The successes of stink bug research and the Stink Bug Working Group in the Southern African avocado and macadamia industries

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ABSTRACT
At the beginning of 2009, a combined initiative from the Avocado (SAAGA) and Macadamia (SAMAC) Growers' Associations resulted in the formation of the Stink Bug Working Group (SBWG). The main reason for this working group was to focus specifically on addressing stink bug damage in the avocado and macadamia industries, but not limited thereto. The mandate of the working group was to investigate short-, medium- and long term solutions to these problems, which at that stage, collectively cost the avocado and macadamia industries an estimated R45 million in damage annually (Winter, 2016a, b). This damage has increased to R6.3 million and R398 million annually by 2016 for avocado and macadamia respectively (Winter, 2016a, b). Short-, medium- and long term goals included: new and alternative chemical control products, pheromone development, trap cropping, degree-day modelling, scouting, GIS monitoring and prediction modelling, and satellite tracking.

The long-term, overall goal of the Stink Bug Working Group is to develop a complete Integrated Pest Management (IPM) model to control stink bugs (but also thrips), to initiate relevant research projects, develop new environmental friendly methods of control and to incorporate the use of "softer" chemicals, when necessary. Successes with all of the above-mentioned goals have been achieved in collaboration with experts from the USA, Australia and The Netherlands. Eight kairomones (plant volatiles) have been identified and six are currently being trialled in the field on two-spotted stink bug. The other two kairomones have been identified for field trials on coconut stink bugs in 2017.

Keywords
Avocado, macadamia, stink bug, research, Stink Bug Working Group (SBWG), Subtrop

OBJECTIVES
The objectives of this paper are threefold namely, 1) to summarise the successes with regards to research, chemical registrations and research outputs of the SBWG from 2009-2016, 2) to inform the avocado and macadamia growers of the successes achieved of the SBWG and 3) to assist in identifying gaps in the research and chemistry and make recommendations for future work.

INTRODUCTION
Before 2009, almost no stink bug research was done in the South African avocado and macadamia industries. The stink bug pest problem already started to increase by that time with an estimated collective annual damage for SAAGA and SAMAC to the value of R45 million in 2009. At the initiative of Piet Muller, an avocado and macadamia grower from Levubu in the Limpopo Province, a Stink Bug Working Group (SBWG) was established in 2009, with Gerhard Nortjé, technical manager of Subtrop, as the chairman.

The mandate of the SBWG was to investigate short-, medium- and long term solutions to these problems, which at that stage included stink bugs and thrips. The first working group meeting was held and the following short-, medium- and long term goals were formulated: area-wide monitoring, GIS prediction and modelling, trap cropping, new and

environmental friendly chemistry and pheromone development. The long term sustainable goals of the SBWG were and still are to develop a complete IPM model, initiate relevant research, develop environmental-friendly control methods, and incorporate "softer" chemicals, when needed.

The SBWG consists of a very dynamic team of professionals, amongst them entomologists, chemists, horticulturists and, even a soil scientist (Dr Gerhard Nortjé). The SBWG collaborates with the Brown Marmorated Stinkbug Working Group (BMSBWG) in the USA, as well as specialists in Australia and The Netherlands. Experts, which were invited to South Africa, include from the USA, Prof Russel Mizell (University of Florida), Dr Tracey Leskey (Chairman of the BMSBWG from the USDA), Dr Rob Morrison (pheromone expert from the USDA) and Dr Frans Griepink from the Netherlands (Director of Pherobank). Collaboration also exists with Dr Mark Wright (University of Hawaii in Manoa) and Dr Ruth Huwer (NSW Department of Primary Industries, Australia).

Local experts, with which the SBWG collaborates, include the likes of Prof Erik Holm and a large percentage of the total number of South African entomologists. Local collaboration with the Universities of the Free State (Prof Schalk Louw and De Villiers Fourie) and North-West (Profs Johnnie van den Berg and Hannalene du Plessis) have also been established.

It was noticed, from the beginning, that the large chemical companies were not interested in developing new chemistry for the relatively small macadamia and avocado industries. In 2009 the total areas in hectares planted to avocado and macadamia, respectively, were 12 900 ha and 17 100 ha. By 2016 these areas have increased to 16 000 ha and 21 500 ha, respectively, which represents a 24% growth in avocado planted and 26% growth in macadamia planted. During 2013, the Subtrop research coordinator initiated a chemical forum with all relevant chemical companies and the Registrar in order to communicate the problem and discuss possible solutions. This chemical forum is currently in its fifth year. This forum was highly successful with individual chemical companies approaching SAAGA and SAMAC with possible chemical solutions. The situation with the chemical industry has thus changed drastically. Chemical trials were initiated and four chemicals/mixtures for stink bug control are currently being trialled.

RESULTS AND DISCUSSION

Previous and current research projects

During the beginning of the SBWG's existence (2009-on going), basic and intensive research focussing on the biology, behaviour, characteristics and control of stink bugs (two-spotted, yellow-edged and coconut stink bug) were done. Table 1 shows a summary of all stink bug-related research done, in progress, and completed during the period 2009-2017.

Table 1. Previous, completed and current research projects and reports during the period 2009-2017.

Year	Project	Researcher
2009-2011	Cryptogran for nutborer control in macadamia	Colleen Hepburn
2009-2011	Determination of important action levels and a prediction model for fruit sucking	Dries Alberts
2009-2011	Integrated management of stinkbug on macadamia	Schalk Schoeman
2009-2013	Monitoring and damage survey of stinkbugs on avocado	Schalk Schoeman
2009-2015	Integrated management of macadamia pests: Field validation of degree day model, promoting of biological control alternatives and integration of control programs into a practical farmer friendly pest management system	Schalk Schoeman
2010-2013	Bats as potential bio-control agents in macadamia orchards	Peter Taylor
2010-2017	Determination of semio-chemicals in avocado and macadamia	Ben Botha
2011-2012	Monitoring of the coconut stinkbug with trap crops	Tshifhiwa Radzilani
2011-2014	Assessment of the thrips species complex and economic loss in macadamia	Colleen Hepburn
2013-2016	Indigenous heteropterans and related volatile secondary metabolic compounds occurring on a range of indigenous trees in South Africa	André Botha
2013-2017	Rearing of stinkbugs (Two-spotted and coconut stinkbug)	Lindi Botha
2015-2016	Environmentally friendly stinkbug control: Practical application of degree days as well as factors that will decrease insecticide decency whilst maintaining efficiency,	Schalk Schoeman
2015-2017	Field and laboratory testing of known volatiles on hemipterans and potential trap design	André Botha
2015-2017	Investigations into the use of Entomopathogenic nematodes (EPNs) for the possible control of the nutborer complex and the impact of these nematodes on the thrips complex occurring on macadamia in South Africa	Willem Steyn
2015-2017	Investigation of possible pyrethroid resistance developing in the two-spotted stinkbug, *Bathycoelia distincta* (Hemiptera: pentatomidae) on macadamia in South Africa	De Villiers Fourie (funded by IRAC)
2016-2017	Environmentally friendly management of the coconut stinkbug in avocado	Schalk Schoeman
2017 onwards	Field trials with 6 kairomones identified for two-spotted stinkbug on Macadamia, and 2 kairomones for coconut stinkbug in Avocado	Ben Botha/ André Botha/ Insect Science

Successes

Research and training successes

The SBWG established excellent working relations with other South African fruit and nut industries (CRI, Hortgro-Science, SAPPA), universities (NWU, UFS, US) and relevant private companies, for example, Insect Science, BioBee and River Bioscience. The overall plan with these relationships was to share resources (researchers, funding, etc.) with possible future collaborations. Relations were also established with experts in Canada (Michael Smith Laboratory, University of British Columbia, Vancouver and Natural Resources Canada, Great Lakes Forestry Centre, Ontario), Kenya (ICIPE - International Centre for Insect Physiology and Ecology) and the Max Planck Institute for Chemical Ecology (Jena, Germany) with regards to chemical ecology. Relations were also established with the USDA BMSBWG and Pherobank, in Holland.

During the past 10 years, scout training of farmers and farm workers formed a very important part of the SBWG's tasks. These scout-training workshops were organised in all production areas by the Subtrop technical advisors and managed by Dr Schalk Schoeman of the ARC-TSC, in Nelspruit. Stink bug factsheets, peer-reviewed research publications, yearbook research reports and technical articles were published and distributed. The Pyrethroid resistance/pruning problem in macadamia is currently addressed by research of the UFS (De Villiers Fourie) with funding from Insecticide Resistance Action Committee (IRAC) funding. Research outputs in terms of trials, publications, study groups, conference papers and training posters from 2009-2016 are shown in Table 2.

Table 2. Research outputs for the SBWG from 2009-2016.

3	Booklets (2 stink bug factsheets)
4	Theses (2 masters and 2 PhD)
13	Training posters
17	Scientific publications
19	Chapters in books
32	Popular publications
38	Lectures at conferences
38	Publications in grower journals
48	Scouting courses
53	Trials in total of which there were 2 trials on avocado (3.77%), 1 trial on litchis (1.87%) and 50 trials on macadamia (94.33%)
117	Study group talks

Successes on the chemical front

The situation with the chemical industry has changed drastically with the establishment of the chemical forum in 2013 – a highly successful initiative. Regular communication exists between the agricultural chemical industry, the Registrar of Chemicals in South Africa and the EU (ECPA – the European Crop Protection Association).

At least 25 letters have been sent to the Registrar in collaboration with chemical companies requesting urgent registration of relevant chemical products for stink bug control. Letters were also sent to the Registrar communicating SAAGA/SAMAC's chemical needs with regards to stink bug control. Towards the end of 2016, at least 6 kairomones to which two-spotted stink bug responds and 2 kairomones to which coconut stink bug responds were successfully identified by Tshwane University of Technology (TUT) and ARC-TSC researchers. In collaboration with the private company, Insect Science field trials were initiated during January 2017, testing these kairomones. These trials are in progress and early results show that the first blend of these kairomones attracts both two-spotted and coconut stink bug successfully. Much work is still ahead. Chemical outputs in terms of chemical trials completed from 2009-2016 is shown in Table 3.

Table 3. Chemical outputs in terms of registration trials completed.

Pesticide	Crop	Number of trials
Abamectin	Macadamia	1
Acephate	Macadamia	1
Indoxacarb	Macadamia	1
Methoxyfenozide	Macadamia	1
Rynaxapyr	Macadamia	1
Trichlorfon	Macadamia	1
X mate FCM	Macadamia	1
Bifenthrin / thiamethoxam	Macadamia	2
Clothianidin	Macadamia	2
Cryptex	Macadamia	2
Cyperfos	Macadamia	2
Esfenvalerate	Macadamia	2
Lambdacyhalothrin / acetamiprid	Macadamia	2
Pheromones against litchi moth	Litchi	2
Beauveria bassiana	Macadamia & avocado	3
Isomate	Avocado & macadamia	3
Sulfoxaflor	Macadamia	3
Thiamethoxam	Macadamia	3
Pymetrozine	Macadamia	4
Lambda-cyhalothin	Macadamia	5
Experimental (proprietary) products	Macadamia	9

Table 4. Comparison between the USA BMSBWG and Subtrop SBWG.

Classification	BMSBWG (USA)	SBWG (Subtrop)
Annual crop loss/damage	$200 million/annum	R404 million/annum
Funding/money spent	$50 million/annum for past 7 years (25% of damage)	R2.5 million over 8 years (0.006% of damage)
Human capital	50 entomologists/specialists (1/ USA state)	Average three entomologists at any given time. One chemist. Small team of horticulturists/soil scientists
Types of stink bugs	Invasive stink bug species – Brown Marmorated Stink bug	Indigenous stink bug species – Yellow edged, coconut stink bug and two-spotted stink bug
Crops affected	Grapes, pear, apples, peach, hazelnuts, berries, vegetables	Avocado, macadamia
Management and control methods	Attract and kill (pheromone), natural enemies, chemical control	Attract and kill (pheromone, kairomones), trap crops, natural enemies, chemical control
Objectives	Landscape management, biological control, prediction tools, economics, outreach	Landscape management, biological control, prediction tools (degree days), economic damage, communication
Successful pheromone/ kairomone development	Yes	Yes. Currently running (Jan-March 2017) field trials with identified kairomones successfully catches two-spotted and coconut stink bugs in macadamia orchards

CONCLUSION

The Subtrop SBWG, an initiative between the Southern African Avocado and Macadamia Growers' Associations, is a success story. It can clearly be seen in Table 4 that the Subtrop SBWG, with much less human capital and financial resources, as well as bigger challenges with regards to species and number of stink bugs, accomplished similar and even better successes with regards to stink bug control and management than the BMSBWG. A comparison between the USA BMSBWG and the Subtrop SBWG gives an indication of the relative successes of the Subtrop SBWG (Table 4).

Both Drs Tracey Leskey and Rob Morisson from the USDA - BMSBWG said the following on their visits to South Africa: *"The Stink Bug Working Group in South Africa is doing all the right things correctly, and the same things needed to achieve success in managing stink bugs than the BMSBWG in the USA. Congratulations to this small team of enthusiastic scientists"*.

The current SBWG strategy was re-evaluated during a Strategic Stink Bug Working Group meeting in 2016 with Emeritus Professor Erik Holm as facilitator. During this strategic meeting, it was emphasised that the SBWG is on the right track and doing the right research/actions in order to control and manage stink bugs, but that SAAGA/SAMAC is under spending to a great extent, and this under spending could eventually be the downfall of the SBWG initiative (see Table 4).

Major findings of the avocado stink bug programme

1) The geographical distribution of coconut stink bug damage was determined. The coconut stink bug is not distributed evenly throughout the production region but appears to be associated with riparian vegetation;
2) Coconut stink bug damage was previously misdiagnosed by earlier researchers, which probably led to an underestimation of the damage potential of this stink bug;
3) A study was done in all 4 major subtropical crops (avocado, macadamia, mango and litchi) to quantify migration patterns of the coconut stink bug during the seasons;
4) Litchi appears to be a very good host and was not previously associated with this pest (results are also published in the scientific domain). If litchis are cultivated close to avocado, a winter treatment in litchis could possibly reduce damage in avocado during spring time;
5) Fruit maturity appears to influence stink bug attacks and a threshold value of 86% moisture was calculated for 'Pinkerton' fruit as a minimum threshold level;
6) When stink bugs invade an orchard, they normally settle along the edges before moving deeper into the orchards. Strong edge effects normally occur which is also in line with various international papers on the same subject;
7) Although some damage occurs early in the season, this stink bug appears to prefer maturing fruit and damage levels usually escalates from January onwards;
8) Coconut stink bugs prefer to feed in the treetops of especially dense trees;
9) Where pruning of any sort was done, it appears to reduce damage significantly;
10) Spraying during the second halve of the production season on commercial estates reduced damage for a few weeks, but invariably 3 - 4 weeks later damage increase again. Increased spray frequency during this time is undesirable because of pesticide residues on the fruit, but without spraying damage, levels are unacceptably high;

11) Solutions to this conundrum are currently being sought and this include:
    a. Development of fungal pathogens which can be used closer to harvest and which will not have a detrimental effect on possible exceedance of MRL levels
    b. The Achilles heel of these pathogens is UV radiation. The addition of reflectants are currently being tested to determine if the environmental persistence of these very handy organisms can be extended
    c. Treat trees along orchard perimeters with a systemic product such as Thiamethoxam early in the season so that it could act as a barrier to invading stink bugs
    d. The mechanism of seasonal succession in macadamia will be investigated. The two-spotted stink bug cannot smell its own defensive volatile compounds but clearly, the other stink bugs can. The possibility of using two spotted stink bug defensive compounds to deter other stink bugs (coconut stink bug) in avocado is clearly a very exiting possibility;
12) Pheromones and kairomones
    a. Defensive compounds of two-spotted and coconut stink bugs were determined. They cannot smell themselves but can possibly smell other stink bugs
    b. Chemical volatiles in all four major subtropical trees were determined when they were most attractive to stink bugs and also when they we most avoided by stink bugs. Search for a common denominator (André Botha's thesis)
    c. Search for sex pheromone for two-spotted and coconut stink bugs. A number of compounds were identified and will undergo first field trials during early 2017. Insect Science partner in the project
    d. New studies with the vibrometer as well as with various sound recordings indicate that mating rituals of these insects are very complex and possibly involve a number of aspects.

Major findings of the macadamia stink bug programme

1) A direct link exists between increased tree density and the number of stink bugs and nut borer damage;
2) Pre-harvest clean up sprays give no real benefit because:
    a) Trees simply compensate for early damage (international confirmation of this statement in Australian macadamia)
    b) there are very few two-spotted stink bugs in the orchards during this time (see Fig. 1 - arrows denote times where pre-flowering clean-up sprays are normally applied during August/September)
3) Post flowering clean-up sprays are however very important as the majority of stink bugs migrate into macadamia at flowering;
4) Two sprays ± 3 weeks apart during this time (late September/early October) were very effective in controlling adults and preventing egg laying;
5) These sprays also synchronised the age of individuals that did survive, which made the calculation of degree-days from eggs to fifth instar nymphs much more accurate;
6) Degree-day values were calculated and bottom cut-off temperature points were calculated with the help of Subtrop and the University of Venda;
7) On going study to quantify natural host plants;
8) Vertical distribution of stink bugs and borers in the trees were determined. Stink bugs have an affinity for treetops;
9) When stink bugs invade an orchard, they normally settle along the edges before moving deeper into the orchards. Strong edge effects normally occur, which is also in line with various international papers on the same subject;
10) Resistance was observed against synthetic pyrethroids in the Nelspruit/White River region;
11) The reason for this appears to be poor spray coverage in the apical regions of tall trees. Most commercial sprayers will only effectively spray trees up to 6 m. Compare orchards and tree sizes in various parts of the world if there is any doubt;
12) Although many stink bug species have been recorded in macadamia, the two-spotted stink bug appears to outcompete all other species and when young green nuts are available. This is most certainly the species of major concern;
13) An interesting question was asked, that if we eliminate this species from the orchard with the use of pheromones, what would happen to the other species? In all likelihood, the second most dominant stink bug species will simply take over where the two-spotted stink bug has left off;

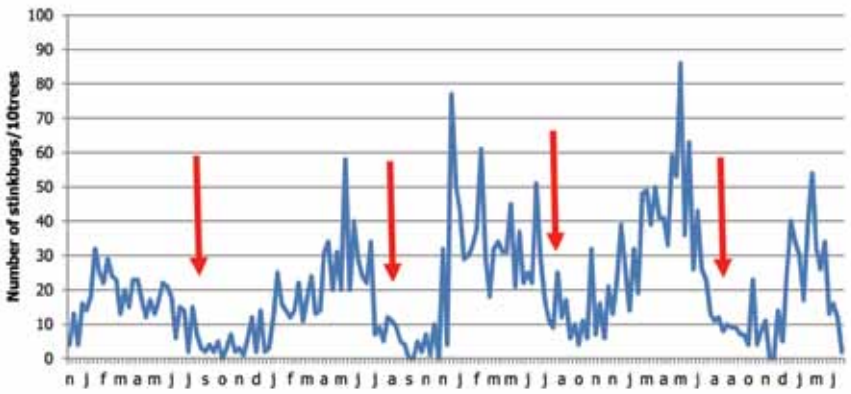

Figure 1. Number of two-spotted stink bugs in orchards during pre-harvest.

14) Because this insect is strongly K selected, knowledge regarding overwintering behaviour will in all probability help to control this pest effectively;
15) Where pruning was combined with degree-day modelling and effective scouting, insect damage was reduced from 11.43/-1.96/10 trees. This means an increase in quality of 583%. Unfortunately, the drastic pruning had a negative effect on yield. It is, however, expected that yield should normalise during the next few years. Insect sprays were reduced from 13 – 9/season and further reductions are expected during the next few years;
16) There will be no silver bullet that will control the two-spotted stink bug. The current trend of increasing usage of pesticides will have to be reversed. The only way this can be effectively done is by pruning and effective pesticide application. Once this is done, all other aspects encompassing natural or biological control can be included in a real workable IPM programme;
17) If no pruning is done, continued pressure will be placed on the currently available pesticides. Resistance build up and poor performance of other chemical products is expected as long as the situation exists. Chlorpyriphos was withdrawn from the market during March 2017 and concerns are voiced in the EU against Acephate. With resistance against pyrethroids in mind, it is clear that the industry is fast running out of options. New chemistry is being tested as a matter of priority but these products have vastly different environmental profiles if compared to the older products. More knowledge regarding population levels of stink bugs on farm level will be required;
18) The big question remains: when is the best time to prune? The answer is very simple: when the trees were planted. The second question comes to mind as nobody has done this: when is the second-best time to prune? The answer is: right now. For further information please site the references in the Reference list.

Acknowledgements

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