteroptera-induced kernel quality problems, factors such as tree canopy management (pruning), the quality of spraying equipment, as well as orchard floor management will also influence the expected degree of insect control. Although these factors varied greatly from farm to farm it was observed that macadamia orchard managers striving to optimise IPM in their orchards usually managed the general agronomic practices in these orchards optimally as well.

When data obtained from Golden Macadamias was analysed, it was observed that farms that monitored and sprayed according to threshold levels tended to have higher (but not statistically significant) Total Kernel Recovery percentages (TKR%) compared to the industry mean (Fixed interval =30.41 IPM 31.84; t_{18} = 1.28 P< 0.217).

Total kernel recovery percentages depend on a number of physiological nut disorders such as onion rings (dark concentric halos on the kernels caused by tannins leaching into the kernel from the shell), discolouring (kernel discoloration caused by a range of factors such as over maturity or even fungal growth), 791 spot (shallow pitting in kernels of mostly the 791 cultivar), early germination, misshapen kernels as well as genetic factors (Sippel *et al.* 2002). Arguably, insects also play a prominent role in determining the total kernel recovery percentages.

Differences between IPM compliant and non IPM compliant farms became even more obvious when the unsound kernel recovery percentage (USK%) was compared. In all instances IPM compliant farms had significantly lower USK% levels than the industry mean, while the farms that sprayed according to fixed intervals again had varying results (Fixed interval = 2.84 IPM = 1.65 t_{18} = 2.61 P, 0.0018) (Table 3.12).

According to Table 3.13 this trend was more prominent when Heteroptera damage was compared between the two crop protection extremes. Heteroptera damage in IPM compliant farms was consistently lower than the industry mean, while results from the fixed interval sprayed farms were again inconclusive (Fixed interval $_{\text{Early damage}}$ = 38.38

IPM $_{\text{Early damage}}$ = 22.25 t_{18} = 2.02 $P < 0.058$; Fixed interval $_{\text{Late damage}}$ = 31.13 IPM $_{\text{Late damage}}$ = 9.67 t_{18} = 2.97 $P < 0.0078$; Fixed interval $_{\text{Total damage}}$ = 53.44 IPM $_{\text{Total damage}}$ = 31.92 t_{18} = 1,89 $P < 0.075$;).

Table 3.12 An analysis of the effect of IPM strategies on total kernel recovery as well as the unsound kernel recovery percentages (Data was obtained from Golden Macadamias (Pty.) Ltd.)

Management strategy	**Total kernel recovery (%)**				**Unsound kernel recovery (%)**			
	2004	**2005**	**2006**	**2007**	**2004**	**2005**	**2006**	**2007**
Fixed interval 1	30.05	30.66	31.43	31.23	2.4	2.53	3.11	3.78
Fixed interval 2	29.73	29.79	29.85	30.56	2.57	1.79	5.45	1.13
Mean	29.89	30.23	30.64	30.90	2.49	2.16	4.28	2.46
IPM compliant 1	34.18	34.88	37.49	35.27	1.43	1.68	1.48	1.33
IPM compliant 2	28.37	27.37	29.85	28.7	2.79	3.12	0.68	0.96
IPM compliant 3	31.23	31.24	32.19	31.37	1.94	1.87	0.86	1.72
Mean	31.26	31.16	33.18	31.78	2.05	2.22	1.01	1.34
Industry mean	30.45	30.72	31.38	32.11	3.28	3.35	2.06	2.17
Number of instances where IPM did better than industry mean	2	2	2	1	3	3	3	3
Number of instances where IPM did worse than industry mean	1	1	1	2	0	0	0	0
Number of instances where fixed interval sprays did better than industry mean	0	0	1	0	2	2	0	1
Number of instances where fixed interval sprays did worse than industry mean	2	2	1	2	0	0	2	1

Table 3.13 An analysis of the effect of IPM strategies on Heteroptera induced kernel damage (Data was obtained from Golden Macadamias)

Management strategy	Stink bug damage/ 4000g sample (g)											
	Early stink bug damage				Late stink bug damage				Total stink bug damage			
	2004	2005	2006	2007	2004	2005	2006	2007	2004	2005	2006	2007
Fixed interval 1	22	32	29	64	17	22	66	29	39	27	47.5	93
Fixed interval 2	23	48	76	13	25	11	69	10	58	29.5	110.5	23
Mean	21.5	40	105	38.5	21	16.5	67.5	19.5	48.5	28.25	79.0	58
IPM 1	20	34	20	22	9	21	6	12	29	55	26	34
IPM 2	16	44	6	31	21	19	2	16	37	63	8	47
IPM 3	2	44	10	18	3	3	1	3	5	47	11	21
Mean	12.7	40.7	12.0	27	11	14.3	3	10.3	23.7	55	15.0	34
Industry mean	26.0	68.5	27.5	31	19.9	24.3	21.8	22	45.9	92.8	49.3	53
Number of instances where IPM did better than industry mean	3	3	3	3	2	3	3	3	3	3	3	3
Number of instances where IPM did worse than industry mean	0	0	0	0	1	0	0	0	0	0	0	0
Number of instances where fixed interval sprays did better than industry mean	2	2	0	1	1	2	0	1	1	2	1	1
Number of instances where fixed interval sprays did worse than industry mean	0	0	2	1	1	0	2	1	1	0	1	1

3.2.3 Discussion

Tables 3.9, 3.11, 3.12 and 3.13 confirm the results of Ironside and Fero (1992) who recorded an increase in saleable kernel over a nine year period after IPM and improved cultural control practices were introduced on a number of farms in Malawi.

On IPM compliant farms, Heteroptera induced kernel damage of less than 1% was recorded during both monitoring seasons (2006/07 and 2007/08) while partially IPM compliant farms (farms where spray decisions were not always based on monitoring) suffered slightly more damage. Apart from the unsprayed farms, producers that sprayed according to fixed intervals suffered the highest Heteroptera-induced kernel losses. In hindsight these results are hardly surprising as fixed interval spraying entails spraying trees irrespective of the economic threshold level. Because damaged nuts generally do not drop early and cannot be differentiated from undamaged nuts, any damage resulting from a mistimed spray (spray after economic threshold level has been reached) must therefore be regarded as additive and will be reflected in the unsound kernel reports of processors.

On the downside, IPM on macadamias demands more technological expertise than the fixed interval spraying approach. The cost benefit ratios presented in Table 3.10 also does not reflect additional costs of employing scouts nor the portion of management time required to interpret scouting results. A comparison between fixed interval spraying and IPM indicates that the advantages of IPM still outweigh the disadvantages by a considerable margin. According to Fig 3.11 the differences in gross margins between these two strategies are approximately R34 440/ha when only four sprays are applied/ season. This difference could be as large as R51 660/ha if six sprays are applied/season. If it is taken into consideration that most processors compensate growers on an exponential basis based on kernel quality, the differences between these two strategies will even be considerably bigger. It can finally safely be assumed that the differences in financial gain highlighted in Fig 3.11 will adequately compensate for the added hidden costs involved in adopting IPM.

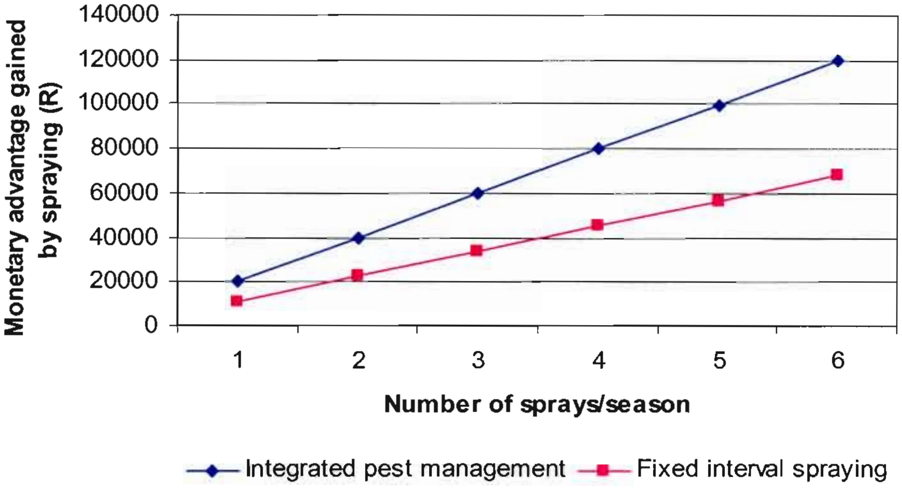


Fig. 3.11 A comparison of the monetary advantages/ha of adopting IPM over fixed interval spraying. Figures from Table 3.10 were used to calculate the values for each strategy. Cost benefit ratios of 1: 29.19 (IPM) and 1:16.6 (fixed interval spraying) were used for the final calculations.

3.3 Distribution patterns of the tortricid and Heteroptera complexes affecting macadamias in South Africa.

3.3.1 Introduction

The macadamia industry regards research into Integrated Pest Management (IPM) as an overarching priority for all production regions (Piet Muller Personal communication). Integrated pest management should however not be regarded as the final destiny of insect management in any crop. Instead it is a continuous series of small improvements that enhances the environmental and economical sustainability of cultivating such a crop. Some important factors that influence insect numbers in a macadamia ecosystem were traditionally not even regarded as important. Tree health, canopy density, host plant resistance and probably nutrient status of soils and trees are important components that were previously overlooked and are expected to have an important but unquantified influence on insect pest numbers.

Clearly the concept of IPM should be expanded to include other non-arthropod pest population regulating mechanisms as well. The aim of this section is therefore to highlight selected aspects of insect pest distribution that will enhance the accuracy of scouting for pest insects and subsequent decision support as well as environmental sustainability of macadamia production.

3.3.2 Results

3.3.2.1 The effect of tree density on tortricids and heteropterans

Many macadamia orchards were initially planted at high densities with the aim of quick income generation and maximum operational efficiency. However, macadamias are very large trees and without proper pruning, medium - high density orchards quickly become unproductive and have increasingly severe heteropteran and tortricid induced nut damage problems. This series of trials were therefore specifically designed to study the link between increased tree density and insect damage in a commercial macadamia orchard.

When insect damage was evaluated on mature trees grown at various densities, Fig. 3.12 demonstrates that the adjusted r^2 value of 0.922 indicates a clear positive relationship between heteropteran induced kernel damage and tree density. A r^2

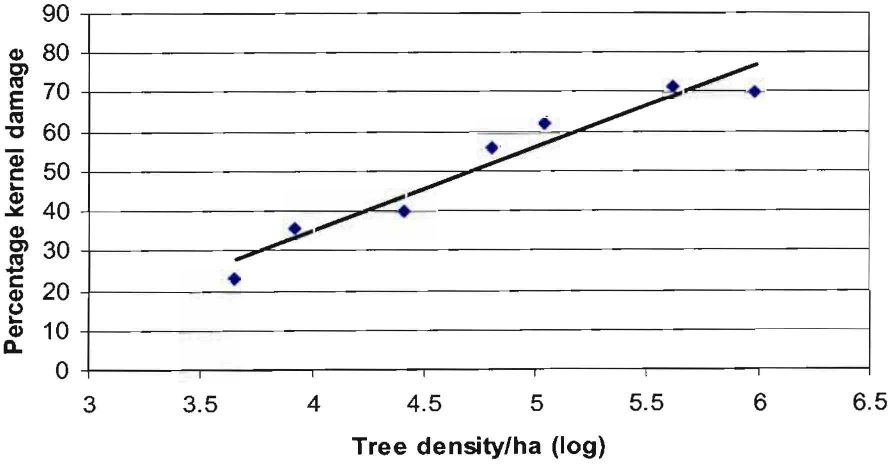


Fig. 3.12 The relationship between planting density (log transformed) and percentage stink bug induced kernel damage on Nelmak 2 nuts. n = 634 and r^2 = 0.922.

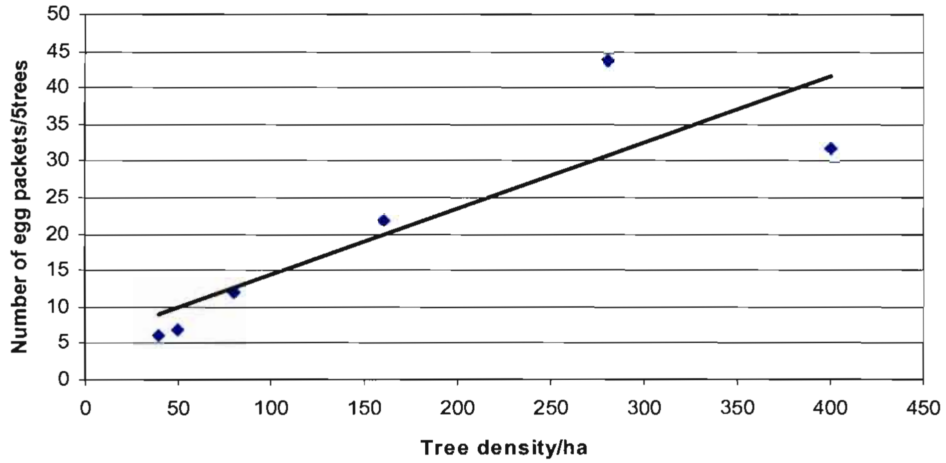


Fig. 3.13 The relationship between number of egg packets of *Bathycoelia natalicola* and planting density on Nelmak 2 nuts. n = 123 packets and r^2 = 0.864.

value of 0.864 indicates that the numbers of egg packets of *B. natalicola* are also positively related to higher tree densities (Fig. 3.13).

During 2006 at Nelspruit, damage induced by tortricid larvae on the density trial ranged from 13 to 44.7 % and the adjusted r^2 value of 0.821 also suggested a strong positive relationship between increasing tree density and the occurrence of tortricid damage to the husk (Fig. 3.14).

Heteroptera damage was more severe than that of the tortricid complex when upper (71.65% Heteroptera; 44.78 % tortricid) and lower (23% Heteroptera; 13.0% tortricid) extremes were compared suggesting that planting density might possibly have a larger influence on the Heteroptera complex.

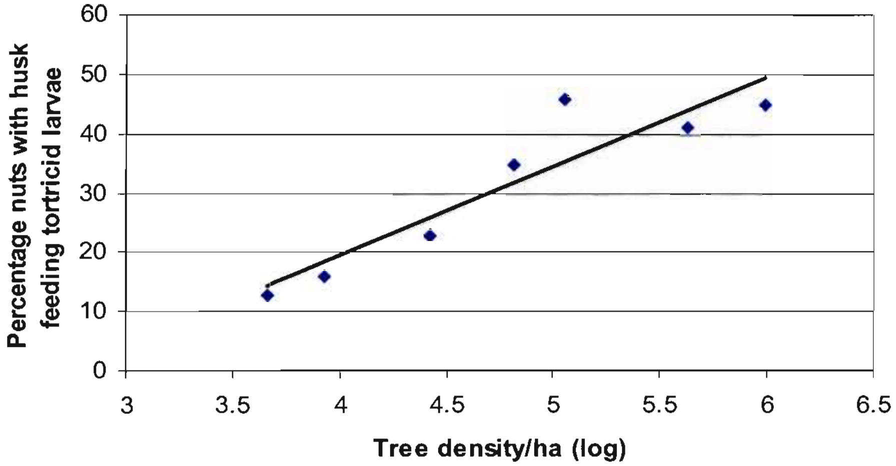


Fig. 3.14 The relationship between planting density (log transformed) and percentage nut borer damage to the inside of the husk of Nelmak 2 nuts. n = 635 and r^2 = 0.821.

3.3.2.2 Distribution patterns of important macadamia insect pests

Damage inflicted by *Bathycoelia natalicola* was heterogeneously distributed and approximately 24% of the trees did not have any damage during both seasons of monitoring (Fig. 3.15). Median damage was in the 20% range and damage 80% and higher was confined to only 2.31 - 7.69% of the trees. Egg packets of *B. natalicola* were also heterogeneously distributed and approximately 41% of the tree trunks which were examined did not contain any eggs. Damage higher than 80% was confined to only 2.31% of the trees.

Pseudotheraptus wayi inflicted significantly less damage and approximately 80% of the nuts that were examined were uninfested. The distribution of tortricid moth damage was similar to *P. wayi* and approximately 80% of the trees were also uninfested.

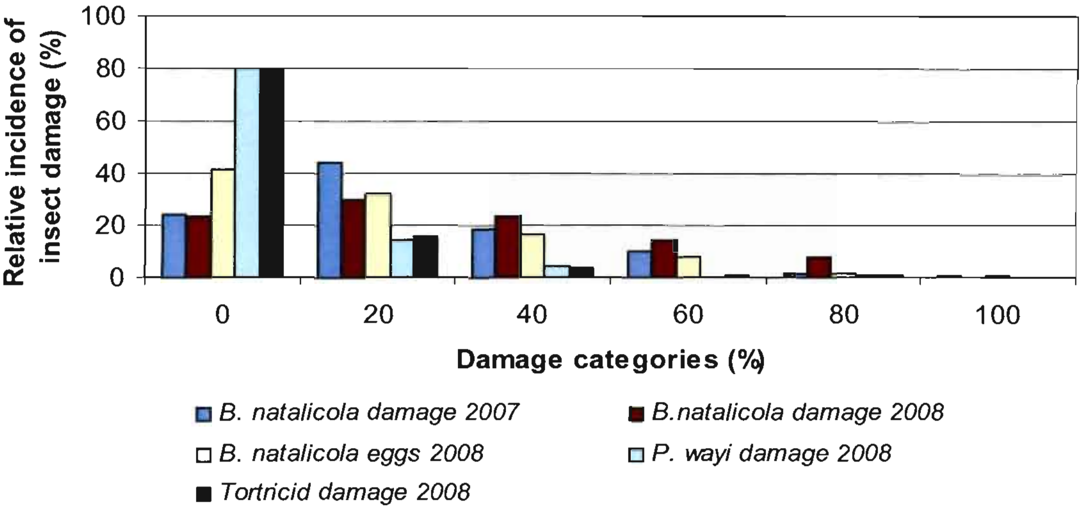


Fig 3.15 Damage distribution of nuts that were exploited by heteropterans and tortricid moths in an organic macadamia orchard during the 2007/08 and 2008/09 production seasons.

3.3.2.3 Areas of increased insect activity (Hot spots)

Prior to this study there was no information available regarding the distribution patterns of macadamia pest insects in South African orchards. Anecdotal evidence suggested that the distribution of both complexes were heterogeneous. As is evident from section 3.1.3.2 the heterogeneous nature of the distribution of both pest complexes has the ability to drastically influence the accuracy of population surveys. Figures 3.16 – 3.20 corroborates this remark as in all cases the distribution of both insect complexes was heterogeneous. Approximately 24% of the nuts were not damaged by *B. natalicola* during 2007 and during 2008 damage were ± 6% higher. Although some slight changes in the position of arbitrarily assigned hot spots of *B. natalicola* occurred when results from the damage surveys carried out in November 2007 and November 2008, as well as

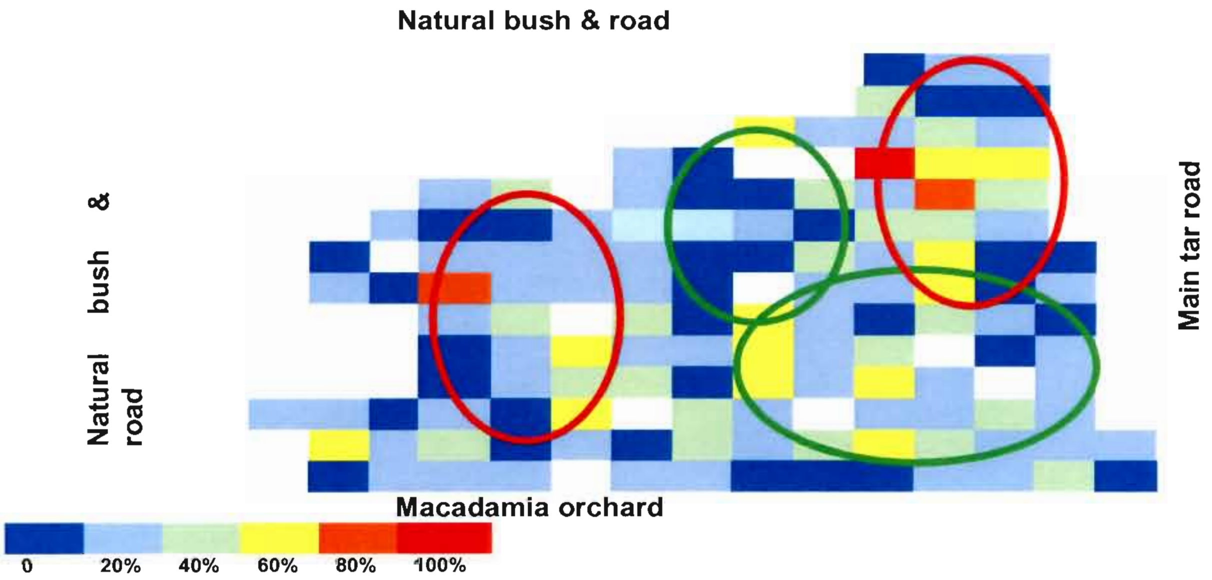


Fig. 3.16 The distribution of ***Bathycoelia natalicola*** damage in an organic macadamia orchard at Brondal based on feeding damage on the inside of the pericarp during November 2007. Presence of possible hot spots are denoted by red circles, while cool spots are denoted by green circles.

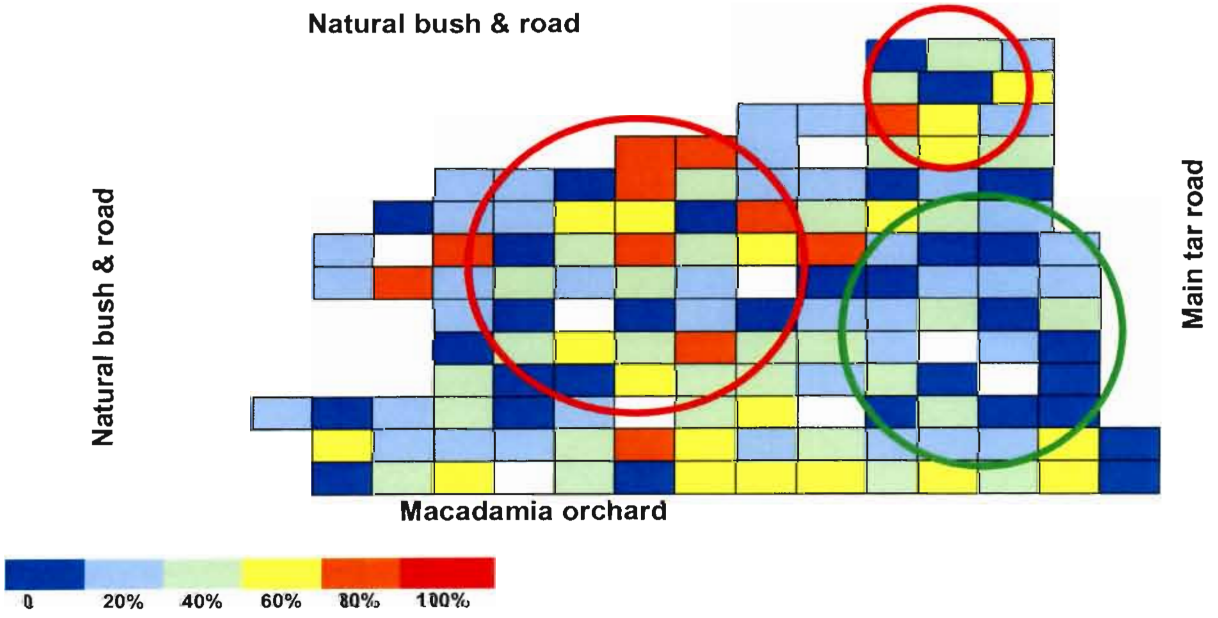


Fig. 3.17 The distribution of ***Bathycoelia natalicola*** damage in an organic orchard at Brondal based on feeding damage on the inside of the pericarp during November 2008. Presence of possible hot spots are denoted by red circles, while a cool spot is denoted by a green circle.

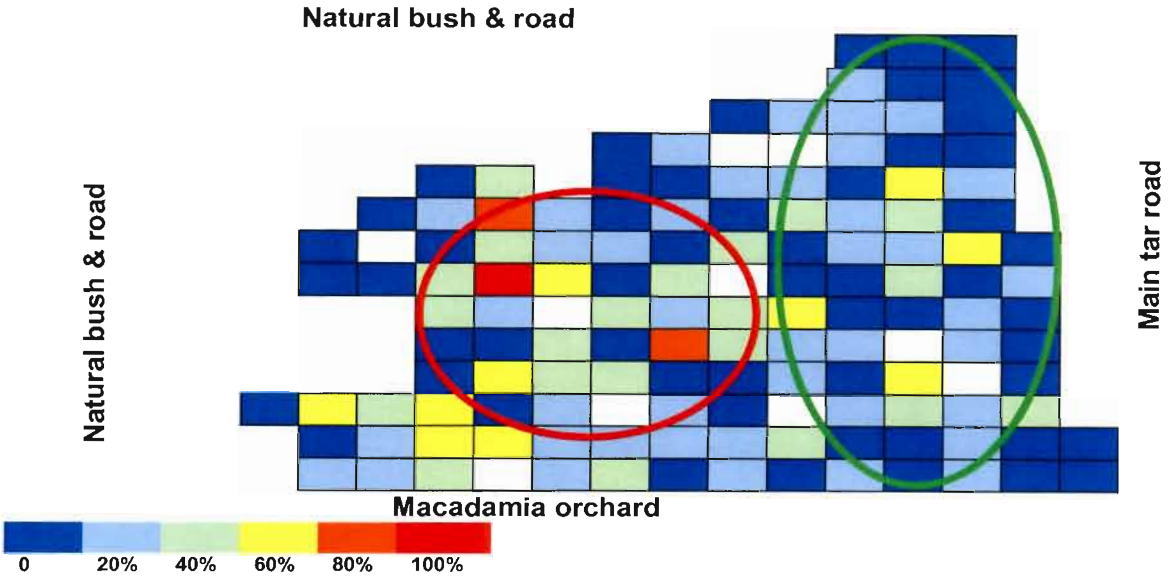


Fig. 3.18 The distribution of *Bathycoelia natalicola* damage in an organic orchard at Brondal based on the number of egg packets/tree during February 2008. Presence of a possible hot spot is denoted by a red circle, while a cool spot is denoted by a green circle.

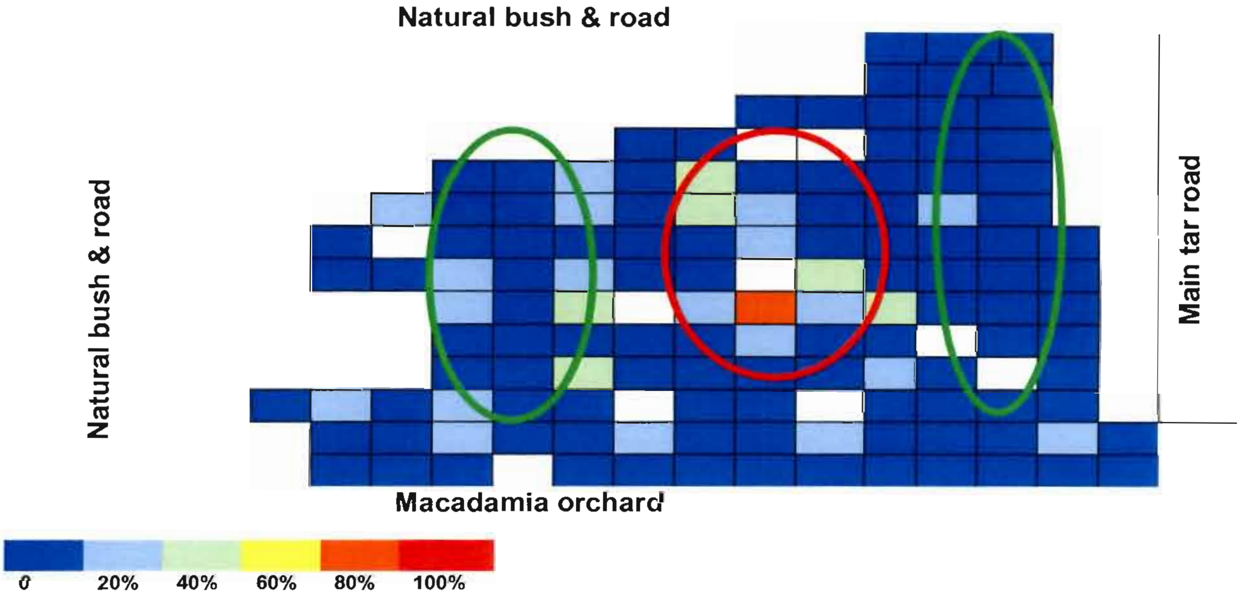


Fig. 3.19 The distribution of *Pseudotheraptus wayi* damage in an organic orchard at Brondal based on feeding damage on the inside of the pericarp during November 2008. Presence of a possible hot spot is denoted by a red circle, while cool spots are denoted by green circles.

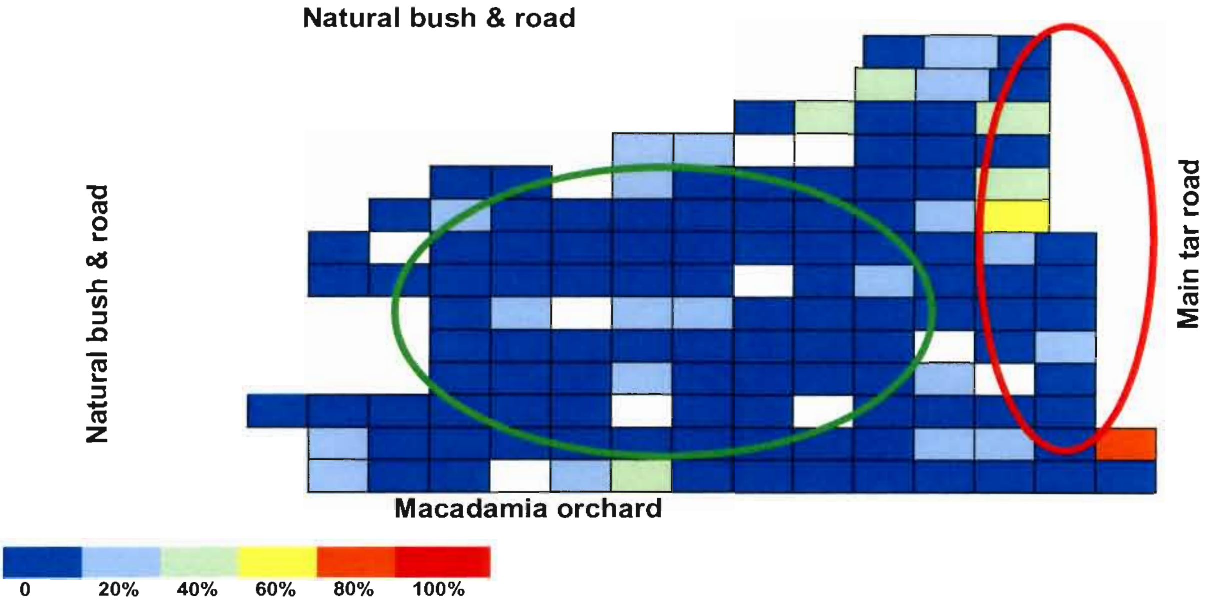


Fig. 3.20 The distribution of tortricid damage in an organic orchard at Brondal based on feeding damage on the inside of the pericarp during November 2008. Presence of a possible hot spot is denoted by a red circle, while a cool spot is denoted by a green circle.

the oviposition survey were compared, Figs. 3.16, 3.17 and 3.18 indicate that their location within this orchard were relatively stable. *P. wayi* damaged only 35 (5.38%) of the nuts and due to these low numbers the reliability of distribution data is probably compromised (Fig. 3.19). Although the tortricid damage also amounted to ± 5.69%, based on results portrayed in Fig. 3.20, it is assumed that infestation by tortricids occurred from the macadamia orchard next to the study area since areas with 40 – 60% damage occurred on the periphery adjacent to that orchard.

3.3.2.4 Presence/absence of edge effects

The absence of any noticeable edge effect was prominent when Figs 3.16, 3.17, 3.18 & 3.19 were compared with each other. Areas of high activity were recorded well within the orchard which is normally indicative of highly mobile insects such as heteropterans. This assumption was confirmed when the number of nuts with heteropteran lesions in the perimeter of the orchard were recorded and compared to the remainder of the trees (Table 3.14). These results contradict recent results (March 2009) on avocados where a prominent edge effect was visible on a number of orchards. A reason for the absence of a heteropteran induced edge effect in the organic macadamia orchard was that pest populations in this orchard were more stable because crop protection remedies used on this farm had little effect on heteropterans (Schoeman & Mohlala 2008). The commercial avocado orchards on the other hand were routinely treated with commercial pesticides which probably resulted in a more unstable ecosystem and the prominent edge effects were therefore probably a function of continued reinfestation from the adjoining bush.

If results from Table 3.14 are compared with Fig. 3.20, tortricid infestation probably originated from one side of the orchard (Adjoining commercially managed macadamia orchard next to main tar road). This observation is further strengthened because the organic orchard is situated immediately downwind of these large commercial orchards (prevailing wind direction in the valley during summertime is north – east to easterly).

Table 3.14 The number of nuts undamaged by heteropterans and tortricids occurring along the perimeter (outermost 2 trees in a row) and inside of an organic orchard in the Brondal area.

Pest insect	Percentage trees without heteropteran damage or eggs (± SE)		t value	P
	Perimeter of orchard (outermost 2 trees in a row)	Remainder of trees in a row		
B. natalicola (Damage 2007)	31.27a ± 7.27	18.2a ± 9.77	2.14	0.07
B. natalicola (Damage 2008)	23.86a ± 7.87	23.43a ± 6.19	0.55	0.94
B. natalicola (Eggs 2008)	49.37a ± 11.85	31.14a ± 13.3	2.04	0.09
P.wayi (Damage 2008)	82.24a ± 13.24	59.96a ± 30.91	1.32	0.23
Tortricid damage	71.07a ± 12.78	92.18b ± 9.37	2.66	0.04

Means within rows follwed by the same letter is not statistically different, rows were calculated separately

n - 650 nuts/130 trees (2007)

n - 650 nuts/130 trees (2008)

3.3.3 Discussion

3.3.3.1 The effect of tree density on tortricids and heteropterans

Increases in insect activity with a concomitant increase in tree density are consistent with Root's (1973), resource concentration hypothesis which states that there is a higher probability of herbivores, finding, remaining on, and consequently becoming more abundant on hosts growing at a high density or abundance. According to Ramert *et al.* (2002) the exact mechanism of the concentration of the resource on the herbivore is not clearly defined by Root (1973) but according to Finch and Collier (2000) their appropriate/inappropriate landings hypothesis indicates that insects will only settle on plants when various host plant factors such as visual stimuli, taste and smell are satisfied.

Varanda and Pais (2006) mentioned that a higher host plant density has two distinct advantages. Firstly these plants are easier to locate and secondly because of a higher resource availability (nuts). Due to the wide spacing, trees grown at lower densities allowed more sunlight to reach the orchard floor. Weeds and grasses were prolific in these areas and according to Ramert *et al.* (2002) any increases in the biodiversity of plant cover has significant sustainable benefits for the producer. Apart from a number of related eco-services higher biodiversity of plants is expected to suppress pest populations due to a concomitant increase in arthropods, some of which are beneficial. These plants may also act as refugia which could account for increases in arthropod numbers. No weeds were present on the orchard floor at the higher tree densities during this study.

Figs 3.16, 3.17, 3.18, 3.19 and 3.20 indicate that these insects concentrate in portions of the orchard most suitable to them. Once these insects have settled and their primary need for food and shelter is satisfied, they are relatively sedentary and will only move if conditions became unfavourable. Waite *et al.* (2000) supported this supposition and indicates that once a female bug has oviposited she probably would stay in the near vicinity. Trees planted at high densities gradually become unproductive when the canopy closes up and without some form of rejuvenation such trees are expected to actually produce fewer nuts as they mature. Dense plants have a more complex architecture which will provide more shelter. In a macadamia ecosystem, the resource concentration hypothesis is probably dependant on a number of factors as well as the interrelationship amongst a number of these. Because these insects are able to inflict economic damage at low densities, the practical value of these findings is that tree pruning is possibly an environmentally sustainable method that will ensure optimum yields on the one hand and lower heteropteran damage on the other hand.

3.3.3.2 Natural distribution patterns of macadamia pest insects

The heterogeneous distribution of heteropterans was confirmed. Areas of higher than average activity ("hot spots") for *B. natalicola* were identified and were relatively stable throughout more than one production season. The reasons why certain trees are apparently more prone to Heteroptera attack remains unclear but the following two theories exist:

a) Heteropterans fly into an orchard and host selection is completely random. This theory is corroborated by Todd (1989) who found that dispersal patterns in rice and soy beans are completely random. Because the trees provide food, shelter and ideal oviposition sites, there is no incentive for a female heteropteran to move. Todd (1989) added that one to several males can often be found in close proximity to females, which results in a clumped distribution. These clusters will become even more pronounced because females oviposit and the migrational ability of the flightless nymphs is limited. Based on mouthpart length, 4th instar nymphs of *B. natalicola* are able to penetrate the husk and shells of most commercial cultivars. If more than three egg packets are deposited on a single tree, damage quickly escalates.

b) Diseased or stressed trees emit so called "phyto-distress" signals. These are volatile chemical signals that indicate that the natural defence mechanisms of the plants are compromised. Over time phytophagous insects have associated these chemical signals with plants that are "safe" to feed on (Schoonhoven *et al.* 2008). Because areas of higher *B. natalicola* activity appears to be relatively stable over time (compare Figs 3.16, 3.17 & 3.18) it would be worthwhile comparing host plant volatiles (allelochemicals) from areas of increased insect activity to areas of reduced insect activity. It might also be worthwhile to determine if areas of increased activity can be located via infrared photography as the accurate identification of such areas might make the interpretation of scouting results more accurate.

3.4. Damage estimates and population trends of the Tortricidae complex occurring on macadamia in South Africa.

3.4.1 Introduction

African totricid moths are polyphagous and Schwartz (1981) recorded 21 cultivated and 14 wild host plants for *Thaumatotibia leucotreta*. This broad host range, together with the mild tropical and subtropical winters, ensures that there is a continuous succession of adult moths throughout the year (Schwartz 1981).

The aim of this study was to determine the status of this guild of insects as economic pests of macadamia and to be able to refine current control procedures.

3.4.2 Results and discussion

Although it was possible to distinguish between late instar larvae of the various tortricid nut borer species, the damage caused by each of them was very similar. It was therefore decided to pool all data and refer to this pest complex collectively as tortricids for the purpose of this section. Nuts collected from the various localities listed in Annexure 3.7 affected by the tortricid complex can be divided into the following three basic risk categories:

3.4.2.1 Category 1: Nuts smaller than 20mm

The effect of nut size on oviposition and larval development

The aim of this study was to clear up the current confusion regarding the specific phenological developmental stage of macadamias most suitable for larval development of tortricids. Some growers are already treating their orchards with costly chemicals immediately after flowering (September/October) while results from Waite *et al.* (1999) indicate that this group of insects are mostly pests of large older nuts. Results of this study are therefore expected to facilitate the accurate timing of chemical control.

Annexure 3.7 summarizes infestation data on eight farms in macadamia producing regions of Mpumalanga and indicates that tortricid induced losses during the premature nut drop period were nearly insignificant. Although exceptionally high damage of 4.91% was recorded in one orchard, mean damage levels were usually in the range of less than 2%.

According to Jones *et al.* (1992) 20 mm is generally the lower nut size limit for oviposition by tortricid moths. However, Fig. 3.21 indicates that tortricid larvae in South Africa exploited small nut size categories as well, because approximately 40% of the larvae were recovered on nuts smaller than 20 mm.

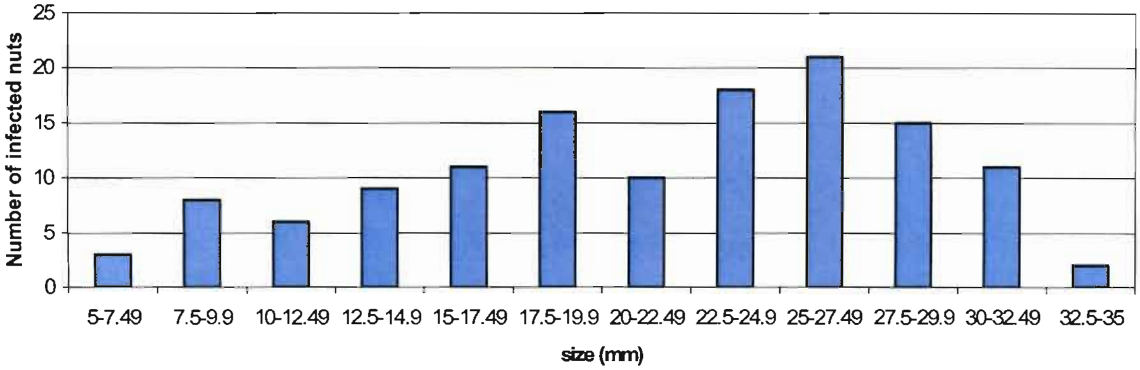


Fig. 3.21 Early season nut size preference (measured medially) of the tortricid complex (n = 130). Nuts were obtained from Burgershall research station from 16 August – 29 December 2002 and from 22 September – 31 December 2003.

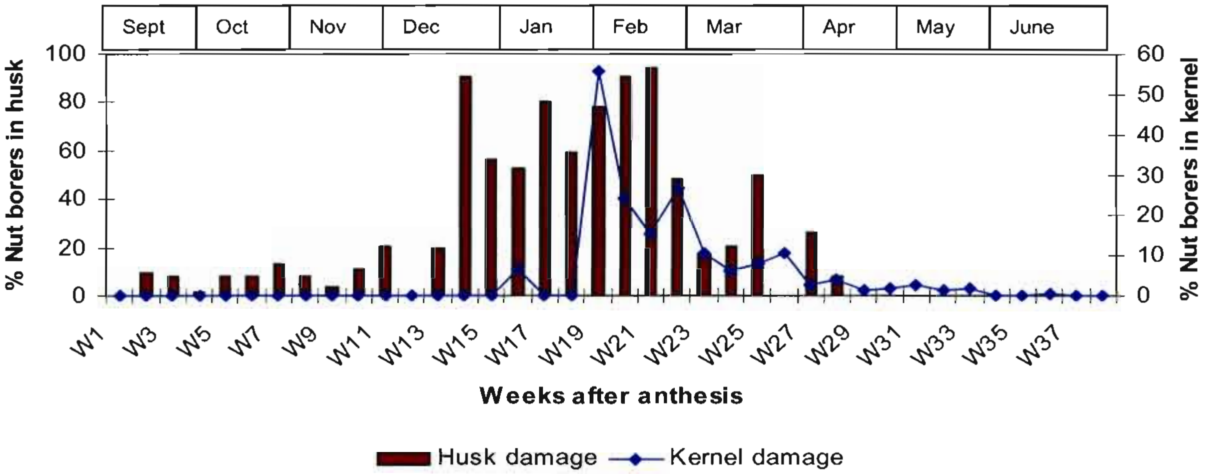


Fig 3.22 Pooled relative seasonal incidence (%) of kernel and exocarp nut borer occurrence during the 2002/03 – 2005/06 seasons at the Nelspruit and Burgershall research stations as well as six commercial macadamia farms in the Nelspruit region (n=41 242 nuts).

Pooled population counts depicted in Fig. 3.22 indicated that the percentage exocarp damage increased sharply from week 13 after flowering. The sharp increase in damage indicates that oviposition and subsequent larval infestation are well synchronized and probably occurred sometime before larval damage to the exocarp was observed.

The window period for control using insecticides is very narrow because sprays have to be directed against the first instar larvae before they burrow into the nuts. Bruwer (2002) and Haaksma (1993) mentioned that spray timing and coverage are critical and proposes that an insecticide with a broad spectrum and a long residual action such as a synthetic pyrethroid be sprayed during November or early December.

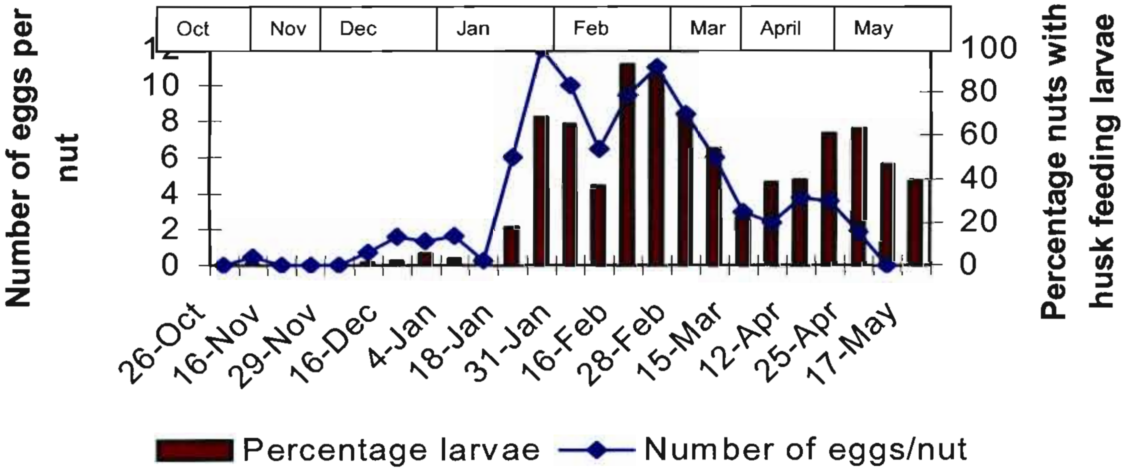


Fig 3.23 Seasonal incidence of tortricid eggs and husk feeding larvae on macadamia at Nelspruit Research Station during 2004/05.

Newton (1998) observed that under natural conditions *T. leucotreta* requires between 31 – 47 days to complete development from an egg to a fully grown larva. Ironside (1995) mention that although the duration of egg to adult moth is temperature dependant, it took *Cryptophlebia ombrodelta* approximately five weeks to complete it's development. La Croix & Thindwa (1986) support these observations and mention that maximum incidence of larval damage is reached approximately 4 weeks after the influx of adult moths.

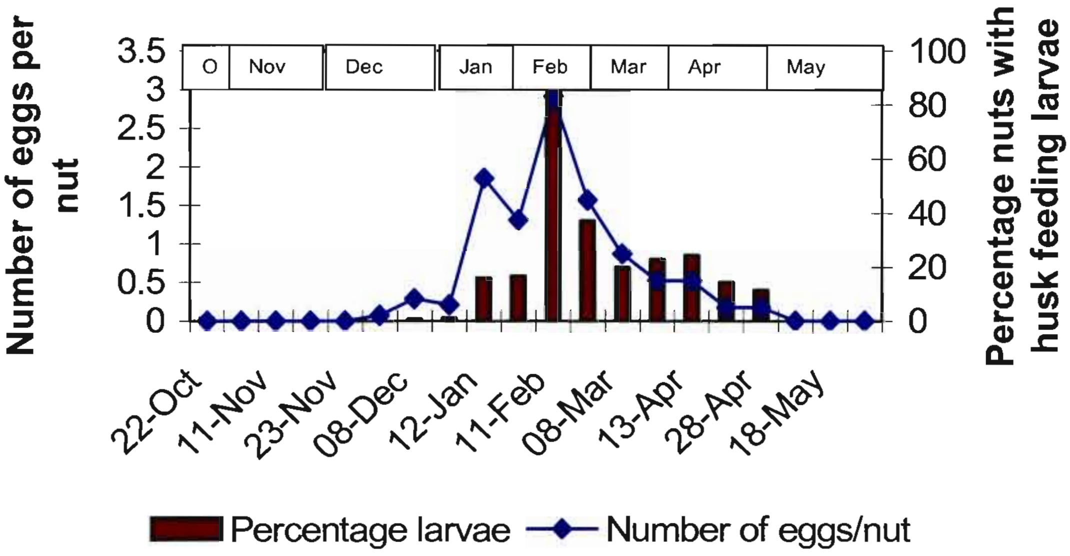


Fig 3.24 Seasonal incidence of tortricid eggs and husk feeding larvae on macadamia at Kaapsehoop during 2004/05.

Since maximum incidence of larvae in the exocarp occurred during week 13 post anthesis, the first eggs should therefore have been laid approximately nine weeks after flowering. According to Figs. 3.23 & 3.24 relative seasonal abundance of oviposition at Nelspruit and Kaapsehoop generally followed the same trend as the incidence of husk damage although in both cases egg laying slightly preceded visible damage symptoms. Joubert (1986) mention that early nut drop (November dump) is complete at nine weeks post anthesis (week three and four of November). This observation is substantiated with results portrayed in Fig 3.40. According to Jones (1994) and Ironside (1983) damage by the tortricid complex leads to premature nut abortion. Under natural conditions, small nuts should desiccate or decompose quicker than the four – five weeks required by a small larva to complete its development. It is thus postulated that female moths possibly make use of some aspect of the host plant's biology (such as volatile secondary metabolites or allelochemicals) to time egg laying so that it does not coincide with natural nut abortion and/or when the nuts will be large enough to sustain a developing larva. The nut size of 20mm observed by La Croix and Thindwa (1986), Ironside (1988), Jones *et al.* (1991), Jones *et al.* (1992), Jones (1994), and Waite *et al.* (1999) probably had little to do with oviposition and was very likely merely coincidental with the end of premature nut drop.

According to Booysen (2002) tortricid moths were captured in small numbers throughout the year but their pheromone trap catches notably picked up from September onwards. Ironside (1983), La Croix and Thindwa (1986) and Jones (1994) supported similar findings and mention that tortricid moths were very active from December – February.

3.4.2.2 Category 2: Nuts between 20 - 30mm

Kernel damage

From 20 weeks post anthesis onwards, kernel damage decreases (Fig. 3.22), even though some larvae were found in the husk. This could possibly be ascribed to the inability of larvae to penetrate the fully lignified shell. La Croix and Thindwa (1986), Ironside (1988) and Jones and Caprio (1992) made similar conclusions regarding the tortricid complexes occurring in Malawi, Australia and Hawaii respectively. Jones (1995a) mention that most tortricid larvae are not able to penetrate the fully hardened shell, but can penetrate the soft or semi hardened shell with relative ease. La Croix & Thindwa (1986) mentions that entry into the shell is always through the side of the shell and never through the micropyle which would very likely have been an easier route.

According to Fig. 3.29 and Wiid-Hobson (2003) shell hardening is normally complete by the week 15 – 18 after anthesis. Kernel damage can be expected when mean nut size reaches 21mm (± nine weeks post anthesis) up to shell hardening (± 15 weeks post anthesis), *i.e.* a period of ± six weeks. This observation is supported by Jones & Follett (1997).

Although Fig. 3.22 indicates that kernel damage was present up to the end of March, it must be taken into account that nuts do not drop immediately upon infestation and that the period of main flowering is not uniform. It is therefore very likely that these nuts were actually infested a few weeks earlier. According to Ironside (1988), nuts only drop approximately three – five weeks after initial infestation but observations during this study indicated that this period varies considerably. In the unsprayed orchard some infested nuts even became mummified and hung on the trees well beyond the natural harvest cycle.

The mean kernel damage of 6.28% observed in this survey (n = 9 594) corresponded relatively well to the observations of Jones *et al.* (1991) of approximately 4 %.

3.4.2.3 Category 3: Nuts larger than 30mm

The effect of husk damage on immaturity of macadamia nuts at harvest

Jones *et al.* 1991 reported that average husk damage over all cultivars in Hawaii was 29 %, which corresponds well with mean damage levels of 22.25% (n = 14 170) observed during this survey. Jones *et al.* (1992) mention that husk damage on certain trial sites was as high as 75%. On a farm at Karino near Nelspruit where macadamias were produced in a predominantly citrus region, an average of 56.1% husk damage was recorded (Annexure 3.7). In macadamia orchards, close to citrus trees, damage levels exceeded 80%. As a result of this infestation, this farm lost approximately 10 tons of nut in shell worth approximately R 250 000 during the 2004/05 season. During the 2005/06 season, a synthetic pyrethroid was applied to trees on this farm at peak oviposition which coincided with the time the mean medial diameter of aborted nuts reached 21 mm and when the premature drop of immature fruit came to an end. To make provision for an appreciable amount of early and out of season nuts, an additional spray was applied four weeks earlier (end of October 2005). Although husk and kernel damage was still higher than the figures presented in Annexure 3.7, the percentage of immature nuts nevertheless decreased significantly indicating that these parameters could be used to time spray applications. When the kernel and husk damage (Annexure 3.7) recorded at farms that were sprayed during November (Annexure 2.3) were compared to farms that where no sprayed during this period, Table 3.15 indicated that farms that were sprayed in November had significant differences in terms of husk damage, but not in terms of kernel damage. A possible reason for this is that oviposition and therefore the incidence of larval damage is not completely synchronized and from Figs 3.22 and 3.23 it is evident that small numbers of larvae and eggs are present relatively soon after anthesis. Once these larvae have burrowed into the husks, they should be effectively out of reach of any insecticide. The November spray probably disrupted oviposition as well as the subsequent larval stages of individuals of the main population peak without affecting kernel feeding larvae that originated from early infestations.

The results of the farm at Karino were omitted from this analysis as it is regarded as an exceptionally high outlier infestation which would have skewed the pest incidence situation on the other farms.

Table 3.15 The effect of a November spray consisting of a synthetic pyrethroid against the tortricid complex on macadamia in terms of husk and kernel damage.

	Mean percentage husk damage ± SD	N	Mean percentage kernel damage ± SD	N
Farms that did spray a synthetic pyrethroid during November	7.07a ± 7.77	4	2.20a ± 2.96	4
Farms that did not spray a synthetic pyrethroid during November	19.2b ± 10.13	11	6.02a ± 3.91	11
t value	2.16		1.77	
P≤	0.050		0.101	

Means followed by the same letter do not differ statistically
Columns were calculated separately
n = Number of farms

However, it is important to note that according to Annexure 3.7, kernel damage in the unsprayed locality at Nelspruit was not much different (range: 3.5 – 11.82%) from the commercial farms (range: 0.28 – 12.63%). This indicated that spray applications normally applied against the Heteroptera complex were probably not timed correctly to be effective against the tortricid complex as well.

Results portrayed in Fig. 3.25 indicate that tortricid damage predispose trees to abort developing nuts prematurely because most nuts that were collected from the ground had significantly more tortricid damage than nuts that were picked from the trees at the same time (Beaumont $_{ground}$ = 5.67, Beaumont $_{tree}$ = 0.44, t_{18} = 6.51, P≤ 0.001; A4 $_{ground}$ = 4.78, A4$_{tree}$ = 1.22, t_{18} = 2.77, P≤ 0.024 and A16 $_{ground}$ = 5.56, A16 $_{tree}$ = 0.78, t_{18} = 3.19, P≤ 0.013). Nuts will only be classified by processors as immature if the development of an immure nut is arrested prematurely before oil accumulation is complete. These nuts have a rubbery texture and are inedible.

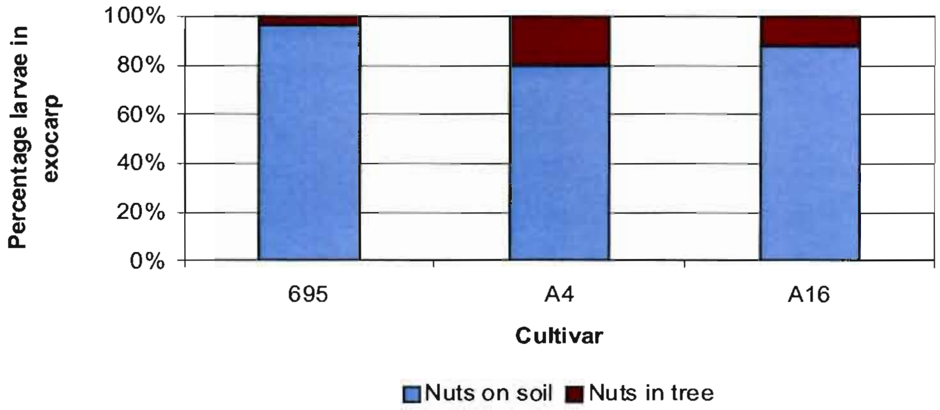


Fig. 3.25 Occurrence of tortricid larvae in the husks of nuts from unsprayed trees. Nuts were collected from the soil and from trees at Nelspruit between 15 April and 9 June 2004 (sample size on trees = 500: sample size nuts on the ground = 496).

The results portrayed in Fig 3.25 support the findings of Waite *et al.* (1999) and mention that kernel damage caused by the tortricid complex is only a small part of the problem. Any damage caused by these insects in the exocarp induces abscission before the kernel is mature. Jones (1994) and Ironside (1983) also mention that damage to the exocarp when nuts are any size may result in abscission.

Jones and Caprio (1992) and Jones (1994) found that kernels are often immature if tortricid induced abscission occurs early in the season, before full oil content of the nut is reached. Larvae consume vast amounts of vascular tissue (Fig. 1.5a) thereby disrupting the flow of water and nutrients from the plant to the maturing kernel. Normal development of the kernel will be arrested if sufficient quantities of exocarp are destroyed, which will result in immature nuts aborting prematurely. These nuts are simply rejected by processors without them knowing the cause of immaturity. Because tortricids feed inside the husk at this stage and the kernels are protected by the hard shell, infested nuts have no external diagnostic features that could be used to differentiate between tortricid induced immature kernels and immature kernels caused by other factors. The total damage caused by these insects is therefore very likely underestimated, which in turn, could influence the effort spent in controlling them.

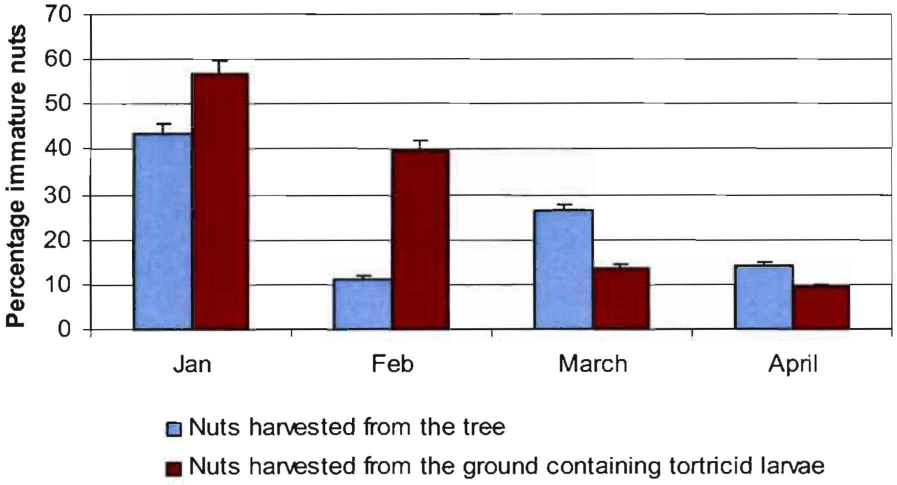
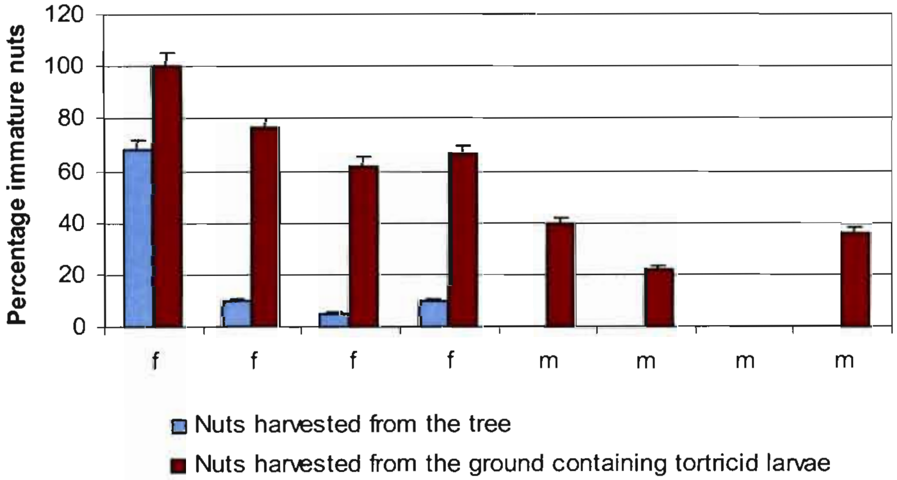


Fig. 3.26 The effect of tortricid larvae feeding on the inside of the macadamia pericarp on maturity of early season nuts on a range of commercial cultivars (741, 344, 816, 791, 788 and Nelmak 2) during the 2004/05 season



Legend

f – February

m – March

Fig. 3.27 The effect of tortricid larvae feeding on the inside of the macadamia pericarp on maturity of early season nuts on the Beaumont cultivar during the 2005/06 season.

This effect of husk feeding on immaturity was quantified during the 2004/05 and 2005/06 seasons and according to Fig. 3.26 prematurely aborted nuts infested with exocarp feeding tortricid larvae during the early season of 2004/05 had a higher percentage immature kernel than nuts that were harvested. According to Fig. 3.27 results from the 2005/06 season on the Beaumont cultivar are also supported by this observation.

It must also be considered that the bulk of the mature nuts only start dropping from March onwards in South Africa, while tortricid larvae only significantly induced immaturity during January and February of the 2004/05 season. In the 2005/06 season tortricid induced immaturity was still prevalent up to the end of March, the probable reason for this is that Beaumont matures significantly later than most other commercial cultivars (Fig. 3.28).

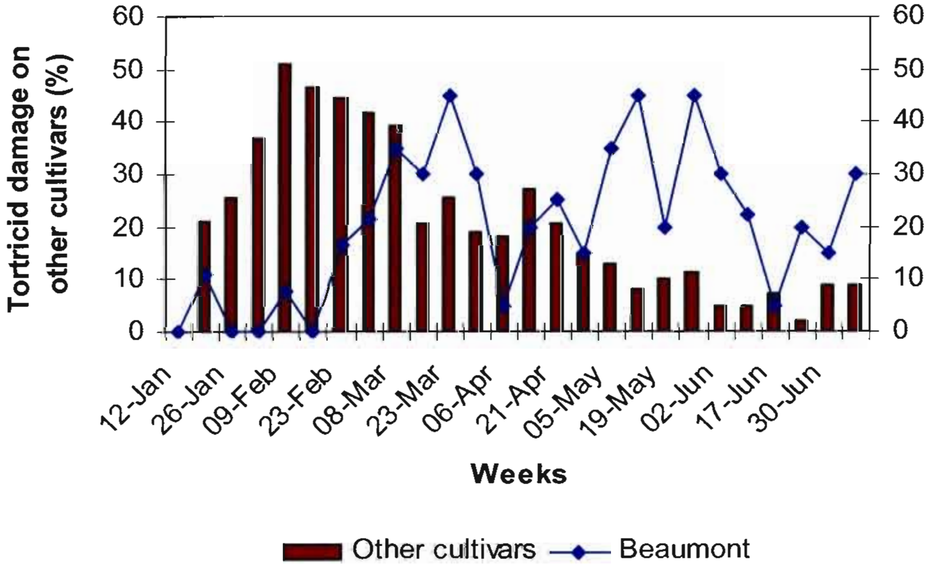


Fig. 3.28 Seasonal incidence of tortricid damage to cultivar Beaumont when compared to a range of commercial cultivars derived from *Macadamia integrifolia* (741, 816, 344, 791, 788 and Nelmak2) during the 2005/06 season.

Jones & Follett (1997) added that nut drop six – eight weeks after the crop reached maximum size will not increase tortricid induced immaturity because sufficient oil accumulation has already occurred and the nuts are considered to be physiologically mature. According to Fig. 3.29 shell hardening in South Africa is normally complete by the second week in January each year.

Tortricid induced immaturity during the late season appears to be a significant problem in orchards were mostly susceptible cultivars, such as 344 (A. Shaw, personal communication), or late maturing cultivars, such as Beaumont are planted in close association with alternative food sources.

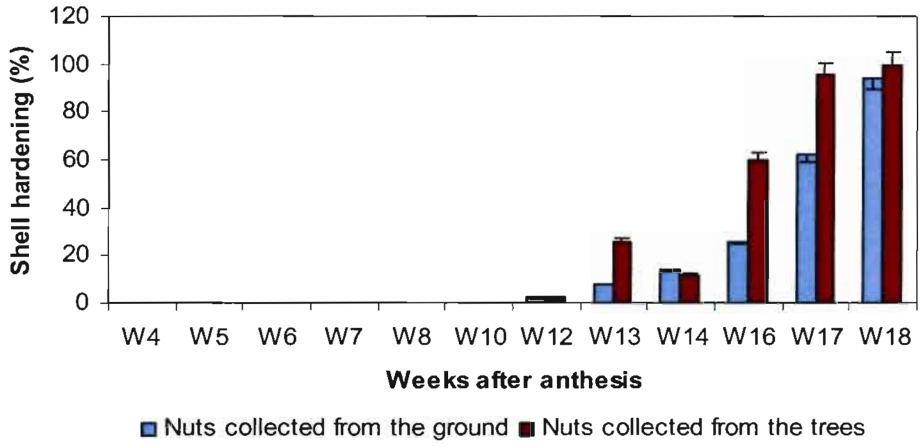


Fig. 3.29 Percentage shell hardening in various commercial cultivars (741, Beaumont, 344, 791, 816, 788 and Nelmak2) of nuts that were collected from trees as well as on the ground during the 2005/06 season in the Nelspruit region.

3.4.2.4 Monetary value of insect induced damage

According to Nunes (2006) the insect component of the total unsound kernel percentage in South Africa increased incrementally from 41% in 1999 to approximately 54% in 2005. Tortricid damage generally varied between 5 % in 1999 to 3 % in 2005. Indirect tortricid damage (immaturity) decreased from 17% in 1999 to 11% during 2004/05. Le Roux (2004) mentioned that during 2003/04 10.43t or 2.16% of the unsound kernel of the South African crop was lost, presumably due to direct kernel damage, while 55.76t or 11.55% of the unsound kernel was lost due to immaturity.

Macadamia nuts could be immature due to a variety of reasons. Severe nutrient deficiencies, drought stress, as well as extreme diurnal temperature variation could also permanently arrest the development of immature nuts (A. Shaw, personal communication). Severe drought stressed and/or nutrient deficient trees are only infrequently encountered in commercial macadamia orchards, but temperature induced immaturity could occur more frequently. While it is impossible to implicate any of these factors post harvest as the causal agent of immaturity, a conservative estimate based on practical experience for tortricid induced immaturity would be in the region of 50%. During 2003/04 total tortricid damage therefore amounted to approximately 38.31t or 7.94% of total unsound kernel recovery. Calculated at R60.00/kg kernel, tortricids were responsible for a loss of approximately R2 298 600.

When tortricid induced kernel damage (Annexure 3.7) was plotted against tortricid induced husk damage an r^2 value of 0.55 revealed a weak positive correlation according to Fig. 3.30. If more data is provided in future, this graph can be used by growers to calculate true yield losses inflicted by this underestimated pest complex.

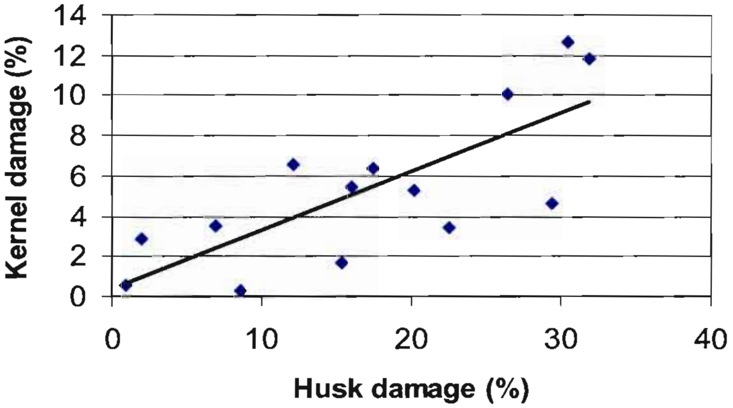


Fig 3.30 The relationship between the percentage tortricid induced husk and kernel damage on a number of macadamia farms in Mpumalanga (r^2 = 0.55, P <0.004, F = 9.32).

3.4.3 Discussion

Tortricids are difficult pests to control because the window period for effective chemical control is very narrow. Sprays have to be directed against recently eclosed first instar larvae before they burrow into the nut. According to Fig 3.22, oviposition appears to be relatively synchronized and an insecticide application ± nine weeks (late November) after anthesis is therefore suggested. Oviposition largely occurred when nuts reached a mean medial diameter of ± 20mm. This relationship is coincidental and is more related to the phenology of macadamia trees (end of premature nut drop). This apparent link between plant phenology/physiology and ovipostion by tortricids currently forms part of a joint research program between the ARC and the subtropical fruit industry.

Although a number of farms are using tortricid pheromones for monitoring, IPM (monitoring and spraying according to predetermined action levels) is mainly directed at the heteropteran complex. Any effect of pyrethroid sprays on the tortricid complex was in most cases unintended. It was nevertheless surprising that damage levels of farms which sprayed according to scouting results (19.08%), differed considerably form the unsprayed (11.64%) and organic farms (7.54%). The IPM compliant farm at Karino also produced citrus which is a major alternative host for *T. leucotreta.* As a result adjoining macadamia orchards were severely infested which probably skewed results of farms that based spraying on scouting results.

Interestingly the sub-optimally managed farm using a fixed interval spraying regime at Hermansburg had considerably less damage (3.68%) than mean damage levels (9.76%) recorded at the Nelspruit farms. A possible reason for this was that this farm traditionally sprays a synthetic pyrethroid during November which probably resulted in lower than average damage percentages. According to Table 3.15 farms that sprayed during November generally had lower tortricid damage levels than farms that did not spray during this period.

The value of tortricid damage is probably less than R3 million annually, but is expected to increase as more orchards come into bearing during the next few production seasons. Chemical control of the heteropteran complex will in future focus on soil applied systemic insecticides, which will result in a decrease of foliar sprays containing mostly pyrethroids. The effect of this reduction in sprays on population levels of tortricids will be difficult to quantify, but could add to the expected increase in tortricid induced damage in future.
After shell hardening a considerable amount of feeding took place inside the pericarp. During this study it was indicated that this type of damage give rise to early abortion and concomitant immaturity.

3.5. Damage estimates and population trends of the heteropteran complex occurring on macadamia in South Africa.

3.5.1. Introduction

Heteroptera as a group is expected to increase its pest status during the next few years due to the following reasons:

- i) Recent environmental conditions (2000 – 2009) were very favourable as most production regions had relatively mild winters linked to warm and wet summer conditions.
- ii) Wet summer conditions during 2000 - 2009 disrupted spraying activities on a number of farms.
- iii) Large macadamia monocultures are coming into production and it is expected that the present upward trend in damage might persist at least for the short to medium term.
- iv) In many cases absent landlords (KwaZulu/Natal) and recipients of restitution farms (Limpopo) are not spraying their orchards adequately.

The main aim of this study was to investigate a range of biological aspects of the Heteroptera complex occurring on macadamia, which could facilitate a more sustainable management strategy for these intractable pests. Major components that received specific attention included a damage survey on eight farms to determine the true magnitude of the problem. The damage profile of the Heteroptera complex was studied in an unsprayed orchard and aspects such as the effect of heteropterans on dropped nuts as well as the effect of tree phenology on heteropteran damage received specific attention.

3.5.2 Results and discussion

3.5.2.1 Economic damage

Results portrayed in Annexure 3.8, give an indication regarding the ability of heteropterans to damage macadamia kernels in South Africa. Kernel damage between 54.73 – 70.98% could be expected under unsprayed conditions. Although not statistically proven, trends indicate that the total damage percentage of the organic farm, was similar to the untreated locality (± 47%). Kernel damage was slightly lower on both farms (46% organic versus 59% unsprayed).

Non IPM compliant farms (insect control is based on calendar sprays) that were well managed had a similar total kernel damage rating as sub-optimally managed farms,

(±14%) (Annexure 3.8). This probably indicates that the subjective criteria used to differentiate between these farms (optimally managed agronomic practices such as irrigation, fertilization and pruning vs. neglected trees) were insufficient or that it simply did not have an important influence on kernel quality.

Early and late season damage at Burgershall varied over the three seasons of monitoring according to Annexure 3.8. Kernel damage at the unsprayed locality at Nelspruit during the 2002/03 season was high, with approximately two thirds of the kernels affected. During the subsequent two seasons damage percentages were similar at approximately 55%, while the 2005/06 season had 71% damage (Annexure 3.8). Whether this apparent upward trend will continue is unclear at the moment but it is expected that the damage will level off once the trees have reached physiological maturity. In contrast IPM compliant farms had damage ratings of less than 2 %. Possible reasons for this could be lower insect pressure or a more efficient spraying program. If the former reason for low kernel quality was valid one would expect a steady increase in damage as the trees mature (see section 3.3). Instead both farmers in the IPM group managed to achieve these levels of kernel quality for a consecutive number of years.

Most commercial farmers spray an average of six times during the season, which limits kernel damage to 15% (range 0.28 – 26.23) kernel damage. Clearly this is still unacceptably high, especially if the current value of the crop is taken into account. Kernel damage on the commercial farms has also recently shown an upward trend (Shorman and Golden Macadamia Processors, personal communication). The heteropteran dilemma is further compounded by the problem that even moderately affected nuts are more difficult to process, as it requires more time, thereby slowing down the entire production line. The end result is that producers have to pay more to have their smaller crop processed. With the current rate of expansion of the macadamia industry in Southern Africa (Lee 2003; Lee 2006), large monocultures are envisaged within the next decade. When this happens, insect and particularly heteropteran induced damage is expected to worsen significantly.

3.5.2.2 Monetary value of insect induced damage

When the annual South African macadamia processor results obtained from Nunes (2006) and Nunes (2007) were pooled, Fig 3.31 indicated that direct and indirect heteropteran damage has shown a slight upward trend since the 1999 harvest season. Fungal infections were included in Fig. 3.31 because the mouthparts of heteropterans are not aseptic and various opportunistic saprophytic fungi could possibly be transmitted to the kernels during feeding.

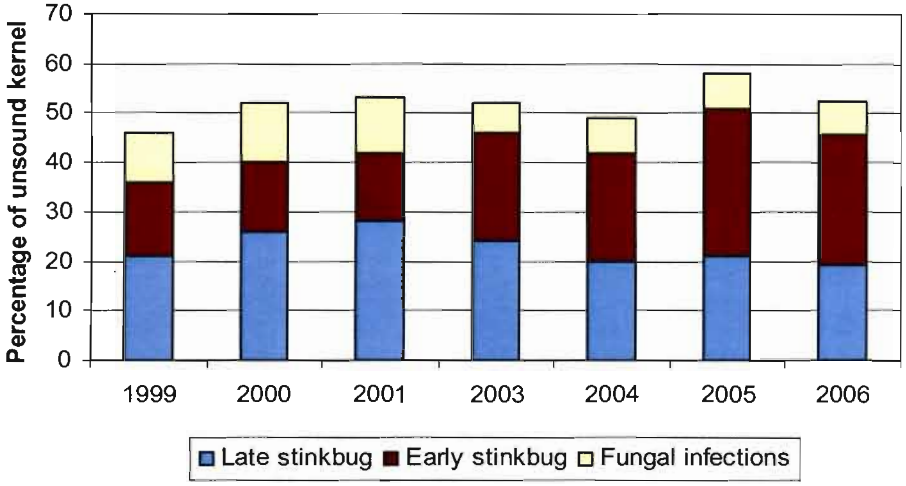


Fig. 3.31 A comparison between fungal infections, early and late heteropteran damage to macadamias in South Africa from 1999 – 2006 (Nunes 2006; Nunes 2007).

In the coffee industry it is well known that the antestia stink bug transmits the two fungi *Nematospora coryli* and *Nematospora gossypii* to mature fruit (Le Pelley 1968). La Croix & Thidwa (1986) isolated the following common secondary fungi from heteropteran induced kernel lesions: *Pullulatia pullulans, Fusarium graminearum, Botryodiplodia theobromae* and *Botryosphaeria ribis*. However, none of these fungi were isolated from heteropteran mouthparts. After heteropteran mouthparts are withdrawn a small drop of fluid is normally evident at the puncture mark. It is likely that spores of saprophytic fungi could germinate in this nutrient rich broth and use these puncture marks to invade the kernel.

Calculated at R60.00/kg sound kernel, Nunes (2006) estimated that the South African macadamia industry lost approximately R24 million due to direct heteropteran damage to kernels during the 2005/06 season. This figure will increase if kernels with fungal infections are added to the total. If the unsprayed orchard at Nelspruit can be used as a worst case scenario, growers in South Africa saved ± R330 million by spraying for heteropterans during 2005/06.

According to Table 3.16 the cost benefit ratio of the organic farm was close to 1:1, indicating that heteropteran control was probably ineffective. These results are confirmed by Schoeman & Mohlala (2008) who reported most organic remedies were ineffective for the control of heteropterans.

Fixed interval (calendar) spraying did reduce heteropteran damage, and a cost benefit ratio of approximately 1:5 was realised. No differences in terms of kernel damage were observed between the two groups of farms that sprayed on a fixed interval basis. Farms that sprayed according to threshold levels had a cost benefit ratio of nearly 1:22. The large differences between the two spray strategies (fixed interval vs. spraying according to threshold levels) may be ascribed to the following:

i) Heteropterans are able to cause damage at low population densities.

ii) Because damaged nuts do not drop and cannot be externally differentiated from undamaged nuts, any damage after the end of premature nut drop period (November) may therefore be regarded as additive.

iii) Because fixed interval spraying is pest density independent any damage after economic threshold values have been reached will be reflected in processor reports as unsound kernel.

Table 3.16 Economic analysis of the effects of an insect control strategy on kernel quality and associated profits on eight farms in Mpumalanga from 2002/03 - 2006/07.

Gross income (R)[a]	Heteropteran kernel damage (%)[b]	Value of damage (R)[c]	Cost of applying four pyrethroid sprays[d]	Advantage gained by applying four pyrethroid sprays (R)[e]	Nett profit[f]	Total cost of insect control[g]	Cost benefit ratio[h]
65760	59 (unsprayed)	38 798					
65760	46 (organic)	30 250	2 053	8 548	33 457	32 303	1:1.04
65760	14 (calendar)	9 206	2 053	29 592	54 501	11 259	1:4.84
65760	1.26 (IPM)	829	2 053	37 969	62 878	2 882	1:21.82

Assumptions and calculations

[a] Gross income

Average nut in shell price – R60/kg

Average yield – 4t/ha

Average kernel recovery 27.4%

$$\text{Gross income} = \frac{4\,000\text{kg} \times 27.4}{100} \times 60 = \text{R}65\,760/\text{ha}$$

[b] Obtained from Annexure 3.8

[c] Value of damage: [a] x [b] /100

[d] It is assumed that four sprays are applied/season. Application cost = R1.64/tree (Table 3.10)

Plant spacing of 8 x 4 m is assumed and the plant population/ha is therefore (100/8) x (100/4) = 313 trees/ha

Cost of 4 pyrethroid sprays/ha is therefore 1.64 x 313 x 4 = R2053

Cost of organic crop protection is more expensive than conventional pesticides, but the same values were used to facilitate comparison.

[e] Value of damage in unsprayed orchard – value of damage in treated orchard [c]

[f] Nett profit = Gross income [a] - value of damage [c] – cost of chemical/ha [d]

[g] Value of damage [c] + Cost of applying 4 pyrethroid sprays [d]

[h] Nett profit [f]/ Total cost of insect control [g]

3.5.2.3 Relative seasonal incidence of damage to kernels

Coming out of winter, heteropteran populations are generally low (Bruwer 1992). Macadamia trees flower and bear profusely early in the season. Because of the combined effect of these two parameters it is expected that the relative incidence of early season stink bug damaged kernels will be significantly lower when compared to damage later in the season (Fig. 3.32). Joubert (1986) found that 86.6% of all *Macadamia integrifolia* derived nuts abort naturally within the first nine weeks after nut set. Of all the nuts that aborted prematurely at the unsprayed locality (Nelspruit) during 2003/04 – 2005/06, only 27.31% of them had heteropteran puncture marks on the inside of the husk. The majority of these nuts were probably uninfested and aborted on account of a range of other factors such as: high temperatures, low humidity, wind, lack of pollination or the intrinsic ability of a macadamia plant to mature only a small percentage of all flowers that were originally set (Waite *et al.* 1999). Although some farmers are already using this principle of compensation for early damage, implications for macadamias and other subtropical crops affected by heteropterans are important and require significant further study.

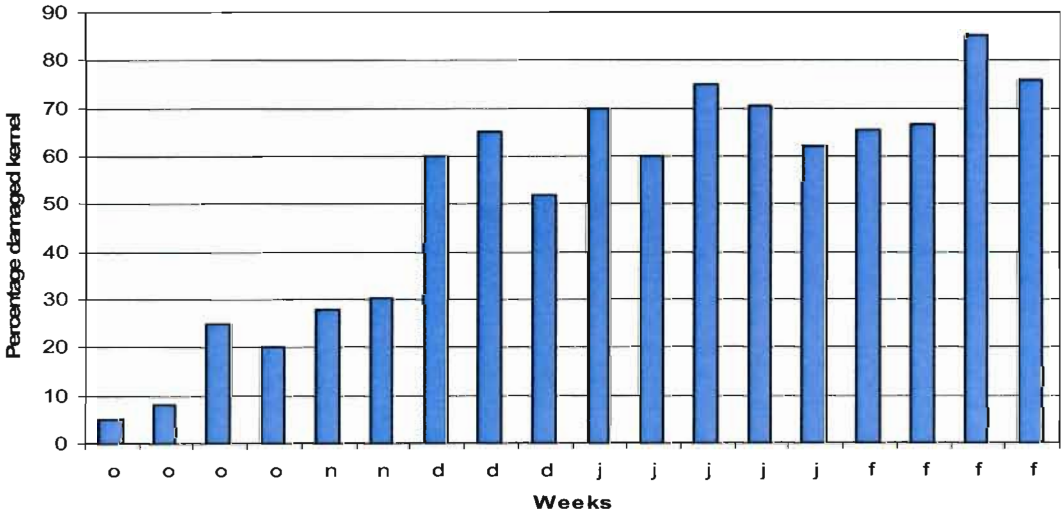


Fig. 3.32 Relative seasonal incidence of macadamia nuts with kernel lesions at the unsprayed location at Nelspruit research station during 2005.

It is a general practice among most growers to apply a "clean up" spray before anthesis. This spray is then followed with another pyrethroid insecticide application within a few weeks. Another pyrethroid containing spray against the tortricid complex is usually applied annually towards the end of November. Sprays applied before and immediately after anthesis were wasteful and detrimental to beneficial insect complexes occurring in macadamia orchards (see section 3.6). This is especially important as populations of beneficial insects are normally low during this time. Repeated area wide chemical disruption with long acting insecticides (such as synthetic pyrethroids) might upset the natural equilibrium to such a degree that beneficial insect populations require a long time to recover (De Villiers and Du Toit 1984).

The effect of the hardening of the shells (seed coat) towards the end of the season on heteropteran induced kernel lesions is also unclear. According to Fig. 3.32 the occurrence of heteropteran induced damaged kernels gradually increased as the season progressed and reached a maximum of ± 60 - 70% towards January 21 in the unsprayed location at Nelspruit. Although Fig. 3.32 only depicts data from the 2005 season, the incidence of heteropterans on this locality during 2003 and 2004 was similar. According to Fig. 3.29 and Wiid-Hobson (2003) this is also when the shell (seed coat) hardens. According to Ironside (1988) and Shearer and Jones (19996) nuts become less vulnerable when the shells harden, yet annually a large portion of damage recorded by the processors is of the late type according to Fig. 3.31. Mitchell *et al.* (1965) and Mitchell & Ironside (1982) mentioned that pentatomids can penetrate the hard woody shell with relative ease.

3.5.2.4 Incidence of heteropteran feeding lesions determined on tree and ground collected nuts

Individuals of *Bathycoelia natalicola* were sporadically observed on naturally aborted nuts in the unsprayed orchard at Nelspruit during 2003/04 and concern was expressed that the unharvested nuts could possibly be damaged. This concern was strengthened by the findings of Jones *et al.* (1991) who mentioned that in Hawaii considerable feeding activity of *Nezara viridula* took place on the ground. However, Table 3.17 indicates no significant differences in terms of damage between nuts on the ground and on trees. The importance of this finding is that the harvest frequency of uncollected physiologically mature aborted nuts in South Africa will not have to be adapted in any way to prevent heteropteran damage.

Table 3.17 Occurrence of heteropteran feeding lesions in the kernels of unsprayed trees of three macadamia cultivars collected on the soil and on trees at Nelspruit during 15 April – 9 June 2004.

Locality where nuts were collected	**Mean number of heteropteran infested nuts collected ±SD**			
	Beaumont	**A4**	**A16**	**n**
Tree	12.33a ± 3.74	10.78a ± 4.63	8.44a ± 4.39	477
Ground	13.44a ± 2.07	10.33a ± 4.33	7.78a ± 3.99	471
t value	0.86	0.38	0.69	
P≤	0.41	0.71	0.51	

Means followed by the same letter do not differ statistically

N. viridula is the only economically significant heteropteran pest of macadamias in Hawaii (Jones and Caprio 1992). Currently *N. viridula* is relatively unimportant on macadamias in South Africa and according to Van den Berg *et al.* (1999) and Van den Berg *et al.* (2001) it constitutes only 0.3% of all hemipterans recorded during a survey in the Nelspruit region. If *N. viridula* also damages fallen nuts in South Africa, its effect will probably be negligent, because damage inflicted by the more dominant indigenous heteropterans will mask the relative minor damage inflicted by this pest.

3.5.2.5 Quantification of seasonal Heteroptera damage

The following series of exposure trials were carried out in an unsprayed mixed cultivar orchard at Nelspruit in order to determine if the phenological development of macadamia nuts have an effect on the ability of heteropterans to inflict damage throughout the season (Refer to section 2.5.4).

- *Effect of selective exposure of macadamia nuts throughout the production season to natural populations of heteropterans in an unsprayed orchard*

As expected Table 3.18 indicated that Beaumont nut clusters exposed to heteropterans relatively soon after the end of premature nut drop (December) had high damage index values. Nuts exposed to heteropterans for the entire season had the highest damage index value. This trend became more obvious when the mean percentage undamaged nuts was quantified using Abbot's formula. According to Table 3.18 exposure to field populations of heteropterans before shell hardening (December – mid January) apparently had the potential to inflict greater damage than thereafter (mid January – harvest).

Table 3.18 Mean percentage damage caused by the Heteroptera complex on unsprayed Beaumont trees throughout the 2004/05 production season. Bags protecting the nuts were removed on a fortnightly basis and unprotected nuts served as a control.

Date of exposure: (fortnight ending)	**Damage Index value (Wheeler 1963)**	**Mean percentage undamaged nuts[a] (Abbot 1925)**	**Mean percentage damage/ fortnight (100 – a)**
15 Dec	24.14	66.04	33.96
3 Jan	26.47	62.62	37.38
14Jan	10.00	86.79	13.21
1 Feb	6.25	92.29	7.71
15 Feb	10.34	86.29	13.71
28 Feb	18.42	74.43	25.57
15 Mar	7.32	90.72	9.28
4 Apr	9.88	86.97	13.03
18 Apr	5.26	93.75	6.25
3 May	4.17	95.35	4.65
Control (Unbagged for the duration of the trial)	68.13		
Heteropterans (exposed for ± 1 month)	34.09		

Nuts exposed to natural populations of heteropterans had the highest damage index value and closely resembles damage levels in the unsprayed orchard (Annexure 3.8). Nuts exposed to caged heteropterans also had high damage index levels indicating that heteropteran damage may occur as long as there are nuts on the trees.

- *The effect of selective protection of macadamia nuts throughout the production season from natural populations of heteropterans in an unsprayed orchard*

By protecting the nuts of the A4 cultivar prior to shell hardening (mid January), Table 3.19 indicated that damage index values were confined to about a quarter of the unbagged control. Abbot's formula also indicated that the greatest advantage was derived from protecting the nuts during the initial two fortnights prior to complete shell hardening (mid January).

According to Joubert (1986) developing macadamia nuts undergo three distinct phenological stages during the season. The first two stages last approximately 14 weeks after flowering. Main flowering normally occurs in the Nelspruit region during the last two weeks of September. It would appear that the initial 14 week period of endosperm development corresponded to the period when nuts are most vulnerable. Data presented in Fig 3.29 confirmed the findings of Wiid-Hobson (2003) that the shells also begin to

Table 3.19 Mean percentage damage caused by the Heteroptera complex on unsprayed A4 trees throughout the 2004/05 production season. Bags protecting the nuts were put in place on a fortnightly basis and unprotected nuts served as a control.

Date of exposure: (fortnight ending)	**Damage index value (Wheeler 1963)**	**Mean percentage undamaged nuts^a (Abbot 1925)**	**Mean percentage damage/ fortnight (100 – a)**
17 Dec	8.33	80.29	19.71
14 Jan	10.42	74.66	25.34
1Feb	26.47	31.5	68.5
16 Feb	29.37	23.67	76.33
1 March	36.46	4.63	95.37
15 March	23.21	40.26	59.74
4Apr	20.97	46.29	53.71
10 May	27.68	28.24	71.76
Control (Unbagged for the duration of the trial)	37.18		

harden after the phase of premature drop. Shells are normally fully hardened by week 18 (Tables 3.18 and 3.19) and macadamia kernel damage was limited after this period. When faced with no-choice situation, cage bound individuals of *B. natalicola*, were able to feed on the kernels of mature nuts. Nuts never become totally impervious against heteropterans according to Table 3.18. When adults of *B. natalicola* were confined to cages, all of the observed damage was regarded as late season lesions, which support the observations of Mitchell *et al.* (1965) and Mitchell & Ironside (1982) who indicated that nuts never became impervious to heteropterans. Typically infected kernels would have an oily nearly translucent appearance (Fig. 3.33). Upon removal of the outer layers of the kernel, white heteropteran feeding lesions were often uncovered (Fig. 3.34). This type of damage is easy to distinguish from the early season damage which normally manifests as big sunken lesions in the kernel (Fig.3.35).

Fig. 3.33 Typical external appearance of macadamia kernels infested by heteropterans late in the season.

Fig. 3.34 Macadamias infested by heteropterans during the late season with the external surface layer removed to exhibit the characteristic white lesions.

Fig. 3.35 Typical external appearance of macadamia kernels infested by heteropterans early in the season during the period of endosperm development and rapid cell division.

3.5.2.6 Risk profile of *Bathycoelia natalicola*

3.5.2.6.1 Relationship between medial nut diameter, kernel distance and seasonal phenological development of Beaumont nuts

This trial was conducted on a commercial macadamia farm using the Beaumont cultivar to determine if the mean medial diameter of a range of nut sizes could be related to the combined husk and kernel thickness (kernel distance) (Refer to section 2.5.5).

According to Fig. 3.36 an r^2 value of 0.972 indicate a clear positive relationship between kernel distance and medial diameter of nuts of the Beaumont cultivar. The seasonal increases in mean medial diameters of Beaumont nuts were measured and are depicted in Fig. 3.37. By combining the data from these two graphs it is possible to estimate the approximate kernel distance by simply measuring the mean medial diameter of nuts or by recording the elapsed time since anthesis.

It is expected that the relationship observed in Fig. 3.36 will only be valid for localities at approximately the same altitude as the Nelspruit region since it has been shown by Jones (1995b) that high altitudes are positively related to thicker husks and shells. Consequently nuts from coastal areas are expected to be more susceptible to heteropterans due to thinner shells and husks.

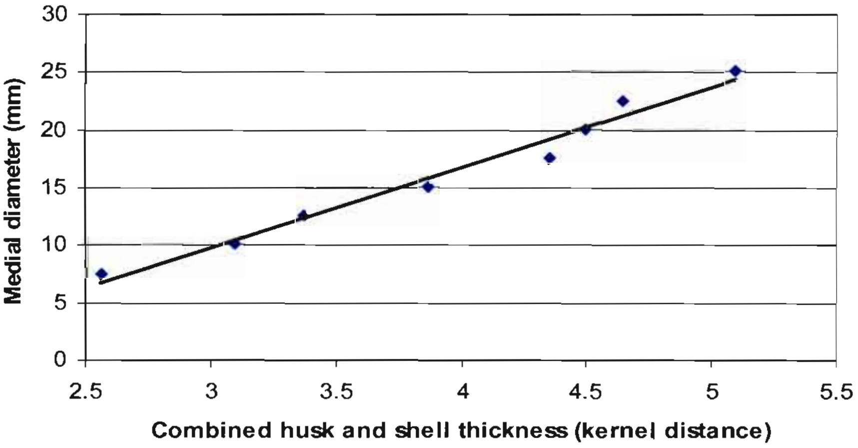


Fig. 3.36 The relationship between mean medial diameter of nuts from the Beaumont variety and the combined mean kernel and husk thickness (kernel distance). Nuts were obtained from Karino approximately 20 km east of Nelspruit (r^2 = 0.972).

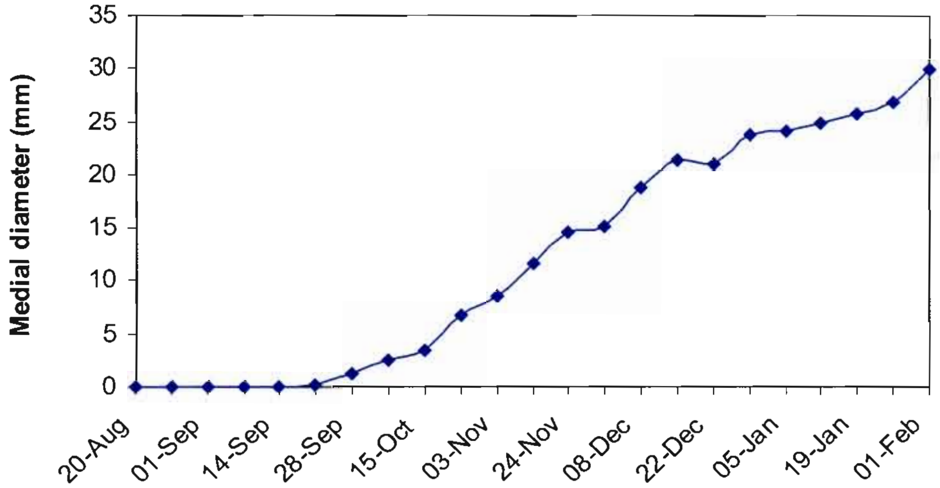


Fig. 3.37 Incremental seasonal increases in medially measured nut diameter (cv. Beaumont) in the Nelspruit region during the 2007 season.

3.5.2.6.2 Mouthpart length of *Bathycoelia natalicola*

This trial was conducted to quantify the seasonal risk profile of *B. natalicola* based only on kernel distance versus the mouthpart (rostrum) length of the respective nymphal stages.

The mouthpart lengths of all stages of *B. natalicola* are represented in Table 3.20. Dyar's law appears to be applicable to the growth of the rostrum of the various nymphal instars of *B. natalicola* as the inter instar growth ratio of the rostrum remains reasonably constant at ± 1:1.42. Using Dyar's constant, it is estimated that the rostrum length of first instar nymphs is ± 2.42mm. These findings in combination with the seasonal rate of increase in shell and husk thickness as shown in Fig.3.37, was used to draw up a risk profile for *B. natalicola* (see Table 3.21).

Considering the universal nature of Dyar's law, it is probably valid for inter-instar growth ratios of mouthpart lengths of other economically important heteropterans as well. Similar profiles can probably easily be calculated provided that the mouthpart length of at least two successive nymphal instars is known. This data can now be used to calculate risk profiles for other cultivars as well.

Table 3.20 Mean length of rostrum and inter instar growth ratios of the rostrum of successive nymphal stages of *Bathycoelia natalicola*.

	Instar 2	Instar 3	Instar 4	Instar 5	Adult
Length of rostrum (mm) ± SD	3.43 ± 0.422	4.88 ± 0.373	6.91 ± 0.606	9.85 ± 0.856	13.6* ± 0.428
Inter instar growth ratio	-	1:1.42	1:1.42	1:1.43	1.38
Number of individuals examined	5	42	31	12	

*According to Bruwer (1992)

3.5.2.6.3 Risk profile of *Bathycoelia natalicola* on the Beaumont macadamia cultivar

Although first instar nymphs do not actively feed (they remain clustered on the empty egg shells and presumably feed on fluid and symbionts that remained in the empty shells after hatching (Knight & Gurr 2007; Prado *et al.* 2009), their inferred mouthpart length of 2.42 mm enable them to feed and damage kernels up to six weeks post anthesis. Second instar nymphs are only able to exploit developing nuts for a further week, but damage is expected to be negligible because macadamias are able to compensate for early crop loss up to nine weeks post anthesis (see section 3.6).

Third instar nymphs are able to damage nuts beyond this apparent critical nine week period and may therefore be regarded as the first stage to really cause damage of economic significance. Mouthpart lengths of the remaining stages are long enough to penetrate the husks and shells of this cultivar up to harvest, therefore insect scouts should be trained to recognise them.

Table 3.21 Damage profile of *Bathycoelia natalicola* on the Beaumont cultivar based on mean mouthpart length versus mean combined husk and shell thickness (kernel distance) during the 2007 season

Date	Medial nut diameter	Mean Kernel distance	Mean mouthpart length of *B. natalicola*					
			1st instar nymph	2nd Instar nymph	3rd Instar nymph	4th Instar nymph	5th Instar nymph	Adult
			2.42	3.43	4.88	6.91	9.88	13.6
			Damage profile	Damage profile	Damage profile	Damage profile	Damage profile	Damage profile
21 Sep	0.25	0.06	1	1	1	1	1	1
28 Sep	1.30	0.32	1	1	1	1	1	1
7 Oct	2.60	0.63	1	1	1	1	1	1
15 Oct	3.47	0.84	1	1	1	1	1	1
22 Oct	6.75	1.64	1	1	1	1	1	1
03 Nov	8.68	2.11	1	1	1	1	1	1
10 Nov	11.66	2.83	0	1	1	1	1	1
24 Nov	14.6	3.54	0	0	1	1	1	1
30 Nov	15.13	3.67	0	0	1	1	1	1
08 Dec	18.96	4.6	0	0	1	1	1	1
15 Dec	21.42	5.2	0	0	0	1	1	1
22 Dec	21.16	5.14	0	0	0	1	1	1
31 Dec	23.83	5.78	0	0	0	1	1	1
05 Jan	24.13	5.86	0	0	0	1	1	1
12 Jan	24.97	6.06	0	0	0	1	1	1
19 Jan	25.8	6.26	0	0	0	1	1	1
24 Jan	27.0	6.55	0	0	0	1	1	1
01 Feb	30.0	7.28	0	0	0	0	1	1

Damage profile

0 – Rostrum is too short to penetrate husk and shell

1 – Rostrum can penetrate husk and shell medially

In contrast with *B. natalicola*, *Pseudotheraptus wayi* has short mouthparts (± 6mm), but according to Bruwer (1992) and Joubert (2001) it secretes such toxic saliva during feeding that even the hard woody shell may be dissolved (Fig. 1.4B). This appears to be a characteristic among certain coreids since Ironside (1980) and Ironside (1984) made similar observations regarding the *Amblypelta* complex occurring on macadamias in Australia. Although mouthpart lengths of *P. wayi* were measured, it is suggested that, because of the severe digestive enzymatic activity mouthpart length plays an unimportant role. The evaluation of an alternative method should therefore be regarded as an important topic for future research.

3.5.2.6.4 Identification of immature stages of *Bathycoelia natalicola*

Immature stages of *B. natalicola* are able to damage macadamia nuts up to harvest (Table 3.21). Many growers were not aware of this and because appreciable morphological and colour variation occurs between successive instars and adults of *B. natalicola* (Fig 3.38 A - F). Potentially damaging stages are therefore often misidentified or overlooked which contributed to economic losses as described by Nunes (2006; 2007). Similar differences regarding external morphology were also evident for the coconut bug (*P. wayi*) (Fig 3. 39 A – E).

3.5.3 Discussion

If not controlled chemically the Heteroptera complex may inflict ± 60% damage which in turn relates to an annual loss of approximately R24 million (Piet Muller, chairman SAMAC, personal communication). Despite the financial benefits of IPM highlighted in Table 3.16, most producers still prefer fixed interval spraying presumably because it is less management intensive.

When the relative seasonal abundance of damage was measured in an unsprayed orchard, damage tapered off during January (Fig. 3.32). This was perplexing as it is known that heteropterans are able to penetrate and damage fully hardened macadamia shells right up to harvest. However, these findings were confirmed by the results of the bagging trial (Tables 3.18 & 3.19). Shell hardening is complete during mid January each year which correspond to the period when the nuts become less susceptible to damage (Fig. 3.29). The hard shell of a macadamia nut must be regarded as a formidable barrier and although it limits damage, it does not totally prevent heteropterans from feeding on

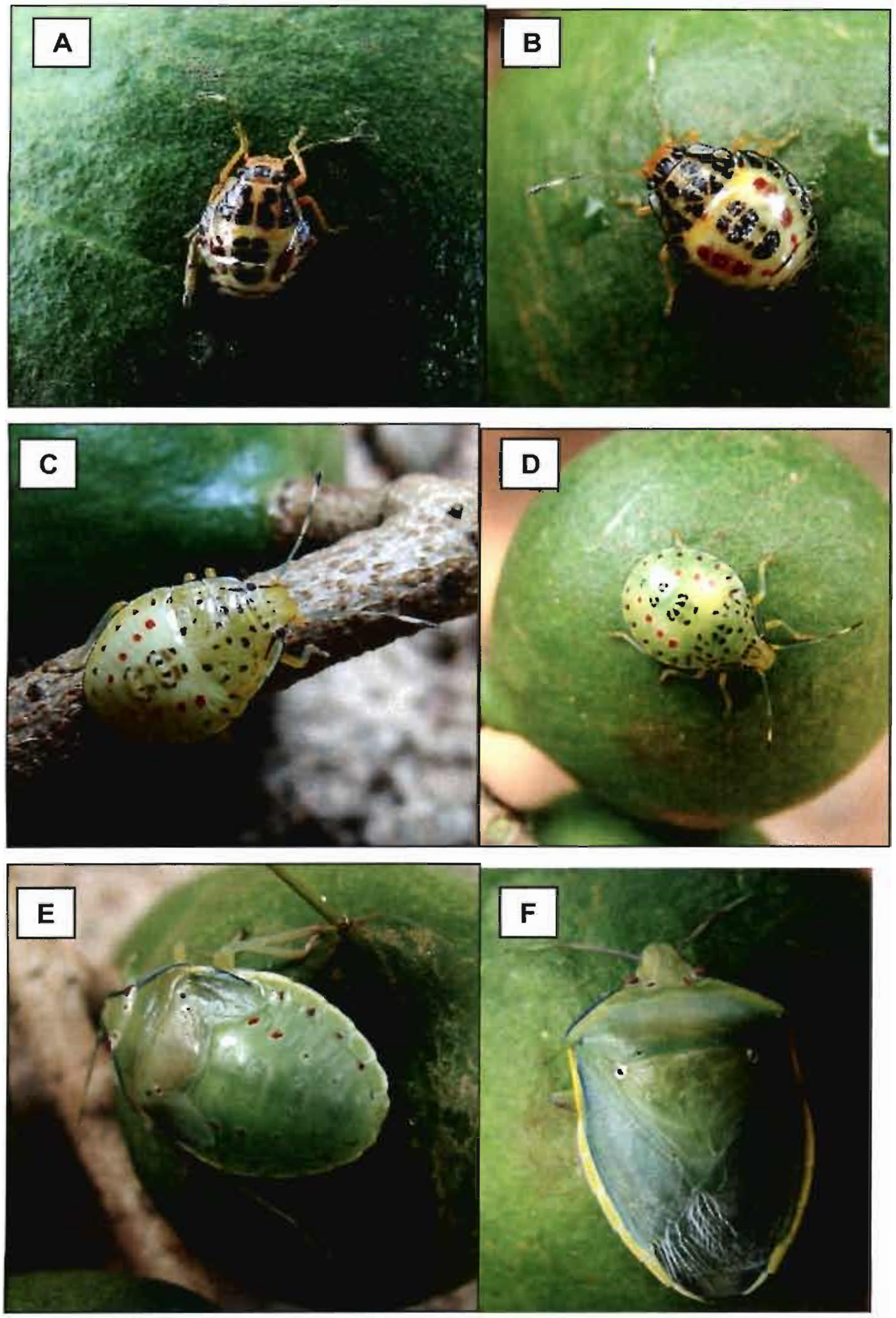


Fig. 3.38 Typical morphological and colour variation occurring in the various respective developmental stages of *B. natalicola.* A: second instar; B: third instar; C: fourth instar; D: fourth instar (colour variant); E: fifth instar; F: adult.

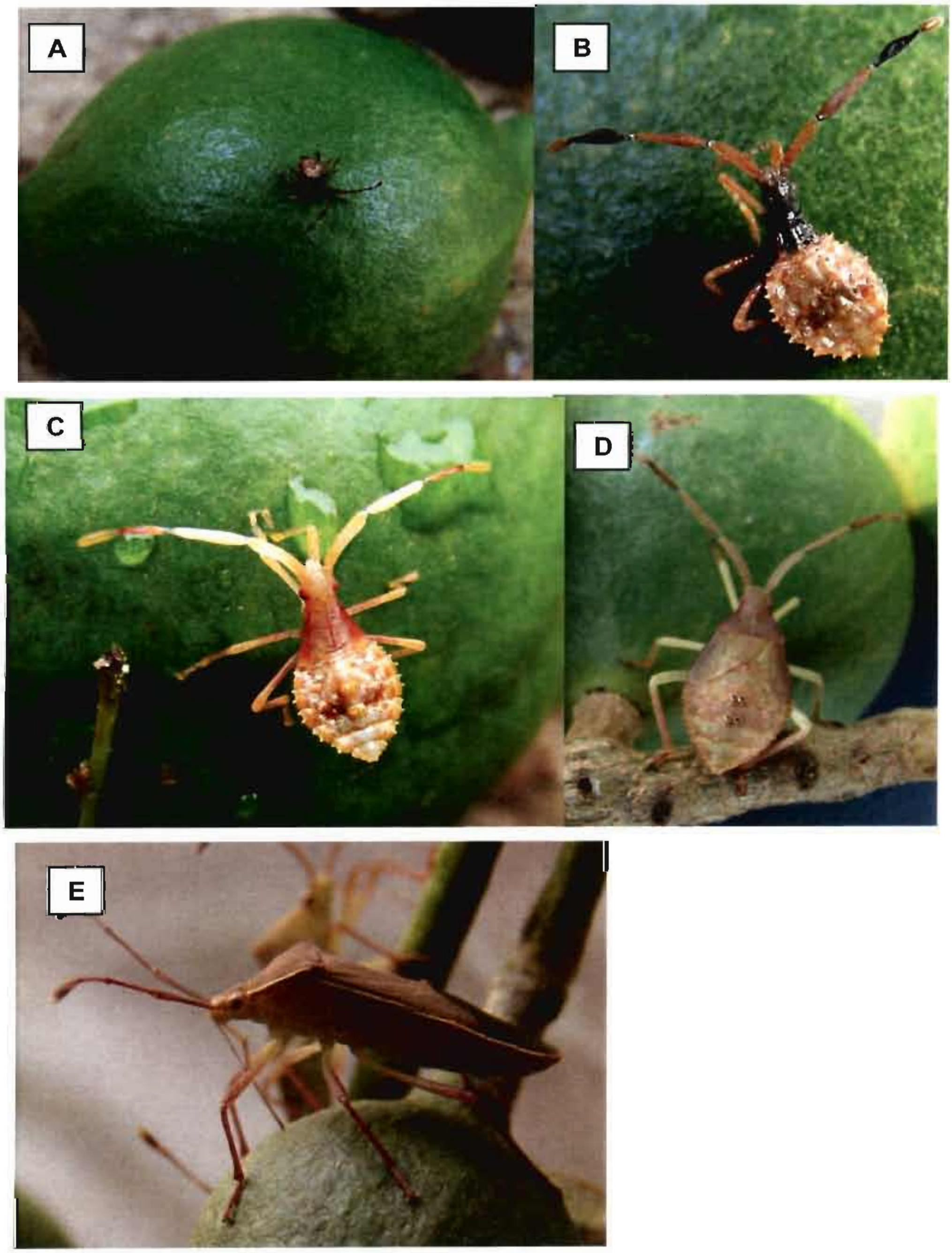


Fig. 3.39 Typical morphological and colour variation occurring in the various respective developmental stages of *P. wayi*. A: first instar; B: second instar; C: third instar; D: fourth instar; E: adult.

the kernel. The South African Heteroptera complex does not damage unharvested aborted physiologically mature nuts and no special precaution regarding fallen nuts have to be taken to limit damage.

3.6 Compensatory ability of macadamias to flower removal and early crop damage: Implications for managing the heteropteran and tortricid insect complexes

3.6.1 Introduction

Quantifying the effect of compensation for early crop loss is an important prerequisite for the reduction of early season insecticide applications. Macadamia trees set many more nuts than they can develop through to harvest. Urata (1954) estimated that each raceme can have up to 300 flowers of which only 6 – 35% develop into immature nuts. According to Anonymous (2000) approximately 99.8% of all macadamia flowers fail to develop in mature nuts. Ito (1980) supported this observation and mentioned that only 0.3% of the nuts are retained completely through to maturity. The research for this study was conducted under commercial conditions and it is assumed that although the effect of heteropterans was significantly reduced, it didn't totally exclude them.

Significant amounts of work have been done researching early season compensation of cotton (Wilson *et al.* 2003; Lei and Gaff 2003), strawberries (English-Loeb *et al.* 1999), pistachio nuts (Daane *et al.* 2005), as well as macadamias (Trueman & Turnbull 1994; Tobin *et al.* 1997). In most cases these crops were able to compensate adequately for early season damage indicating that the reduction of early season sprays could probably be feasible for macadamias in South Africa as well.

It is also especially important to maintain macadamia trees free of pesticide residues during the early season period immediately before and after flowering as bees and concomitant cross pollination can significantly influence nut-set (Trueman & Turnbull 1994; Wallace 1999). Additionally, beneficial insect populations generally become active during this period and disruptions by area wide applications of broad spectrum insecticides could increase the risk of outbreaks of secondary pests (De Villiers and Du Toit 1984).

The specific objectives of this study were therefore to:

i) Simulate the effect of insect feeding by manually removing flowers during full bloom.

ii) Quantify the effect of withholding early season insecticidal sprays on kernel quality and quantity on a commercial basis.

iii) Quantify the effect of heteropteran feeding damage on nut abortion during the early season.

3.6.2 Results

3.6.2.1 Natural abortion rate of two major macadamia cultivars in South Africa

To determine the natural pattern of early fruit abortion the following trial was conducted in an unsprayed orchard at Nelspruit (Refer to section 2.6.1). Trueman & Turnbull (1994) found that that premature nut drop normally terminates ± 70 days post anthesis. Most of the premature nut drop occurred within the first nine weeks after full flower in this study (Fig.3.40) and confirmed the findings of Trueman & Turnbull (1994).

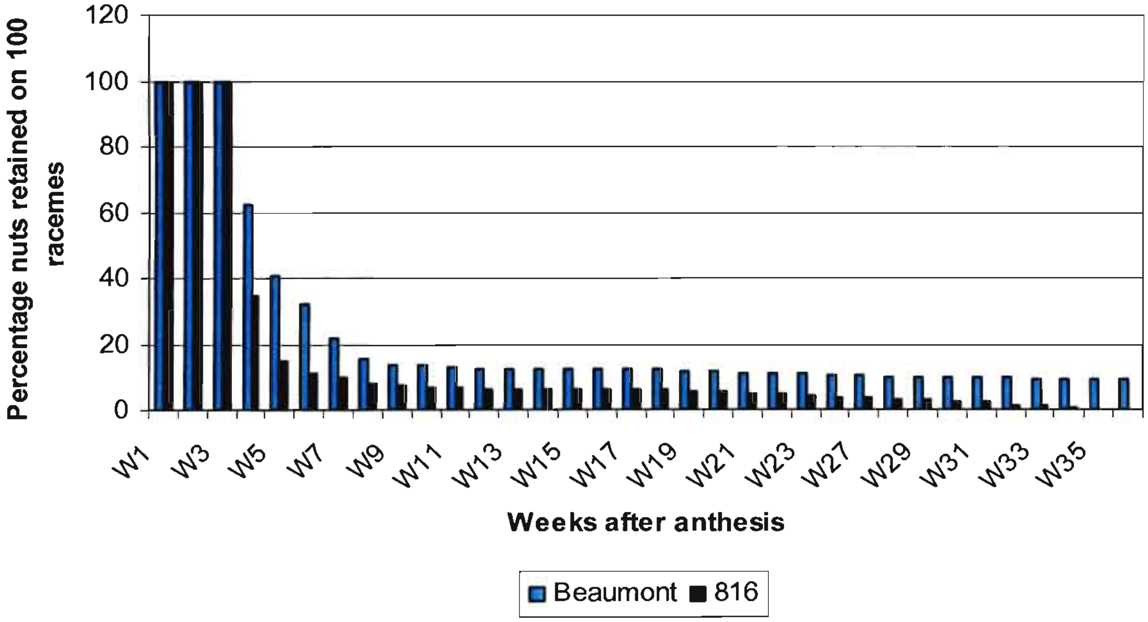


Fig. 3.40 Natural pattern of nut abortion throughout the first 36 weeks after anthesis

The majority (86.56%) of the fruit on 100 marked Beaumont nut clusters dropped within this period, while 93.23% of the nuts from the *Macadamia integrifolia* derived 816 cultivar dropped within the same period. This compares favourably with a figure of 86.8% during a similar study *on Macadamia integrifolia* at Nelspruit by Joubert (1986).

3.6.2.2 Effect of heteropteran feeding on nut abortion

To determine the rate of heteropteran induced premature nut abortion throughout the first nine weeks after anthesis a series of exposure trials were carried out with *Pseudotheraptus wayi* and *Bathycoelia. natalicola.*

A: The effect of time post anthesis on nut abortion

According to Bruwer (1992) small nuts damaged by heteropterans tend to drop. This period is very short when the nuts are young and gradually increases as the nuts become more mature.

When the relative seasonal abundance of nuts on the tree with heteropteran induced kernel lesions were compared to nuts collected from the soil, it is evident that nuts collected from the tree had fewer lesions earlier in the season (Fig. 3.41). This is not surprising as young nuts damaged by heteropterans are expected to abort very quickly due to the death of the embryo. However, as the season progressed the differences between the two groups became less evident. During early December more or less equal numbers of kernel lesions were discernible on nuts recovered from the tree, as well as those collected from the soil, indicating that insect induced abortion probably no longer occurred spontaneously. This period also corresponds to the end of the premature nut drop period as portrayed in Fig.3.40.

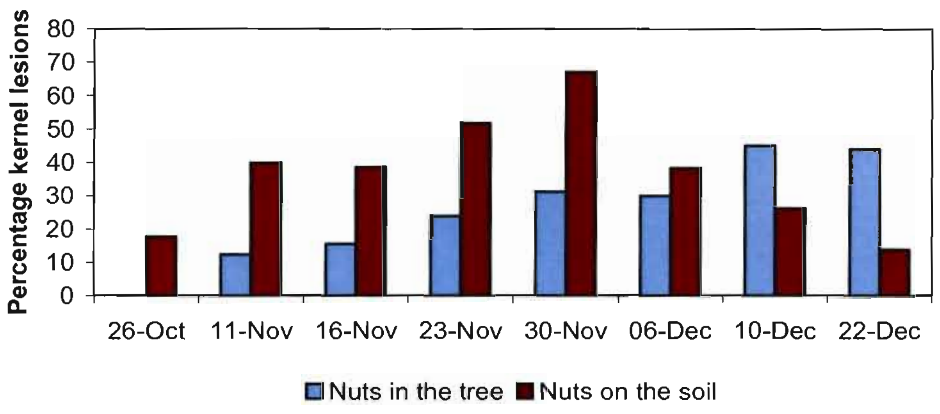


Fig. 3.41 The relative seasonal abundance of heteropteran lesions occurring on nuts (cv. A16) harvested directly from the tree, as well as nuts that had aborted during the early season, at the unsprayed site at Nelspruit.

B: Exposure to heteropterans during October (4 weeks post anthesis)

When nuts were exposed to *P. wayi* during the second fortnight of October 2003, the insect induced abortion rate was much higher than the natural abortion rate (Fig. 3.42).

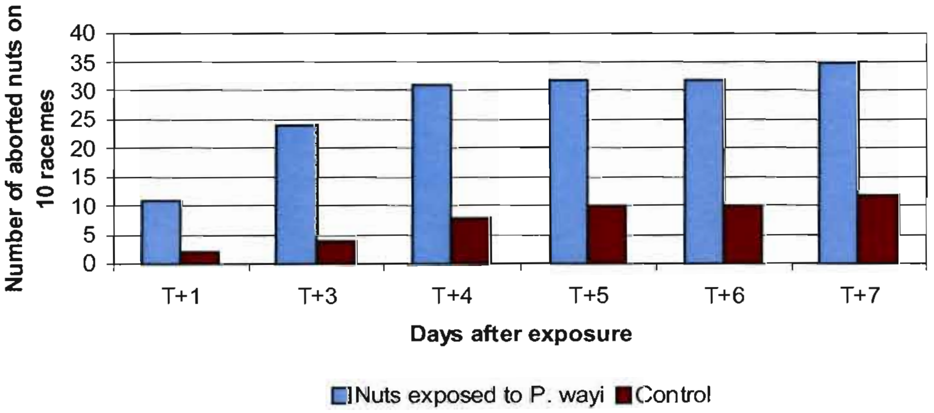


Fig. 3.42 Effect of caged individuals of *Pseudotheraptus wayi* on cumulative nut abortion (days after exposure) of the cultivar Beaumont during 2003. Mean nut size was 7.83mm. (T+ denotes days after exposure).

When nuts were exposed during October 2004/05 to individuals of *B. natalicola* abortion rates were also high (Fig.3.42). If Fig 3.42 is compared to Fig 3.43, it becomes evident that *P. wayi* and *B. natalicola* induced nut abortion occurred more or less up to day T+4 (four days after exposure). Hereafter the abortion rates levelled off and nuts that aborted then probably aborted due to the range non heteropteran related factors that were described in section 3.6.1.

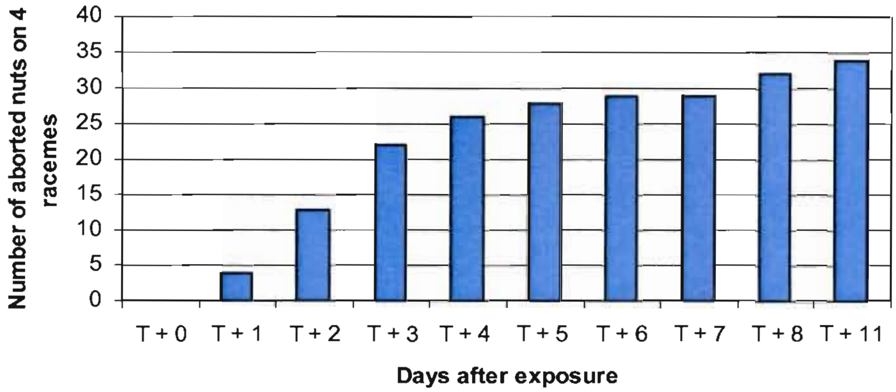


Fig. 3.43 Effect of caged individuals of *Bathycoelia natalicola* on cumulative nut abortion (days after exposure) of Beaumont nuts at Nelspruit during October 2004. (T+ denotes days after exposure).

C: Exposure to heteropterans during November (8 weeks post anthesis)

When nuts were exposed to *B. natalicola* ± 4 – 5 weeks later during the November 29, 2004, Fig. 3.44 indicates a tendency of no differences between the natural abortion rate and the insect induced rate up to early December. This observation supports the earlier findings of Bruwer (1992) in this regard who found that heteropteran induced abortion are reduced after the end of November.

Early in the season when the nuts are small, embryos die off and concomitant abortion occurs relatively quickly. When the nuts developed beyond a critical minimum size, extraction of kernel material during a single feeding event is then probably insufficient to ensure death of the embryo and consequently these nuts no longer abort. Externally it is impossible to identify such damaged nuts prior to cracking. Heteropteran feeding from early December onwards will therefore compromise the quality of the nuts as well as payment to the growers. It is also important to note that damage after early December is bound to be additive because damaged nuts do not readily abort and damaged nuts cannot be distinguished from healthy nuts.

If severe heteropteran infestations occur after December it could result in multiple feeding events on individual nuts. Embryo death and concomitant abortion could still occur under these circumstances, even until late in the season. Normally this type of damage is limited, but wide-spread nut losses have been observed in some of the higher density orchards where insect control is insufficient. Unless significant out of season flowering occurred, any aborted nuts during the period December – January should therefore be a reason of major concern for most growers as it is normally a reliable indicator of heteropteran damage.

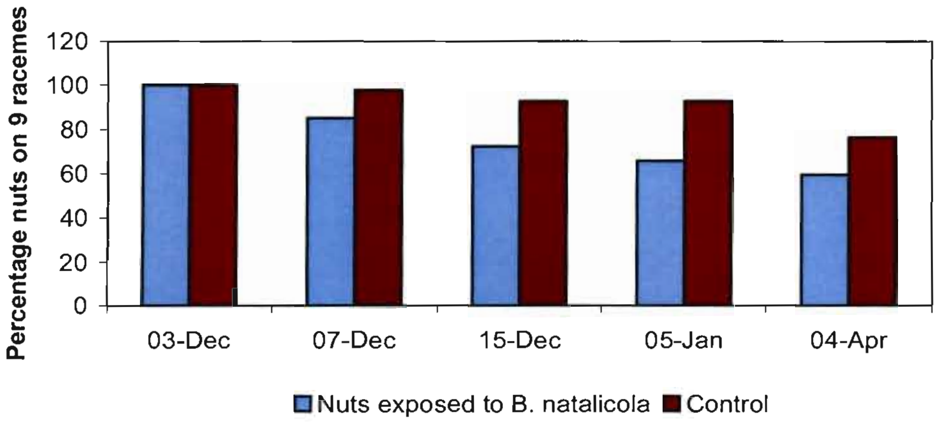


Fig. 3.44 The effect of *Bathycoelia natalicola* on the rate of nut abortion of Beaumont nuts from 29 November 2004 – 04 April 2005, exposed at the end of premature nut abortion (30 November) at Nelspruit

3.6.2.3 Artificial simulation of early season damage

Given the difficulties of manipulating populations of heteropteran pests in field experiments, manually inflicted or simulated damage is a relatively simple method used during this set of experiments to study the responses of plants to herbivore damage (Refer to section 2.6.3). According to section 3.3 the distribution of heteropterans is heterogeneous which could compromise the reliability of conventionally collected field data (see section 3.2.3.2). Wilson *et al.* (2003) supported this viewpoint and confirms that simulated damage has the advantage that it can be inflicted more uniformly. Macadamia trees flower profusely and are normally tall and very dense, the combination of these three factors therefore make it very difficult to estimate the correct percentage of flower removal accurately.

Although Table 3.22 indicated that there were no significant statistical differences between the lower flower removal estimate (13.3%) and the control at Burgershall, the higher flower removal estimate differed significantly from the other two treatments. Beaumont trees used during this trial were therefore able to compensate for early season flower loss to a limited degree.

Table. 3.22 The ability of macadamias (cv. Beaumont) to compensate in terms of yield for an estimated 13.3% and 25% flower removal during full bloom (Mean nut in shell mass & number of nuts/tree) at the Burgershall research station.

Estimated flower removal	Mean number of nuts/ tree	Mean mass /tree	Mean mass/ nut (g)
25%	194.4a	1440a	7.41
13.3%	291.2b	2180b	6.15
Control	324.2b	2440b	7.53
F value	8.86	9.69	
P≤	0.05	0.05	
LSD(5%)	73.9	543.6	
CV%	18.8	18.5	

Means per column followed by the same letter do not differ significantly at P<0.05

Mean mass of nuts as well as the mean number of nuts per tree were analysed separately

CV - coefficient of variation

LSD – least significance difference of means

Using the untreated control as a benchmark, an estimated 25% flower removal (Fig. 3.45) from the Beaumont cultivar was able to reduce the yield indicating that trees were not able to compensate for such high levels of flower removal.

Due to the lack of suitable trees as well as the high variability of the data at Nelspruit, a reliable statistical comparison between the treatments could not be done. However, the data from this trial is included (Table 3.23), as it indicates that compensation during the early season occurred. Even at the 30% flower removal estimate crop reduction was negligible when benchmarked against the control. An important difference between the two groups of trees was that the trees at Nelspruit were considerably younger, smaller and therefore more productive.

Table. 3.23 The ability of macadamias (cv. Beaumont) to compensate in terms of yield for an estimated 16% and 30% flower removal during full bloom (Mean nut in shell mass & number of nuts/tree) at the Nelspruit research station.

Estimated flower removal	Mean number of nuts/ tree	Mean mass /tree (g)	Mean mass/ nut (g)
30%	665.7	5078.33	7.62
16%	709.7	5423.67	7.64
Control	705.7	5557.67	7.88
F value	0.07	0.07	
P≤	0.05	0.05	
CV%	23.5	30.5	

Means per column followed by the same letter do not differ significantly at P<0.05
Mean mass of nuts as well as the mean number of nuts per tree were analysed separately
CV - coefficient of variation

Tobin *et al.* (1997) mention that nut growth and abscission are complex and dynamic processes which are influenced by variety, age and condition of the tree. Flowering in older trees are normally less synchronized. Although this asynchrony will allow these plants to mobilise nutrients from damaged nuts to new developing nuts, spontaneous abortion does not readily occur once nuts developed beyond a certain critical point. Asynchronous flowering and a relative small crop in relation to tree size could possibly explain why compensation at Burgershall was less effective on older mature Beaumont trees. This only emphasises the dynamic nature of these processes and that older and therefore less productive trees should be treated differently from younger, more productive trees.

3.6.2.4 Commercial field trials quantifying the effect of withholding early season sprays.

A:Tortricid complex

The effect of tree compensation for early damage was quantified in a small commercial orchard at Burgershall mainly to reduce the current dependency of macadamia growers on chemical insecticides, but also to optimise the effect of beneficial insects due to fewer area wide disruptions with chemical pesticides (Refer to section 2.6.4). According to Annexure 3.7, the tortricid complex damaged only 1.79% of the developing nut crop on representative macadamia farms in the study area during 2002/03 – 2005/06 (n = 17 478). Although a large variation occurred between different farming types in terms of early tortricid damage (range 0.41 – 6.5%), insect induced abortion was always considerably less than the natural abortion rate. This trend of low tortricid infestations is therefore valid for other South Africa production regions as well. Although damage in coastal areas is expected to be slightly higher than this figure due to thinner husks and shells, it still needs to be confirmed scientifically. According to Table 3.24 no statistically significant differences between the three pesticide application regimes in terms of tortricid induced husk and kernel damage was observed despite a slightly higher incidence of tortricid damage at Burgershall during 2003/04.

Fig. 3.45 The magnitude of an estimated 25% flower removal on four year old Nelmak 2 trees at the Nelspruit research station.

Table 3.24 The effect of withholding early season sprays on the mean percentage damage of husk feeding tortricid larvae at Burgershall during the 2003/04 season.

Cultivar	Two applications during premature nut drop period *(Oct, Nov)* followed by the normal spraying regime *(Dec, Feb & March)*		Single application during premature nut drop period (Dec) followed by the normal spraying regime *(Feb & March)*		Control - Standard spraying programme *(Aug, Oct, Nov, Dec, Feb and March)*		P≤	CV	SEM
	Mean % damage ± SD	N	Mean % damage ± SD	N	Mean % damage ± SD	N			
791	1.10 ± 0.16	270	1.01 ± 0.20	280	0.98 ± 0.33	192	0.01	34.5	0.10
695	0.79 ± 0.10	277	0.74 ± 0.02	278	0.86 ± 0.12	138	0.01	33.2	0.07
344	1.57 ± 0.49	269	1.26 ± 0.21	270	1.02 ± 0.19	181	0.01	39.1	0.13
741	2.23 ± 0.66	235	1.85 ± 0.53	283	1.85 ± 1.33	178	0.01	43.1	0.23
Total	3.606 ± 1.22	1051	2.86 ± 1.37	1111	2.68 ± 3.74	689	0.01	42.3	0.34

CV - coefficient of variation

SEM – standard error of the means

Tables 3.24 and 3.25 suggest that the application of early sprays had no effect on the incidence and pest status of tortricids. This was not surprising, as results discussed in section 3.4.2.3 indicated that the correct spraying time for these insects should be approximately nine weeks after anthesis (late November/early December). The application during early December was timed correctly, but because all three treatments were sprayed during this period, no differences between the treatments were evident.

Despite a slightly higher incidence of tortricid larvae in the husks of mature nuts, the same pattern prevailed during the 2004/05 season. According to Table 3.25 the early season sprays again had little effect on the incidence of tortricid damage. Jones and

Tome (1992) confirm this observation and report that tortricid damage to maturing macadamias had little effect on yield, unless more than 25% of the nuts were damaged.

Table 3.25. The effect of withholding early season sprays on the mean percentage damage of husk feeding tortricid larvae at Burgershall during the 2004/05 season.

Cultivar	No sprays during premature nut drop period *(Initial application 2nd November)*) followed by the normal spraying regime *(Jan & Feb)*		Standard spraying programme (*Aug, Oct, Nov, Jan & Feb)*		P≤.	CV%	SEM
	Mean % damage ± variance	N	Mean % damage ± variance	N			
791	1.92 ± 3.17	239	1.42 ± 2.08	223	0.01	31.8	0.13
695	0.33 ± 0.42	241	0.00	240	0.01	27.0	0.06
344	3.25 ± 9.29	198	1.92 ± 8.63	186	0.01	40.7	0.19
741	6.04 ± 19.17	166	6.08 ± 14.27	202	0.01	18.2	0.13
Total	11.58 ± 69.72	844	9.42 ± 36.27	851	0.01	22.3	0.2

Various cultivars were analysed separately
CV - coefficient of variation
SEM – standard error of the means

B: The Heteroptera complex.

According to Annexure 3.8, the Heteroptera complex damaged 14.02% of the developing nut crop in South Africa (n = 17 635*)* from 2002/03 – 2006/07*.* Although a large variation occurred between different farming types in terms of early Heteroptera damage (range 1.78 - 55.6%) insect induced abortion was always less than the natural abortion rate.

From Table 3.26 it is evident that apart from Beaumont (695), fixed interval spraying programmes based on two sprays during the premature nut drop period differed significantly from the control. When fixed interval spraying based only on a single spray during the premature nut drop period was considered, cultivar 344 also didn't differ significantly from the control.

Table 3.26. The effect of withholding early season sprays on the mean percentage occurrence of heteropteran induced kernel lesions at Burgershall during the 2003/04 season.

Cv.	Two applications during premature nut drop period *(Oct, Nov)* followed by the normal spraying regime *(Dec, Feb & March)*		Single application during premature nut drop period (Dec) followed by the normal spraying regime *(Feb & March)*		Control – Standard spraying programme *(Aug, Oct, Nov, Dec, Feb and March)*		P≤	CV%	LSD	SEM
	Mean % damage ± variance	N	Mean % damage ± variance	N	Mean % damage ± variance	N				
791	2.48a ± 0.74	274	2.49a ± 0.61	298	1.29b ± 0.52	298	0.01	30.0	0.59	0.15
695	0.89a ± 0.13	270	1.10a ± 0.24	261	0.77a ± 0.03	261	0.01	38.4		0.09
344	2.32a ± 0.63	273	2.02ab ± 0.39	277	1.41b ± 0.86	277	0.01	34.0	0.61	0.16
741	2.23a ± 0.70	212	2.35a ± 0.58	259	1.04b ± 0.27	259	0.01	32.6	0.57	0.15
Total	3.99a ± 2.09	1029	3.96a ± 1.67	1095	1.91b ± 1.83	1095	0.01	30.8	0.95	0.25

Means per row followed by the same letter do not differ significantly

CV - coefficient of variation

SEM – standard error of the means

LSD – least significant difference

Considering the natural abscission pattern of immature nuts (Fig. 3.40), the single application during December was probably applied much too late. The trees at Burgershall were more than 10 years old and flowering was not synchronised, which compounded the problem, as some nuts were probably in an advanced stage of maturity long before the initial application of pesticides.

The applications during October and November should have been sufficient to control heteropterans and the high incidence of kernel lesions on cultivars 741, 344 and 791 in Table 3.26 was perplexing. To clarify matters, a simplified trial was done during the subsequent season.

During 2004/05 the initial insecticide application was applied during the November 2 which was still well within the nine week period of premature nut drop (Fig. 3.40). According to Table 3.27, no statistically significant differences were evident between the treatment and the control (for all four cultivars except 741) indicating that spraying twice before the end of October 2004, had no discernible effect on heteropteran induced kernel lesions.

Table 3.27 The effect of withholding early season sprays on the mean percentage occurrence of heteropteran induced kernel lesions at Burgershall during the 2004/05 season.

Cultivar	No sprays during premature nut drop period *(Initial application 2nd November))* followed by the normal spraying regime *(Jan & Feb)*		Control - Standard spraying programme (*Aug, Oct, Nov, Jan & Feb)*		P≤	CV%	SEM
	Mean damage ± variance	N	Mean damage ± variance	N			
791	8.42a ± 4.27	231	6.08a ± 6.63	200	0.01	19.6	0.15
695	1.08a ± 2.27	194	0.33a ± 0.42	231	0.01	32.4	0.09
344	3.25a ± 2.02	185	5.42a ± 13.72	175	0.01	24.2	0.15
741	3.92a ± 4.08	156	7.00b ± 10.18	187	0.01	17.0	0.12
Total	16.67a ± 12.06	766	18.83a ± 35.06	793	0.01	5.6	0.07

Means per row followed by the same letter do not differ significantly

CV - coefficient of variation

SEM – standard error of the means

Interestingly, Table 3.26 indicates that Beaumont (695) was one of the cultivars that was not adversely affected by withholding early season sprays during the 2003/04 trials. Damage ratings of this cultivar in Table 3.26 were also significantly lower than any of the other cultivars. According to section 3.1.2.2 Beaumont appeared to be resistant to heteropterans. The reason for this contradiction is probably because Beaumont is also the only cultivar that does not drop mature nuts spontaneously when approaching physiological maturity. During the resistance assessments in section 3.1.2.2, aborted Beaumont nuts were collected underneath the trees to standardise methodology. These nuts probably dropped because they were excessively damaged by heteropterans which in turn may have lead to a significant underestimation of the resistance capacity of this cultivar. In this trial the Beaumont nuts were harvested from the trees and results indicated that Beaumont nuts are resistant against heteropterans. This observation is confirmed by a recent study conducted at Maclands in Levubu (Alberts & Pretorius 2006).

3.6.3 Discussion

Natural abortion of immature nuts occurs up to approximately nine weeks after full bloom. Macadamias generally produce vast numbers of flowers and nuts, but less than 0.5% of the flowers develop into mature nuts. For farmers these findings are important as early insecticide applications could possibly be withheld without any negative effects in terms of yield and quality.

Because flowering in older trees are asynchronous, early November should possibly be the latest date for withholding the first insecticide application. Tortricid moths are generally regarded as pests of mature nuts, therefore withholding early season sprays will have little or no effect on nut damage. These results are also confirmed by Jones and Tome (1992).

When insect damage was simulated by removing racemes, it became evident that macadamias were able to compensate for early damage. This observation is supported by the results from the second commercial trial at Burgershall during 2004/05, where the first early season insecticide application was only applied during November. The initial spray was applied within the nine week period and no statistically significant differences were evident between the treatment and the control indicating that withholding early season sprays had no detrimental effect on the quality of the nuts.

These results are consistent with the research of Tobin *et al.* (1997) who found that removal of 30% of nuts from a macadamia cluster had a marginal effect on yields when damage was inflicted approximately 90 and 120 days post anthesis. Working on pistachio nuts which are affected by a similar guild of phytophagous insects, Daane *et al.* (2005), found that the plants affected by heteropterans can compensate for early season loss by merely shedding fewer nuts later in the season. Beede *et al.* (1996) confirmed this observation and found that pistachios can compensate for up to 40% early damage without significantly affecting yield or quality. However, both Daane *et al.* (2005) and Tobin *et al.* (1997) concur that compensation for mid and late season heteropteran damage does not occur.

However, withholding early season insecticide applications must not be regarded as a general recommendation. Insect monitoring should still be judiciously applied during the early season as economic damage may occur if the heteropteran induced nut abortion rate comes close or exceeds the natural abortion rate. Trueman & Turnbull (1994) found that a 40% reduction in flowers had no effect at all on the final yield. Beede *et al.* (1996), Tobin *et al.* (1997) and Daane *et al.* (2005) worked with early crop removal estimates of 40%, 30% and 40% respectively, which should probably be very close to the upper limit of heteropteran damage that can be tolerated.

Older trees and some varieties such as cultivar 791 have an inherent tendency to flower out of season (even during the winter). If this occurs, significant heteropteran damage may be expected.

At a time when the possibility of insecticide resistance is threat due to the overuse of synthetic pyrethroids, this approach should be of specific interest for crop consultants and farmers.

Annexure 3.1. Relative seasonal abundance of naturally aborted nuts during the 2002/03 and 2003/04 seasons at Burgershall of 15 commercial macadamia cultivars with a medial diameter larger than 10 mm. The yellow shaded area denotes the most susceptible cultivars listed in table 3.2 (863, 800, 294) while the blue shaded area denotes hybrid cultivars (LN1, LN2 and 695).

Cultivar	Number of nuts larger than 10 mm (medial)												
	W32 (%)	W35 (%)	W37 (%)	W38 (%)	W39 (%)	W40 (%)	W41 (%)	W42 (%)	W43 (%)	W45 (%)	W46 (%)	W47 (%)	W48 (%)
863	1(50)		3 (30)		4 (30.77)	16 (30.77)	9 (8.41)	15 (4.37)	208 (11.94)	138 (6.65)	34 (2.52)	3 (0.68)	23 (0.68)
800				3 (37.5)	1 (7.69)	3 (5.77)	2 (1.87)	48 (13.99)	61 (3.5)	50 (2.41)	25 (2.98)	5 (1.13)	11 (2.03)
294		1 (100)			2 (15.38)	6 (11.54)	16 (14.95)	12 (3.5)	26 (1.49)	103 (4.96)	21 (1.15)	5 (1.13)	22 (2.7)
Ln2								1 (0.29)	152 (8.73)	230 (11.08)	69 (4.59)	18 (4.06)	26 (1.35)
Ln1									11 (0.63)	168 (8.09)	126(17.43)	56 (12.64)	62 (21.62)
695								1(0.29)	21 (1.21)	195 (9.39)	155(20.63)	62 (14.0)	20 (8.11)
344			1 (10)			11 (21.15)	25 (23.36)	36 (10.5)	148 (8.5)	38 (1.83)	82 (7.57)	6 (1.35)	14 (3.38)
741	1 (50)			2 (25)	1 (7.69)	5 (9.62)	20 (18.69)	71 (20.71)	110 (6.31)	116 (5.59)	69 (4.59)	19 (4.29)	33 (0.68)
789						9 (17.30)	16 (14.95)	57 (16.62)	259 (14.87)	72 (3.47)	53 (5.96)	13 (2.93)	12 (1.35)
816							3 (2.81)	28 (8.16)	204 (11.71)	100 (4.82)	65 (5.28)	32 (7.22)	29 (4.73)
814					3 (23.08)			8 (2.33)	107 (6.14)	173 (8.33)	49 (7.57)	22 (4.97)	22 (8.11)
791			5 (50)		1 (7.69)		10 (9.35)	48 (13.99)	134 (7.69)	196 (9.44)	79 (4.82)	85 (19.19)	52 (13.51)
660				2 (25)		2 (3.85)		6 (1.75)	175 (10.05)	212 (10.21)	93 (7.34)	35 (7.9)	72 (13.51)
Ne2									9 (0.52)	212 (10.21)	71 (6.19)	79 (17.83)	57 (14.86)
788			1 (10)	1 (12.5)	1(7.69)		6 (5.61)	12 (3.5)	117 (6.71)	73 (3.52)	34 (1.38)	3 (0.68)	12 (3.38)
Total	2	1	10	8	13	52	107	343	1742	2076	1025	443	467
Susceptible Integs*(%)	1 (50)	1 (100)	3 (30)	3 (37.5)	7 (53.85)	25 (96.15)	27 (25.23)	75 (21.87)	295 (16.93)	291 (14.02)	80 (7.8)	13(2.93)	56 (11.99)
Susceptible hybrids (%)	0	0	0	0	0	0	0	2 (0.58)	184 (10.56)	593 (28.56)	350 (34.15)	136 (30.7)	108 (23.13)

*Integs = *Macadamia integrifolia* derived cultivars; W = week

Annexure 3.2 Relative seasonal abundance of tortricid larvae on naturally aborted nuts of 15 macadamia cultivars on the Burgershall research station during the 2002/03 and 2003/04 seasons. The yellow shaded area denotes the most susceptible cultivars listed in table 3.1 (863, 800, 294) while the blue shaded area denotes hybrid cultivars (LN1, LN2 and 695).

Cultivars	Number of infested nuts									
	August		September		October		November		December	
	N	%	N	%	N	%	N	%	N	%
863	2	100	2	50	3	6.98	6	13.04	4	16
800			1	25	3	6.98	4	8.7	2	8
294					4	9.30	5	10.87	1	4
Ln2					2	4.65	2	4.35	0	00
Ln1							2	4.35	2	8
695							2	4.35	0	0
344					6	13.95	6	13.04	1	4
741					3	6.98	3	6.52	1	4
789					8	18.60	6	13.04	2	8
816			1	25	1	2.33	0	0	1	4
814					3	6.98	1	2.17	0	0
791					6	13.95	0	0	5	20
660					2	4.65	6	13.04	5	20
Ne2							1	2.17	1	4
788					2	4.65	2	4.35	0	0
Total	2		4		43		46		25	
Susceptible integs* (%)	2 (100)		3 (75)		10 (23.26)		15 (32.61)		7 (28)	
Susceptible hybrids (%)	0		0		2 (4.65)		6 (13.04)		2 (4)	

N – population size.

*Integs = *Macadamia integrifolia* derived cultivars

Annexure 3.3 Mean kernel distances (husk and shell thickness) for nine cultivars at the Nelspruit experimental farm. The dark shaded areas denote kernel distances higher than the mean while the yellow shaded areas denote relatively small kernel distances

Cultivar	**Husk thickness (mm)**			**Shell thickness (mm)**			**Kernel distance (Husk & shell thickness)**		
	Proximal	**Medial**	**Distal**	**Proximal**	**Medial**	**Distal**	**Proximal**	**Medial**	**Distal**
A16	4.37a	3.75a	4.89a	3.0f	2.4ed	6.05a	7.37	6.15	10.94
A4	3.00cd	2.58d	3.24cd	4.53a	3.24a	6.03a	7.53	5.82	9.27
816	4.04b	3.31b	4.32b	3.84cd	2.37de	4.72cd	7.88	5.68	9.04
741	3.17c	2.89c	4.12bc	3.80cd	2.67bc	5.10bc	6.97	5.56	9.22
Nel2	3.02cd	2.98c	3.37cd	3.87c	2.77b	4.89bcd	6.89	5.75	8.26
788	2.88cde	2.96c	3.84c	3.42e	2.48cde	6.02a	6.30	5.44	9.86
Beaumont	2.70 de	2.54d	2.85f	3.29e	2.25e	4.51d	5.99	4.79	7.36
344	2.72de	2.54d	3.49d	3.57de	2.24e	5.18b	6.29	4.78	8.67
791	2.63e	2.44d	3.13ef	4.2b	2.55bcd	4.85bcd	6.83	4.99	7.98
Average	3.17	2.89	3.69	3.72	2.55	5.26	6.89	5.44	8.95
C.V.	23.11	20.3	19.65	15.69	20.62	16.62			
F value	35.32	26.36	39.48	31.88	17.56	24.13			
LSD	0.33	0.26	0.32	0.28	0.25	0.42			
P	0.05	0.05	0.05	0.05	0.05	0.05			

Columns were calculated separately

Means within collumns followed by the same letter do not differ significantly

Annexure 3.4 Kernel distances (husk and shell thickness) for 15 macadamia cultivars at the Burgershall experimental farm. Gray shading denotes kernel distances significantly higher than the mean while yellow shading denotes cultivars with relative small kernel distances.

Cultivar	Husk thickness (mm)			Shell thickness (mm)			Kernel distance (husk & shell hickness) (mm)		
	Proximal ± SD	Medial ± SD	Distal ± SD	Proximal ± SD	Medial ± SD	Distal ± SD	Proximal	Medial	Distal
863	2.39j ± 0.64	2g ± 0.4	2.62h ± 0.61	3.3cd ± 0.34	1.78de ± 0.33	3.66g ± 0.64	5.69h	3.78h	6.28h
789	2.73hi ± 0.65	2.57f ± 0.5	3.45ef ± 0.67	3.22d ± 0.37	1.91dc ± 0.32	3.81gf ± 0.62	5.95gh	4.48g	7.26fg
816	3.62d ± 0.54	3.15ed ± 0.4	3.85c ± 0.52	3.49bc ± 0.5	1.83dce ± 0.38	3.68g ± 0.58	7.11de	4.98de	7.53fg
294	4.2bc ± .82	3.82ab ± 0.61	4.21b ± 0.72	4.21a ± 0.57	2.17b ± 0.43	4.6c ± 0.55	8.41a	5.99ab	8.81bcd
NE2	3.53d ± 0.96	3.59c ± 0.67	3.64cde ± 0.81	3.27d ± 0.58	2.18b ± 0.31	3.98def ± 0.44	6.8ef	5.77b	7.62f
LN1	3.04fg ± 0.79	3.04e ± 0.64	3.78cd ± 0.98	2.98e ± 0.42	1.78de ± 0.42	4.48c ± 0.8	6.02gh	4.82ef	8.26e
814	3.24ef ± 0.68	2.61f ± 0.56	3.3fg ± 0.72	3.3cd ± 0.41	1.97c ± 0.41	3.89efg ± 0.71	6.54f	4.58fg	7.19g
344	3.17efg ± 0.78	2.7f ± 0.49	3.56def ± 0.5	4.19a ± 0.53	2.42a ± 0.41	4.93ab ± 0.67	7.36cd	5.12d	8.49de
LN2	2.91hg ± 0.58	2.99e ± 0.52	3.77cd ± 0.59	2.98e ± 0.44	1.77de ± 0.27	5.11a ± 0.6	5.89gh	4.76ef	8.88bc
695	3.36ed ± 0.7	3.32d ± 0.65	3.47ef ± 0.62	2.72f ± 0.35	1.91dc ± 0.49	4.13ed ± 0.54	6.08g	5.23cd	7.6f
660	2.76h ± 0.48	2.63f ± 0.39	3.59cde ± 0.61	3.33cd ± 0.51	1.82dce ± 0.3	3.89efg ± 0.46	6.09g	4.45g	7.48fg
791	2.48ij ± 0.53	2.5f ± 0.33	3.14g ± 0.54	4.1a0.58 ±	2.38a ± 0.65	4.21d ± 0.54	6.58f	4.88ef	7.35fg
741	4.01c ± 0.59	3.63bc ± 0.41	4.13b ± 0.66	3.63b ± 0.58	2.36a ± 0.45	4.5c ± 0.57	7.64bc	5.99ab	8.63cde
788	4.5a ± 0.79	3.71bc ± 0.54	5.03a ± 0.81	2.79ef ± 0.44	1.68e ± 0.24	4.87ab ± 0.86	7.29cd	5.39c	9.9a
800	4.36ab ± 0.66	3.9a ± 0.49	4.4b ± 0.73	3.54b ± 0.5	2.3ab ±0.38	4.69bc ± 0.66	7.9b	6.2a	9.09b
Average	3.35	3.08	3.73	3.4	2.02	4.3	6.75	5.1	8.03
LSD	0.27	0.21	0.27	0.19	0.16	0.25	0.36	0.26	0.38
C.V.	20.56	62.79	35.41	14.17	19.62	14.6	13.14	12.85	11.76

F value	48.9	16.82	18.39	45.86	20.01	28.1	42.65	52.3	48.29
P	0.05	0.05	0.05	0.05	0.05	0.05			

Columns were calculated separately

Means within collumns followed by the same letter do not differ significantly

Annexure 3.5 Resistance/tolerance indices (compiled from Tables 3.1, 3.2 and 3.3) of 17 commercial macadamia cultivars towards the African tortricid complex during the 2002/03 and 2003/04 seasons at Burgershall and Nelspruit research stations. Light grey shading denotes significant susceptibility while dark grey shading denotes cultivars with significant resistance/tolerance.

Cultivar	2002/2003 season			2003/2004 season						Total	Number of observations	Index value
	Nst Husk	B/hall husk	Nst kernel	Nst Eggs	B/Hall Eggs	Nst Husk	B/hall Husk	Nst Kernel	B/hall Kernel			
863		1			3		3		4	11	4	2.75
800		4			4		4		4	16	4	4.00
741Nst	1		1	2		1		1		6	5	1.20
741 Bhall		1			3		4		4	12	4	3.0
294		2			2		2		1	7	4	1.75
344	2	1	1	3	2	2	2	1	2	16	9	1.78
789		3			2		3		2	10	4	2.50
816	1	1	1	3	2	3	2	2	1	16	9	1.78
814		3			2		1		2	8	4	2.0
791	2	1	2	2	2	2	2	3	2	19	9	1.78
LN2	3	4	2	2	2	2	1	2	2	20	9	2.22
660		1			3		3		3	10	4	2.50
LN1		4			3		3		4	14	4	3.5
788	2	1	1	2	2	2	2	1	1	14	9	1.56
Beaumont	4	4	4	2	2	3	2	3	3	27	9	3.0
NE2		3			2		2		1	8	4	2.0
A4	3		4	3		3		4		14	4	3.50
A16	2		1	4		4		4		11	4	2.75

Scale

1. -- Bottom 25th percentile
2. – 25 – 50th percentile
3. – 50 – 75th percentile
4. – Top 25th percentile

Legend

Nst - Nelspruit
Bhall - Burgershall

Annexure 3.6 Resistance/tolerance indices (complied from Tables 3.5 & 3.6 as well as Figures 3.5 & 3.6) of 17 commercial cultivars towards the Heteroptera complex during the 2002/03 and 2003/04 seasons at Burgershall and Nelspruit research stations. Light grey shading denotes cultivar damage indices higher than the median while the dark grey shading denotes cultivars with significant resistance/tolerance.

Cultivar	2002/2003 season			2003/2004 season				Total	No. of observations	Index value
	B/hall early damage	B/hall kernel damage	Nst Kernel damage	B/hall early damage	Nst early damage	B/hall kernel damage	Nst Kernel damage			
863	4	3		3		3		13	4	3.25
800	4	3		4		2		13	4	3.25
741 Nst			1		1		1	3	3	1
741 Bhall	2	1		3		1		7	4	1.75
294	3	4		3		4		14	4	3.5
789	3	1		3		1		8	4	2
344	3	3	3	2	2	3	3	19	7	2.71
816	2	3	4	2	2	4	3	20	7	2.86
814	2	3		3		3		11	4	2.75
791	2	1	1	3	2	3	2	14	7	2
LN2	2	1	3	2	3	1	3	15	7	2.14
660	2	1		2		1		6	4	1.5
LN1`	2	1		2		1		6	4	2
788	2	1	3	2	2	3	3	16	7	2.29
Beaumont	2	3	2	2	4	4	3	20	7	2.86
NE2	2	3		2		2		9	4	2.25
A4			3		2		3	8	3	2.67
A16			3		2		3	8	3	2.67

Scale
1. - Bottom 25th percentile
2. – 25 – 50th percentile
3. – 50 – 75th percentile
4. – Top 25th percentile

Legend
Nst - Nelspruit
Bhall - Burgershall

Annexure 3.7 Tortricid damage on eight farms with different spray strategies ranging from unsprayed, organic, fixed interval spraying to IPM compliant farms during 2002/03 – 2005/06.

Locality	Damage to specific phenological stage							
	Premature nut drop (%)		Husk damage (%)		Kernel damage (%)		Total damage (%)	
	Infested nuts	N	Infested nuts	n	Infested nuts	n	Infested nuts	n
Unsprayed orchards								
Nelspruit 2002/2003	*		512 (29.34)	1745	67 (4.64)	1445	579 (18.15)	3190
Nelspruit 2003/2004	10 (0.41)	2442	642 (20.13)	3189	96 (5.23)	1835	748 (10.02)	7466
Nelspruit 2004/05	14 (3.72)	376	108 (31.86)	339	48 (11.82)	406	170 (15.17)	1121
Nelspruit 2005/06	26 (3.95)	659	75 (6.86)	1094	10 (3.5)	286	111 (5.44)	2039
Subtotal	50 (1.44)	3477	1337 (21.0)	6367	221 (5.56)	3972	1608 (11.64)	13816
Organically managed orchards								
Organic (2005/06)	23 (3.83)	600	53 (15.92)	333	15 (5.47)	274	91 (7.54)	1207
Fixed interval spraying (suboptimally managed)								
Hermansburg 2004/05	10 (2.54)	394	3 (0.88)	342	1 (0.57)	175	14 (1.57)	911
Hermansburg 2005/06	14 (2.98)	470	26 (12.09)	215	11 (6.51)	169	51 (5.97)	854
Subtotal	24 (2.93)	819	29 (5.21)	557	12 (3.49)	344	65 (3.68)	1765
Fixed interval spraying (optimally managed)								
Burgershall 2002/2003	81 (1.21)	6672	67 (8.56)	782	2 (0.28)	715	150 (1.84)	8169
Burgershall 2003/2004	62 (2)	3101	579 (30.35)	1908	225 (12.63)	1782	866 (12.75)	6791
Burgershall 2004/2005	16 (4.91)	326	264 (15.3)	1726	15 (1.7)	884	295(10.54)	2936
Burgershall 2005/2006	21 (4.69)	448	140 (22.44)	624	18 (3.44)	580	179 (10.84)	1652

Kaapsehoop 2004/05	8 (2.06)	389	69 (26.34)	262	16 (10.06)	159	93 (11.77)	810
Kaapsehoop 2005/06	5 (1.11)	450	32 (17.39)	184	10 (6.35)	155	47 (5.96)	789
Subtotal	193 (1.7)	11386	1151 (20.98)	5486	286 (6.68)	4275	1630 (7.71)	21147
IPM compliant farms (optimally managed)								
Kiepersol 2004/2005	18 (6.5)	277	4 (1.98)	202	4 (2.84)	141	26 (4.19)	620
Barberton (2005/06)**	1 (0.24)	424	0(0)	193	0 (0)	181	1(0.13%)	798
Karino (2005/06)	4 (0.89)	450	579 (56.10)	1032	21 (5.16)	407	604 (31.97)	1889
Subtotal	23 (2.0)	1151	583 (40.85)	1427	25 (3.43)	729	631 (19.08)	3307
Total	313 (1.79)	17478	3153 (22.25)	14170	559 (6.28)	9594	4025 (9.76)	41242

- *Tortricid damage levels were not assessed.
- ** Tortricid population levels were specifically monitored and spraying occurred at the correct time.

Annexure 3.8 Heteropteran damage on a number of farms with different spray strategies ranging from unsprayed, organic, fixed interval spraying to IPM compliant farms during 2002/03 – 2006/07

Locality	Damage to specific phenological stage					
	Premature nut drop (%)		Kernel damage (%)		Total damage (%)	
	Infested nuts	n	Infested nuts	n	Infested nuts	n
Unsprayed orchards						
Nelspruit 2002/2003	*	*	950 (65.74)	1445	950 (65.74)	1445
Nelspruit 2003/2004	425 (21.61)	1967	1447 (54.73)	2644	1872 40.06)	4611
Nelspruit 2004/05	206 (39.39)	523	281 (55.31)	508	487 (47.24)	1031
Nelspruit 2005/06	229 (34.75)	659	274(70.98)	386	503 (43.29)	1045
Subtotal	860 (27.31)	3149	2952 (59.24)	4983	3812 (47.46)	8032
Organically managed orchards						
Organic farm 2005/06	273 (45.5)	600	408 (48.06)	849	681 (47.0)	1449
Organic farm 2006/07	139 (55.6)	250	43 (34.96)	123	182 (48.79)	373
Subtotal	412 (48.47)	(850)	451 (46.4)	972	863 (47.37)	1822
Fixed interval spraying (suboptimally managed)						
Hermansburg 2004/05	81(23.28)	349	41 (15.89)	258	122 (20.10)	607
Hermansburg 2005/06	94 (20.0)	470	23 (13.61)	169	117 (18.31)	639
Subtotal	175 (21.37)	819	64 (14.99)	427	239 (19.18)	1246
Fixed interval spraying (optimally managed)						
Burgershall 2002/2003	189 (2.83)	6672	2 (0.28)	715	191 (2.62)	7387
Burgershall 2003/2004	242 (7.82)	3094	50 (2.8)	1783	292 (5.99)	4877
Burgershall 2004/2005	156 (47.85)	326	439 (28.16)	1559	595 (31.56)	1885

Burgershall 2005/2006	168 (37.5)	448	183 (31.5)	581	351(34.11)	1029
Kaapsehoop 2004/05	76 (21.78)	349	28 (11.72)	239	104(17.69)	588
Kaapsehoop 2005/06	72 (16.0)	450	31 (22.3)	139	103 (17.49)	589
Barberton 2005/06	73 (17.22)	424	17(8.99)	189	90(14.69)	613
Subtotal	976 (8.30)	11763	750 (14.41)	5205	1726 (10.17)	16968
IPM compliant farms (optimally managed)						
Kiepersol 2004/2005	9 (3.28)	274	5 (2.76)	181	14 (3.08)	455
Karino 2005/06	8 (1.78)	450	2(0.34)	591	10(0.96)	1041
Karino 2006/07	33 (10.0)	330	5 (2.75)	182	38 (7.42)	512
Subtotal	50 (4.74)	1054	12 (1.26)	954	62 (3.09)	2008
Total	2473 (14.02)	17635	4229 (33.72)	12541	6702 (22.21)	30176

* heteropteran damage levels were not assessed

CHAPTER 4

Conclusion

4.1 Introduction

Integrated Pest Management (IPM) is a sustainable approach to manage pests by combining the use of all practical methods of pest control including biological, cultural, physical and chemical methods, in a manner that attains the macadamia grower's goals while minimizing economic, health and environmental risks. Although macadamia is a relative new crop in South Africa producers quickly realised that this crop protection approach is probably not sufficient to address the needs of this fledgling industry. Knight & Gurr (2007) made similar observations for a range of crops affected by *Nezara viridula* and added an extensive list of alternative control procedures that may suppress populations of this destructive insect.

The main aim of this research was to investigate some of these alternatives. Firstly, before significant efforts are spent to promote principles of monitoring for macadamia pest insects and spraying according to threshold levels, it was important to determine if the adoption of these basic principles was economically advantageous for macadamia growers.

Risk and the perception of risk among the growers is another important factor that will determine how various growers will approach the current crop protection dilemma. Furthermore, impact of aspects of the biology of the pests, as well as that of its host plant, possible defence reaction(s) of the host plant, as well as a range of interactions between all these processes will have to be studied to determine if it can be practically used in a commercial insect management program.

It is also important to critically analyse the current research and determine if this effort has significantly contributed to the advancement of IPM. Lastly, an analysis of this nature would not be complete if possible solutions to the *status quo* are not suggested.

4.2 Contribution of project to environmentally friendly insect management of macadamias

The following specific research statements were addressed during this study

a) Are there cultivar differences in terms of integrated pest management?
b) Quantification of damage profiles of the tortricid and Heteroptera pest complexes.
c) Are there advantages of monitoring for macadamia pest insects and subsequent spraying according to threshold levels over fixed interval spraying?
d) Quantification of distribution and dispersal patterns of Heteroptera and tortricid complexes.
e) Quantification of compensation for early season insect damage.

4.2.1 Cultivar resistance of 17 macadamia cultivars to the Heteroptera and tortricid complexes.

Prior to this study no work regarding cultivar differences in terms of insect resistance had been done in South Africa. None of the cultivars were resistant against the Heteroptera complex, with Beaumont (HAES 695) a possible exception. However, in pure stands of Beaumont trees, the nuts are also damaged. Where Beaumont was planted in mixed orchards these nuts were considerably less damaged than any of the other cultivars. The husks of Beaumont nuts contain copious amounts of sticky resin which do not occur in such large quantities in other cultivars. It is therefore possible that this resin could deter heteropterans to some degree. Similarly, the presence of hydrocyanic acid in cultivar 791 could also act as a possible deterrent. While large kernel distances (such as cultivar 788) could cause resistance, clearly other factors must be involved as well which indicates that resistance against heteropterans involve a number of genes.

All hybrid cultivars, except Nelmak 2, appeared to be particularly susceptible to the tortricid complex but the smooth skinned *M. integrofolia* derived cultivars such as cultivars 800 and 344 were particularly damaged, which also supports the multi gene theory for resistance/tolerance.

Macadamia production peaked when this research was initiated during 2003. Prices were approximately 50% higher than in 2008/09 and prospective growers had to wait 24 months and longer for new trees. If these economic conditions persisted nurserymen could possibly have used insect resistance as a marketing tool. At present it is unlikely that any commercial grower would make cultivar changes even in the unlikely event of identifying a resistant cultivar since the economic consequences would simply be too big.

4.2.1.1 Practical implications and suggestions

Macadamia is a long term crop and most of the cultivar choices had been made on the basis of income generation potential. It is not easy to change cultivars once these choices had been made. Fortunately, Beaumont appears to be the cultivar of choice and indications are that it is also the most tolerant cultivar to damage induced by heteropterans. Ideally combinations of susceptible cultivars should be planted in association with Beaumont, but this work will require at least five years before the trees come into bearing and meaningful results will be obtained. It is foreseen that some damage will still occur even with the most optimal cultivar combination(s). A more practical approach would be to plant a leguminous trap crop in close proximity to the macadamias. Not only will it be easier to monitor heteropterans in the trap crop, it could possibly even reduce the infestation of macadamias.

4.2.2 Damage profile and economic importance of the tortricid complex

Damage caused by the tortricid complex was previously only quantified by the annual kernel quality reports issued by the various processors of macadamia nuts. Because these reports indicate that damage is seldom higher than ± 2% of the unsound kernel, many growers were simply not concerned. From Annexure 3.7 it is evident that tortricid infestations on most commercial farms did not differ significantly from the unsprayed farm that was used as a benchmark. The suggestion that tortricid control is very ineffective was expected as the window of opportunity for effective chemical control is very narrow and depends on oviposition peaks of these moths. Because these insects were regarded as of minor importance, little attention was given to this subject by commercial farmers.

Damage surveys indicate that a large proportion of immature nuts (± 11.5% of the unsound kernel) could possibly be linked to tortricid infestation. Most larvae cannot penetrate the hard woody shell after approximately 15 -18 weeks post anthesis and tunnel extensively on the inside of the husk tissue. As the developing nut depends on water and nutrients to complete its development, this type of feeding cannot be sustained and the nuts either abort if the embryo is compromised or simply continue to hang on the tree but never accumulate sufficient oil to mature fully. The percentage of nuts that abort prematurely vary between farms but could be as high as 20%.

If immaturity is linked to premature abortion and kernel damage, tortricids are certainly economically important pests that should be monitored more closely. It has been reported that tortricid moths only oviposit on nuts once they are bigger than 20mm (Ironside 1988, Jones 1994 & Waite *et al.* 1999). After comparing the phenology of macadamias to actual damage in the nuts, it was concluded that this association was probably coincidental and that the nuts only became attractive to gravid female moths after the period of natural drop (November dump) came to an end.

4.2.2.1 Practical implications and suggestions

The ideal time for a foliar applied chemical is ± nine weeks after anthesis, when the nuts attained a medial diameter of ± 20mm. In older orchards flowering tends to be more asynchronous, but a single corrective spray during the last week of November should be sufficient in most instances.

Although the population levels of these moths appear to be relatively low in most cases, population outbreaks may occur if the correct combination of host plants and environmental conditions occur.

4.2.3 Damage profile and economic importance of the Heteroptera complex

Although a significant amount of attention was devoted to the Heteroptera complex in the past, a few new aspects of the biology of this complex was studied which will increase the efficacy of insect pest control.

The principles of insect scouting was not specifically addressed in this study, but the better understanding of especially the two major pest complexes, as well as interactions between these complexes facilitated the development of a scouting strategy for macadamia insects pests. This research culminated in a macadamia insect pest scouting module which in turn will form the basis of an insect management computer programme (see section 4.3).

This scouting programme has already expanded to the avocado industry and it has the potential to be of benefit for other major subtropical crops, such as litchis and mangoes as well.

Many growers were also not able to identify the nymphal stages of economically important heteropterans and scouting was therefore nearly exclusively based on the occurrence of adults. Mouthpart lengths of 4th stage nymphs of *Bathycoelia natalicola* were long enough to penetrate the husks and shells of all commercial macadamia cultivars.

Prior to this study many growers stopped spraying for heteropterans when the first macadamia nuts start maturing (February – March) in order to comply with post harvest application intervals of pesticides dictated by the GLOBALGAP initiative. Heteropterans, but specifically *B. natalicola* are able to damage any nut as long as it remains on the trees (sometimes up to June/July). Macadamias are most vulnerable to heteropteran attack after the end of premature nut drop (end of November) until complete lignification of the shell (middle of January).

4.2.3.1 Practical implications and suggestions

Control should preferably be based on nymphal stages from the 4th stage onwards. This is important as most nuts damaged after December do not fall but continue to hang in the tree up to harvest and essentially this type of damage is therefore regarded as additive.

According to Bruwer (1999) the highest incidence of heteropterans occurs when the nuts begin to mature. It would therefore be logical to harvest these nuts by hand rather than to wait for the nuts to drop naturally, since the risk for damage increases significantly towards the end of the season. This decision will have to be based on economic benefit and the risk of Heteroptera damage must outweigh the added cost of harvesting.

4.2.4 The advantages of monitoring for macadamia pest insects and subsequent spraying according to threshold levels over fixed interval spraying.

Many growers regard insect monitoring as an unnecessary complication and some growers have monitored according to recommendations, but unreliability of current monitoring techniques linked with insufficient sample size have led to economic damage. In most of these cases the growers concerned have adopted a 4 - 6 weekly fixed interval spraying programme with mixed results. The reasons for the mediocre results are two-fold:

a) Growers do not spray according to threshold values.
b) Because all damage after December is essentially additive, damage can quickly escalate if pest incursions occurred unnoticed.

The advantages of a pest monitoring program over a fixed interval programme were demonstrated but current monitoring methods are still far from the ideal.

4.2.4.1 Practical implications and suggestions

If nuts of a high quality will determine compensation, growers probably do not have an option but to adopt a pest insect monitoring programme. The current programme still has many shortcomings, but the net result of a fixed interval programme is mediocre quality nuts and consequently mediocre compensation. In a lacklustre global economic environment this is a strategy South African farmers can probably ill afford.

4.2.5 The effect of planting density on pest insect populations

Initial recommendations indicated that macadamias should be planted at a high density (4m x 6m; 417 trees/ha) or even closer (2m x 4.5m; 1111 trees/ha) (Snijder 2003). Since 2003 experience has indicated that if not properly pruned these trees quickly become unmanageable and unproductive within a very short time span. Limited space forced these trees to grow upright and trees in the region of eight – 11m tall are not uncommon. Most sprayer rigs have a vertical operational limit of ± six m (Drew 2003). Additionally dense macadamia trees tend to flower only in the upper reaches of the trees and since these areas cannot be properly protected, heteropteran and tortricid damage gradually increases as the size of the crop dwindles. The relationship between increasing tree density and increasing insect damage was quantified during this study.

Heteropterans and tortricids are heterogeneously distributed which could compromise insecticide application decisions, because the estimated experimental error made during insect scouting is high. Interestingly, areas of increased Heteroptera activity (hot spots) appear to remain stable, which could indicate the probable involvement of so called phytodistress chemicals.

4.2.5.1 Practical implications and suggestions

Pruning should be an important practice in all high density orchards. Not only will proper pruning increase the size of the crop, due to better sunlight penetration and the concomitant improvement in flowering, it should also increase the quality of the crop by decreasing insect damage.

Growers must take cognisance that the experimental error made during population sampling could probably be high due to the occurrence of hot spots. Ironside (1988) and Man (1984) mention that approximately 1 – 1.5% of the trees in a management block of 5 ha or less should be scouted. At a planting density of 420 trees/ha it would mean that approximately 21 – 32 trees will have to be sampled in a 5 ha management block. In reality growers rarely sample more than 10 trees per management block.

4.2.6 Compensatory ability of macadamias towards pest insects

Prior to this study, the standard spraying regime was to apply a synthetic pyrethroid prior to flowering to clean up the orchard, wait for flowering to more or less finish and then continue with 4 - 6 weekly insecticide applications, until the crop is harvested in May/June during the subsequent year. During a standard year a minimum of six foliar sprays are normally applied, but some farmers have applied as many as 12 sprays. The presence of secondary pests and concomitant increases in kernel damage indicated that the situation was out of control.

The way forward was not to increase the sprays as that would have worsened the situation. The frequency of foliar sprays had to be reduced without affecting kernel quality. Determining the ability of a macadamia tree to compensate for early damage was a logical first step that had to be taken. Research proved that withholding early season sprays had no effect on kernel quality and probably led to a reduction of at least 2 pyrethroid sprays.

4.2.6.1 Practical implications and suggestions

Spraying before flowering and immediately afterwards is not necessary unless flowering is suboptimal and Heteroptera numbers are sufficiently high to damage more nuts than would have dropped naturally during the November dump period. Fortunately this happens very rarely. Bruwer (1999) mentions that four distinct population peaks of *B. natalicola* occur per annum. The first of these occurs during August and present research indicated that it is not necessary to spray for heteropterans during this period, but it would very likely be necessary to spray the remaining three peaks. Three sprays will not be too disruptive to the general orchard ecology and should also indicate the maximum number of foliar sprays that should be allowed if integrated pest management is to function optimally.

4.3 Suggested topics for future research

1) The species complex of tortricid moths needs significant clarification. Control and monitoring are currently based on species specific sex pheromones and constitutes a significant portion of the annual pesticide expenditure.

2) Accurate monitoring and decision support for managing the Heteroptera complex
    a) Trap crops for the monitoring of heteropterans.
    b) Degree-day models to determine optimal times for spray application.
    c) Expand the current monitoring computer program to include degree days, as well as related meteorological information.

3) Because the tortricid and Heteroptera complexes affect other subtropical crops, such as avocados, litchis, mangoes, granadillas and guavas, attention to area-wide insect management should be considered.

4) The effect of thrips on crop quality and quantity should be determined.

5) The effects, as well as the species composition and relative seasonal abundance of the indigenous natural enemy complex, were not specifically addressed during this study. These topics received attention from Bruwer (1992) and Schoeman *et al.* (2002), but a significant amount of time passed and it is probably important to once again reassess the contribution of these important insects in an IPM program.

4.4 Final remarks

The basis for any sound insect management program is to monitor pest populations and to use insecticides strategically when threshold levels have been reached. During the past five years the macadamia industry moved closer to this ideal, but there is still a long road ahead. The current programme is clearly beneficial to the growers, because other subtropical fruit industries are also expressing interest to adopt these principles.

Most growers have moved away from a fixed interval spraying programme. This study, and the concomitant publicity associated with it, could have contributed towards this mind shift. However, the insistence that growers have to adhere to GLOBALGAP principles by some of the processors was probably instrumental in speeding up the process.

In some cases the spray frequency of foliar applied insecticides decreased from ± six to ± four/crop cycle and fortunately processor reports do not indicate significant increases in heteropteran induced kernel damage.

If the scouting programme functions ideally, no more than three sprays should probably be required per season. This will only be achieved if the accuracy of population monitoring is significantly improved, which should form a major part of future research regarding the integrated management of macadamia pests.

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