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Review

Stink bug IPM on macadamias in South Africa: Current status and the road ahead

P. S. Schoeman*

Agricultural Research Council-Institute for Tropical and Subtropical Crops, Private Bag X 11208, Nelspruit 1200, South Africa.

ABSTRACT

This article is a summary of past accomplishments by a number of entomologists working in the South African macadamia nut industry, on the Heteroptera complex. A range of aspects regarding the biology and subsequent control of these intractable pests are discussed. A short overview of chemical control strategies as well as the current status regarding biological control is provided. An exciting addition to conventional biological control is the usage of bats as predators. Provisional results indicate that this option may be considerably more practical than previously anticipated as some bat species routinely prey on various heteropterans. An overview regarding the species complex affecting macadamia as well as the relative seasonal abundance of most important phytophagous heteropteran species are discussed. This work also relates to monitoring and subsequent spray decision support. Although various trap crops were investigated in the past by a range of researchers, none of these plants did lure any of the most economically important stink bugs in appreciable numbers. The effects of tree density as well as tree height on stink bug populations were investigated and recommendations are given regarding the manipulation of these parameters to the detriment of stink bugs. Strong edge effects were observed, early in the production season when stink bugs initially migrate into macadamia orchards. Early treatment of orchard perimeters is suggested as a possible environmentally friendly alternative method to full blanket sprays currently in use. The recent quantification of a shift in sensitivity towards synthetic pyrethroids indicates that alternative, more environmentally-benign control techniques should be investigated. A brief guideline for some of these ideas as well as a critical evaluation of the current status of IPM in the South African macadamia industry is provided.

KEYWORDS: macadamia, integrated pest management, heteroptera, pesticide resistance

INTRODUCTION

Initial research on integrated pest management in macadamias dates back to the late 1970's [1]. Macadamia was a fledgling industry during this time and according to [2] approximately 5000 ha was planted with the crop by 1993. Initial research implicated *Nezara viridula* as the main pest [1] but it wasn't until 1992 that the current dominant stink bug (*Bathycoelia distincta*) was associated with kernel damage [3].

The foundation upon which most of the subsequent research was based was laid by [3]. Initial research focussed on correct identification of the species complex as well as a comprehensive study regarding the relative seasonal abundances of three of the economically most important stink bug species. Research was also done regarding usage of systemic insecticides for the control of these insects as well as an all-inclusive study on the damage phenology.

*Schalk@arc.agric.za

The following synopsis must therefore be regarded as a brief summary of some of the work that was done by a number of researchers after this period (1999-2014).

Critical evaluation of current status of IPM

Integrated Pest Management (IPM) can be defined as follow: IPM is an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. This information, in combination with available pest control methods, is used to manage pest damage by the most economical means, and with the least possible hazard to people, property, and the environment [4].

Despite groundbreaking work by previous researchers on biological control of citrus pests in the Lowveld region, true IPM has thus far not been achieved in the South African macadamia industry yet. The term IPM should rather refer in this context to Integrated Pesticide Management as very few other components of insect management currently form part of the toolkit employed by growers to manage these intractable pests.

With the past successes of the citrus industry in mind, it is clear that sufficient expertise currently exists in the country to make IPM a practical reality. Why are most growers currently spraying on a prophylactic basis? And why is nearly the entire control programme of stink bugs in macadamia based on the application of the same group of chemicals? It is important to take a moment and consider the various factors affecting crop protection in the macadamia industry, because only when these problems are well defined can proper solutions be sought.

The Southern African Macadamia Association (SAMAC) realise that IPM is one of the key factors ensuring the sustainable production of high quality nuts to the discerning export market. In this regard, a number of projects focussing on sustainable macadamia production have been supported in the past. A stink bug working group consisting of various experts in the subtropical and agrochemical industries was formed a few years ago with the main aim of tackling this problem on a holistic front. Recently the ranks of the working group were strengthened by the addition of the pecan industry which is currently facing similar problems. The following sections will give a brief overview of some of the more important research findings as well as actions currently taking place.

Economic implications

Although heteropterans generally occur in relatively low numbers, they are able to inflict remarkably serious damage. A contributing factor to the economic importance of this group of insects is the inherent inability of the trees to shed slightly damaged nuts. Unprocessed nuts (de-husked but unshelled) damaged by heteropterans are also indistinguishable from undamaged nuts and undergo the entire processing route with obvious concomitant cost implications. Damage percentages vary according to the location of each orchard and with varying levels of management but in cases where orchards were left unsprayed for a few seasons, figures of as high as 80% were not uncommon [5].

Biological control

All the major stink bug pests except *Nezara viridula* are indigenous to Southern Africa and consequently most major natural enemies are also indigenous. Despite this, the tachinids: *Trichopoda giacomellii* and *Trichopoda pennipes* were imported and released by [6, 7]. Although both species established successfully, levels of biological control did not increase significantly.

In contrast to macadamias most of the citrus pests were exotic and spectacular successes were achieved with classical biological control. Because this option is not open for South African macadamia farmers, the only other viable option is to conserve natural enemies as much as possible by applying softer insecticides during January/February (when natural enemies are most abundant) [8]. Most farmers adopted this practice but due to the lack of suitable registered pesticides to choose from, disruptive sprays are sometimes applied during critical periods out of necessity.

Biological control by vertebrates is often overlooked in many cases. Bats are well known predators of a wide range of insects. SAMAC is also partially funding research investigating the efficacy of bats in macadamia orchards in the northernmost macadamia production region of South Africa. Results are promising as heteropterans constitute a significant proportion of the diet of a number of bat species [9].

Although heteropterans are generally arboreal, individuals with fungal mycosis are however, often recovered from the orchards, especially during the late season. The most common pathogen was identified as *Beauveria bassiana*. Laboratory trials with one of the isolates indicated considerable pathogenicity but subsequent field trials were disappointing. Follow up work with a combination of *Beauveria bassiana* and low rates of Beta cyfluthrin 125 g/L SC @ (1 ml/100 L) provided excellent control. A synergistic effect is suspected as similar observations were made in the literature regarding various pathogen/pesticide combinations [10].

Chemical control

The first registration work with Cypermethrin 200 g/L EC and Deltamethrin 250 g/L EC was done by [1] during 1984. 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*. According to [11], 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 [12] 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 [12] and both were found to be effective against heteropterans although they had significantly shorter residual periods compared to synthetic pyrethroids.

Various systemic insecticides (Aldicarb GR 150 g/kg, Monocrotophos SL 400 g/L, Imidacloprid SC 350 g/L and Methamidophos AL 500 g/L) were evaluated by [13, 14, 15] against the heteropteran complex. Although some of these chemicals did limit insect damage, registration was never attempted. Additionally the undiluted chemical had to be handled in some cases and this posed an unacceptable health risk [16].

Currently there are 32 registered products and 11 active ingredients registered for stink bug control in macadamias. Most of the products unfortunately consist of synthetic pyrethroids (IRAC group 2A) (Table 1) which offers growers very little variety to choose from.

Pest complex and important aspects of the biology

Approximately 40 heteropterans were recovered from macadamias thus far [3] but *B.distincta* is the most dominant stink bug on macadamias in South Africa and represents more than 90% of heteropterans recovered when immature nuts are present on the trees [17]. After the nuts reached maturity during March/April, stink bugs with shorter mouthparts (winter complex) became more dominant. Apart from *B. distincta*, *A. raptoria* and *P. wayi*, only mature insects were recovered which seems to indicate that macadamia is not a preferred host plant for the winter complex but may act as a temporary overwintering refuge.

Table 1. IRAC classification of the various products registered for control of stink bugs in macadamias.

Group	Subgroup	Chemical subgroup or exemplifying active ingredient	Active ingredient
1	1B	Organophosphates	Acephate (not registered yet but registration is pending)
3	2A	Pyrethroids	Various (8 active ingredients & 28 registered products)
4	4A	Neonicotinoids	Thiamethoxam & Imidachloprid
9	9B	Pymetrozine	Pymetrozine
11		Entomopathogens	Broadband

P. wayi is possibly the second most damaging bug in macadamia but is under represented in Table 2 because it was difficult to locate this unobtrusive insect in dark macadamia orchards with the branch tapping method.

Spray decision support, monitoring and scouting

Due to low population numbers, the elusive nature of *B. distincta* and *P. wayi* and because no pheromone has yet been discovered, very few farmers are currently monitoring for these pests. Because of the low pest numbers and inaccurate monitoring methods, it is very easy to either over- or under-estimate the population density in an orchard. In the past this combination of factors has led to economic damage with a result that even more farmers adopted a prophylactic spraying regime.

It is also important to note that after the end of November (end of premature nut drop) any damage in the orchards is essentially additive which further lowers the tolerance for damage (see section on economic implications).

To address this problem but also to possibly predict stink bug population trends, a monitoring programme was initiated during 2010 [18]. Initial results indicate that three nymphal peaks can accurately be predicted with degree days. Results of this monitoring program are currently communicated to farmers with a website that is updated on a weekly basis (http://subtropgoggas.co.za).

For the last 5-6 years SAMAC has also embarked on a training programme for insect scouts in all production regions. A training module was also published during 2013 as a step-by-step manual highlighting all aspects of insect scouting [19]. During 2014 a series of short training DVDs were also released by SAMAC highlighting various aspects of macadamia cultivation including crop protection.

A research project focussing on chemical communication of *B. distincta* and *P. wayi* was initiated about 5 years ago. Despite a considerable amount of effort and international collaboration, no promising chemicals have thus far been identified (B. Botha personal communication). A project was also recently (May 2014) approved to investigate the effect of various host plant volatiles on economically important indigenous stink bugs.

Observations regarding substrate-borne vibrational signals emitted by *B. distincta* appear to be very promising as insects were lured over relatively large distances to the source of the vibration (loudspeaker) (B. Botha personal communication).

Trap crops

During an extensive search a few natural host plants were located for *P. wayi* and *B. distincta*. *B. distincta* was recovered from the indigenous Kei apple *Dovyalis caffra* as well as from mango, litchi and avocado [20]. This insect was located in low numbers on these plants during the autumn/ winter. On avocado, deep lesions corresponding to mouth-part lengths of *B. distincta* were observed in approximately 5% of damaged fruits which indicates that this crop might be a better host for *B. distincta* than previously anticipated [21]. Provisional results from an ongoing M. Sc study indicate that *Crotalaria juncea* is also an occasional host for *P. wayi* [22]. None of the host plants located thus far lure these two pests in appreciable numbers and would therefore unfortunately not be commercially suitable for use as trap crops. A project is also underway to quantify the effect of cultivating various pod bearing crops in the working rows on soil health as well as arthropod communities in the orchards (K. Steyn personal communication).

Tree density and height

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 (10-15 m tall) and without proper pruning, medium-to-high density orchards quickly become unproductive and have increasingly severe insect-induced nut quality problems. When heteropteran damage was evaluated on mature trees grown at various densities, a clear positive relationship between heteropteran-induced kernel damage and tree density ($r^2 = 0.922$) was demonstrated. The presence of egg packets of *B. distincta* was also positively related to higher tree densities ($r^2 = 0.864$). At the end of the season when nut quality is normally determined,

Table 2. Numbers and seasonal occurrence of dominant stink bugs recovered from a mature mixed cultivar macadamia orchard at Nelspruit with the branch tapping method from November 2010-March 2015 [17].

Season		Dominant Heteroptera species collected					N
		Pseudotheraptus wayi Brown	*Pseudatelus raptoria* Germar	*Bathycoelia distincta* Distant	*Chinavia pallidoconspersa* Stal	*Nezara prunasis* Dallas	
Summer 2010/11	n	1	1	224	9	1	237
	%	0.42	0.42	94.51	3.8	0.42	
	AR	3	3	1	2	3	
	SO	Feb	Mar	Nov-Mar	Nov-Mar	Mar	
Winter 2011	N	2	3	179	48	48	288
	%	0.69	1.04	62.15	16.67	16.67	
	AR	4	3	1	2	2	
	SO	May, Jun	Jun, Aug	Apr-Sept	Apr-Sept	Apr-Sept	
Summer 2011/12	N	6	1	218	10	2	243
	%	2.47	0.41	89.71	4.12	0.82	
	AR	3	5	1	2	4	
	SO	Oct, Nov, Feb, Mar	Nov	Oct-Mar	Oct-Mar	Oct	
Winter 2012	N	3	5	321	68	37	446
	%	0.67	1.12	71.97	15.25	8.30	
	AR	5	4	1	2	3	
	SO	Apr, May, Jun	May, Jun, Jul	Apr-Sept	Apr-Sept	Apr-Sept	
Summer 2012/13	N	8	11	466	4	4	502
	%	1.59	2.19	92.83	0.8	0.8	
	AR	3	2	1	4	4	
	SO	Oct, Nov, Jan, Feb, Mar	Oct-Mar	Oct-Mar	Dec, Jan, Mar	Oct, Jan, Mar	
Winter 2013	N	11	9	252	112	26	410
	%	2.68	2.2	61.46	27.32	6.34	
	AR	4	5	1	2	3	
	SO	Apr-Jul	Apr, May, Jul, Sept	Apr-Sept	Apr-Sept	Apr-Sept	
Summer 2013/14	N	19	15	360	32	4	430
	%	4.42	3.49	83.72	7.44	0.93	
	AR	3	4	1	2	5	
	SO	Oct-Mar	Oct-Mar	Oct-Mar	Oct-Jan, Mar	Oct, Nov, Feb	
Winter 2014	N	9	13	460	96	13	591
	%	1.53	2.2	77.83	16.24	2.2	
	AR	4	3	1	2	3	
	SO	Apr-Jun, Aug, Sept	Apr-Aug	Apr-Sept	Apr-Sept	May-Aug	
Summer 2014/15	N	10	15	281	14	1	321
	%	3.12	4.67	87.54	4.36	0.31	
	AR	4	2	1	3	5	
	SO	Oct, Dec-Feb	No-Jan, Mar	Oct-Mar	Oct-Dec, Jan, Mar	Oct	

Table 2 continued..

Winter (Total)	N	25	30	1212	324	124	1715
	%	1.46	1.75	70.67	18.89	7.23	
	AR	5	4	1	2	3	
	SO	Apr-Sept	Apr-Sept	Apr-Sept	Apr-Sept	Apr-Sept	
Summer (Total)	N	44	43	1549	69	12	1717
	%	2.56	2.5	90.22	4.02	0.7	
	AR	3	4	1	2	5	
	SO	Oct-Mar	Oct-Mar	Oct-Mar	Oct-Mar	Oct, Nov, Jan, Feb, Mar	

n = Total number of individuals, % = Percentage of grand total of individuals caught, AR = Abundance ranking, SO = Seasonal occurrence.
N = Total number of insects collected.

nuts occurring in the higher tree portions were significantly more damaged by *B. distincta* and *P. wayi* than nuts which occurred closer to ground level [23].

Immigration patterns

An important research question currently being addressed is to determine if migration of *B. distincta* is a single event during the early season or if there is continuous migration of insects in and out of the orchards throughout the season. Currently all evidence points toward the former and if this can be proven, it will have a considerable beneficial impact on crop protection.

Clear edge effects were observed early in the season when *B. distincta* moved into macadamia orchards. This observation will have to be tested again during the current season but the effect of varying neighbouring plant communities will also have to be factored in to gain better understanding of the process. Considerable savings regarding pesticide applications could be made by early season perimeter spraying if edge effects are consistently present in all orchards.

Because of the difficulties in quantifying movements in and out of orchards, the microelectronics division of the University of Johannesburg was contacted. The aim of this collaborative effort is to tag insects with an electronic device and then plot its movement over time. This will provide valuable information regarding the insect's diurnal activity patterns as well migratory behaviour. The project is currently in the concept phase and no results are available yet.

Stink bugs are generally polyphagous, have keen eyesight and are able to fly well. These factors ensure that they can move between crops with ease if conditions become unfavourable on a specific crop. Little information regarding the relative seasonal abundance of stink bugs is currently available for other subtropical crops. Initial attempts in quantifying these migratory patterns relied on damage symptoms but little detailed information was gained with this study. Since February 2013, mango, litchi, avocado and macadamia orchards were surveyed on a fortnightly basis with a thermal fogging machine. Results from this study indicate that *P. wayi* may utilize litchis as a temporary winter refuge because relatively large numbers of adults were recovered from this crop during June/July. A discrete spray consisting of an environmentally friendly product during this time might break this seemingly continuous cycle in subtropical crops and could possibly help to reduce overall spray applications in the subtropical fruit industry in general. Complete results of this study will be published during the spring/summer of 2016.

Host plant resistance

No cultivar that was tested offered significant resistance but when Beaumont (HAES 695) was grown in combination with other cultivars, damage was considerably reduced in Beaumont [5]. The resistance mechanism is currently unknown but this observation opens up the possibility of using sacrificial plants.

Mechanical aspects of spraying

Macadamias are lush, large and very dense trees. Because the industry expanded nearly exponentially during the previous decade a considerable amount of trees were initially still relatively small and manageable. Since then an appreciable number of trees have reached maturity and from Fig. 1 the crop protection problem currently experienced by the industry is self-explanatory. This problem is considerably exacerbated by the tendency of insects to occur mainly in the apical tree portions. Inadequate spraying, dense trees and the overuse of synthetic pyrethroids probably are main causal factors for a shift in sensitivity to synthetic

Fig. 1. Example of commercial orchard sprayers not able to reach the preferred habitat of phytophagous stink bugs in the tops of mature macadamia trees.

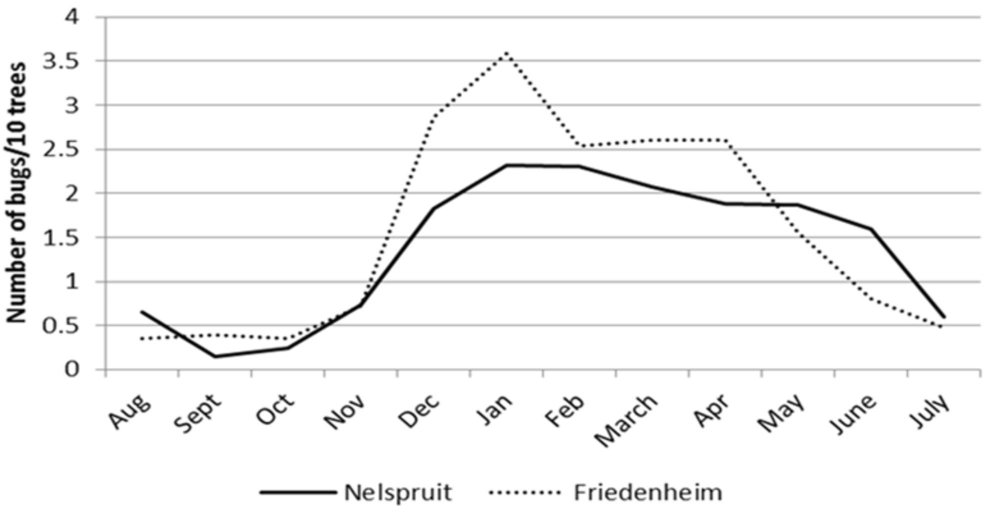

Fig. 2. Average relative seasonal distribution of 3025 two spotted bugs (*Bathycoelia distincta*) (1801 Nelspruit and 1224 Friedenheim) from November 2010-January 2014 in relation to basic phenological milestones of macadamia under South African conditions.

pyrethroids which is currently experienced. The magnitude of the apparent resistance problem throughout all production regions has not been quantified yet but the occurrence of this phenomenon, albeit in isolated pockets should send clear warning signals to producers that current insect control practices are not sustainable and should change.

Spring clean-up sprays

A common practice employed by some growers is to apply a general clean-up spray during spring. However a summary of monitoring data for the last four years clearly indicate that very little *B. distincta* activity was present in trial orchards (Fig. 2) during this time (August/September).

Because macadamia trees set much more nuts than they can ever mature, previous research also indicated that a degree of tolerance for damage exists immediately after flowering.

SUMMARY

South African farmers are normally quick to adopt new technology if proven to be effective. More sensitive spraying during peak abundance of parasitoids as well as the cessation of so-called pre-blossom clean up sprays are a case in point. However, the industry still is a long way from attaining the ideal of integrated pest management. Main problems at the moment are:

1) Lack of accurate monitoring methods.
2) Macadamias are very big, dense trees which make the physical act of spraying very difficult and probably hastened the development of resistance.
3) The polyphagous nature of the bugs as well as their high mobility, low population density and low tolerance for damage by the processors makes accurate threshold-based insect control very difficult.
4) Lack of diversity in the pesticide toolkit.

All these practices are currently receiving attention and the development of a shift in sensitivity towards synthetic pyrethroids provided various role players in the crop protection industry with the impetus to change current management practices. Aspects that will receive specific attention during the next decade include:

1) Biological control (bats, arthropods and conservation agriculture).
2) Monitoring (electronic tracking, pheromones, internet based degree day model and trap crops).
3) Cultural methods (pruning, insect immigration studies and orchard canopy management).
4) Chemical methods (area wide control during early season, management in overwintering hosts and early season perimeter treatments).

Macadamias in South Africa is a young and dynamic industry that requires equally dynamic solutions to problems that are unique to the South African sub-continent. It is believed that the current research questions that are being addressed will continue to keep this industry competitive globally.

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