The Phenologies of *Macadamia* (Proteaceae) and Thrips (Insecta: Thysanoptera) Communities in Mpumalanga Province, South Africa

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Abstract

Macadamia (Proteaceae) is indigenous to Australia; four of the nine species have been used in plant breeding for cultivation and the production of a rapidly growing product. First introduced to Hawaii in the 1880s, macadamias' potential as a crop was only really considered in 1910. It is due to the early Hawaiian pioneers' research and the development of Hawaiian cultivars upon which most of the current world's production is based today. Prior to the 1980s, cultivation in Australia was based mainly on Hawaiian cultivars. Extensive research has been conducted on cultivar development, performance, best practice, production, crop protection and processing.

South Africa has become one of the world's leading producers and exporters of macadamias. The cultivation of macadamia in South Africa began 80 years ago, but the phenology of macadamia has not been rigorously studied under local conditions, and neither has the thrips communities in macadamia. Data collected during this study on the macadamia phenological stages can be used as a foundation on which seasonal data of all insect pests can be plotted, as a basis on which an extensive Integrated Pest Management (IPM) programme can be developed for the macadamia industry in South Africa.

Extensive sampling of thrips communities present in macadamias was undertaken over two years, with more than 142,000 individuals collected. The most basic, common trait into which specimens could be sorted were colour groups. Specimens from each colour group were identified through slide-mounting individuals. Fifteen species of thrips were identified to species-level, excluding specimens from the Panchaetothripinae, *Haplothrips* and *Scolothrips* which occurred only periodically. The presence of larvae indicated that macadamia is a host plant for some species. Due to their size and morphology, identification of the total collection could not be processed to species level using a dissection microscope, although *Scirtothrips aurantii* Fauré were distinguishable from other species and their distribution over the seasons observed.

Due to logistical constraints and events beyond the author's control, the results are mainly qualitative. There seems to be phenological variation within and between cultivars. The date of anthesis and duration of immature nut-drop was estimated; some cultivars set out-of-season flowers and nuts; this "secondary crop" could have far-reaching effects on the implementation of an IPM programme. Comparisons of the phenological data of macadamia and thrips showed the highest abundances and diversity of thrips species occurred when flowers were present.

An extensive study of abscised nuts showed no significant difference between most cultivars or at the sites where management practices were implemented and those sites where these practices were not. There was however a consistent difference between the two seasons. There was no difference in maturity of abscised nuts, regardless of whether thrips damage to the husk was present or not. Excessive *Bathycoelia distincta* (Hemiptera: Pentatomidae) damage was found on the kernels of the abscised nuts processed for maturity testing, which is more likely to have been the primary cause of abscission.

The Author's opinion is that thrips damage to the outer husk does not lead to abscission of maturing nuts. Ascertaining the cause of abscission at nut-set and immature nut-drop is more problematic as there are numerous other potential causes. Damage to new flush, especially the late summer flush essential for the build-up of carbohydrates and resources for the following yield, should be carefully monitored and controlled when necessary.

This thesis is dedicated in loving memory of my late husband,

Randall Hepburn,

my friend, colleague, teacher, mentor, and champion;

the person who shared with me his incomparable knowledge

and love of insects…and that's how it all began.

Con te partirò.

Declaration

The following thesis has not been submitted to any university other than Rhodes University, Grahamstown, South Africa. The work presented here is that of the author.

DATE: 30 March 2017

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List of Abbreviations

ARC – Agricultural Research Council, South Africa.

ARC-ITSC – Agricultural Research Council, Institute for Tropical and Subtropical Crops, Nelspruit, South Africa.

ARC F'heim – Agricultural Research Council, Friedenheim Research Station, Nelspruit, South Africa.

ARC-PPR (formerly PPRI) – Agricultural Research Council, Plant Protection Research, Pretoria, South Africa.

Due to the limited number of different cultivar plantings available for research purposes, some of the sites were not orchards but rows (blocks) of a particular cultivar in a mixed planting cultivar orchard. However, for ease of reference, whether describing an orchard or cultivar block, all are designated as "study sites" in this study.

ARC Nel D – Nelmak D cultivar site at the ARC-ITSC, 8 – 9-year-old trees (2011/2012 & 2012/2013 seasons).

ARC Old Nel 2 – Nelmak 2 cultivar site at the ARC-ITSC, 43-year-old trees (2012/2013 season).

ARC VO Nel 2 – Nelmak 2 cultivar site at the ARC-ITSC Variety Orchard, 13-year-old trees (2011/2012 season).

ARC F'heim B'mont – Beaumont cultivar site at the ARC Friedenheim Research Station, 6 – 7-year-old trees (2011/2012 & 2012/2013 seasons).

ARC VO B'mont – Beaumont cultivar site at the ARC-ITSC Variety Orchard, 13 – 14-year-old trees (2011/2012 & 2012/2013 seasons).

ARC VO A4 – A4 cultivar site at the ARC-ITSC Variety Orchard, 13-year-old trees (2011/2012 season).

ARC VO A16 – A16 cultivar site at the ARC-ITSC Variety Orchard, 13 – 14-year-old trees (2011/2012 & 2012/2013 seasons).

ARC VO 788 – 788 cultivar site at the ARC-ITSC Variety Orchard, 13-year-old trees (2011/2012 season).

ARC VO 816 – 816 cultivar site at the ARC-ITSC Variety Orchard, 13-year-old trees (2011/2012 season).

CF 788 – 788 cultivar site at the Commercial Farm, 4 – 5-year-old trees (2011/2012 & 2012/2013 seasons).

CF Nel D – Nelmak D cultivar site at the Commercial Farm, 6 – 7-year old trees (2011/2012 & 2012/2013 seasons).

CF 816 – 816 cultivar site at the Commercial Farm, 4 – 5-year old trees (2011/2012 & 2012/2013 seasons).

CF B'mont – Beaumont cultivar site at the Commercial Farm, 12 – 13-year old trees (2011/2012 & 2012/2013 seasons).

CF Nel D – Nelmak D cultivar site at the Commercial Farm, 12 – 13-year old trees (2011/2012 & 2012/2013 seasons).

Disclaimer

Any opinion, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Research Foundation.

1 Introduction, Aims and Selection of Study Sites

Summary: It is essential that an in-depth study be conducted on the phenologies of both macadamia (Proteaceae) and thrips (Thysanoptera) to assess the interaction between host plant and the insects. This chapter describes the aims of this study, the necessity for this research to be conducted under South African growing conditions, collecting data on the performance of the different cultivars, the timing at which the thrips species occur in macadamia orchards and determining thrips damage to new flush and husks. A synopsis of the cultivation of macadamia in South Africa, the study area in Mpumalanga Province where the study was conducted, and the natural vegetation in the area are presented. A list of the study sites used during the two growing seasons, why these were chosen and their relevance to the rest of the study are explained.

1.1 Introduction

Agricultural entomologists need to study a crop's phenology under the environmental conditions in the new adoptive country, the occurrence, biology and phenology of both endemic and invasive insect pests associated with the crop, and their various interactions (Binns and Nyrop 1992, Higley and Peterson 1994, Pedigo and Rice 2006).

It is of vital importance to first define the plant's developmental stages, and the timing and duration of these stages throughout the season. Once the phenology of the plant has been established, data about the seasonal occurrence of all insect pests associated with the crop can be superimposed, thus providing accurate data on their presence, reproduction, pest pressure, and preferences for specific developmental stage(s) of the plant. Once this information is gathered, management and control decisions can be made on how best to control these pests, should it become necessary. This thesis pursues this agenda in the context of a South African macadamia crop and its associated thrips.

1.1.1 Macadamia (Proteaceae)

A comprehensive understanding of the cultivation of macadamia is crucial to implementing and co-ordinating crop protection and farming practices to control macadamia pests in South Africa. Some macadamia cultivars are more suited to specific regions and perform better under certain conditions (climate, altitude, latitude and longitude, soils *et cetera*), which may also affect the phenology and performance of the variety. The phenological stages can either increase or decrease the length of the growing period, and therefore the occurrence, immigration and pressure of pest populations.

A general concept of macadamia phenology is applied to all cultivars grown in South Africa, but closer investigation is required to see how the imported cultivars perform under South African conditions when exposed to the local macadamia pest community. Furthermore, the general phenology does not take into account events, such as out-of-season flowering and/or fruit-set, which provide an extended period of available food for pests, and the repercussions these protracted developmental stages have on the final quantity and quality of the yield.

1.1.2 Thrips (Thysanoptera)

To date only a single study has been carried out on thrips species occurring in macadamia orchards in South Africa, that by de Villiers and van den Berg (2003). Two species were found: the South African citrus thrips, *Scirtothrips aurantii* Fauré, and the greenhouse thrips, *Heliothrips haemorrhoidalis* (Bouché). These species were reported as not of significant importance except occasionally in nurseries.

Research conducted in both Australia (Ironside 1996, Gallagher *et al.* 2003), and Hawaii (Jones 2002), found that, although certain thrips species caused sporadic infestations, thrips are classified as minor pests; chemical control is only used when populations are extremely high

1.2 Aims of this study

The purpose of this study was to gather information on interactions between macadamia plants and thrips communities in South Africa by focussing on the following points:

1. Review of the history and botany of macadamia and its cultivation in South Africa;
2. Study the phenology of the macadamia cultivars used in this study;
3. Review thrips biology and the pest species associated with other South African crops;
4. Find out what thrips damage looks like in macadamia;
5. Determine thrips species present in macadamia in South Africa;
6. Study the seasonal occurrence and phenology of key thrips species in macadamia and relate it to host plant phenology;
7. Ascertain whether premature fruit-drop and subsequent abscission in macadamia are attributable to thrips damage; and
8. Determine whether thrips damage to the outer husk is "cosmetic" damage, or if maturity of the kernel is affected.

1.3 Synopsis of macadamia cultivation in South Africa

Since the first importation of macadamia seeds from Hawaii to South Africa, more than 80-years ago (Reim 1991), further introductions of cultivars from Hawaii, Australia and California have been made (McConachie 1980, Hardner *et al.* 2009). Over eighteen different macadamia cultivars are presently grown in South Africa, most of Australian or Hawaiian origin. Hawaiian cultivars are by far the most commonly grown, followed by Australian and the four hybrid cultivars, (Nelmak 1, Nelmak 2, Nelmak 26 and Nelmak D), developed in South Africa. The hybrid cultivar 695 (Beaumont), imported from California, has the highest percentage of plantings in South African, amounting to 31% in 2013 (Fig. 1.1) (Anon. 2013a).

Even though evaluations and selections of imported macadamia cultivars have been carried out over the years to determine which perform best under South African conditions (Allan 1989 in Hardner *et al.* 2009, Allan1995, Allan *et al.* 1999), no extensive study has been made on the phenologies of these cultivars. The South African macadamia industry has, in the past, relied heavily upon research conducted primarily in Hawaii and Australia, and applied/adopted these methods here. In some instances, information on the cultivation of macadamia can be adapted to South African conditions (e.g. nursery practices, orchard layout, soil preparation, fertilizer applications, irrigation systems, and pruning to name a few). However, information on the performance and production of the various cultivars under South African conditions, and the control of diseases and insects which occur here, cannot simply be adapted from data collected in a foreign country.

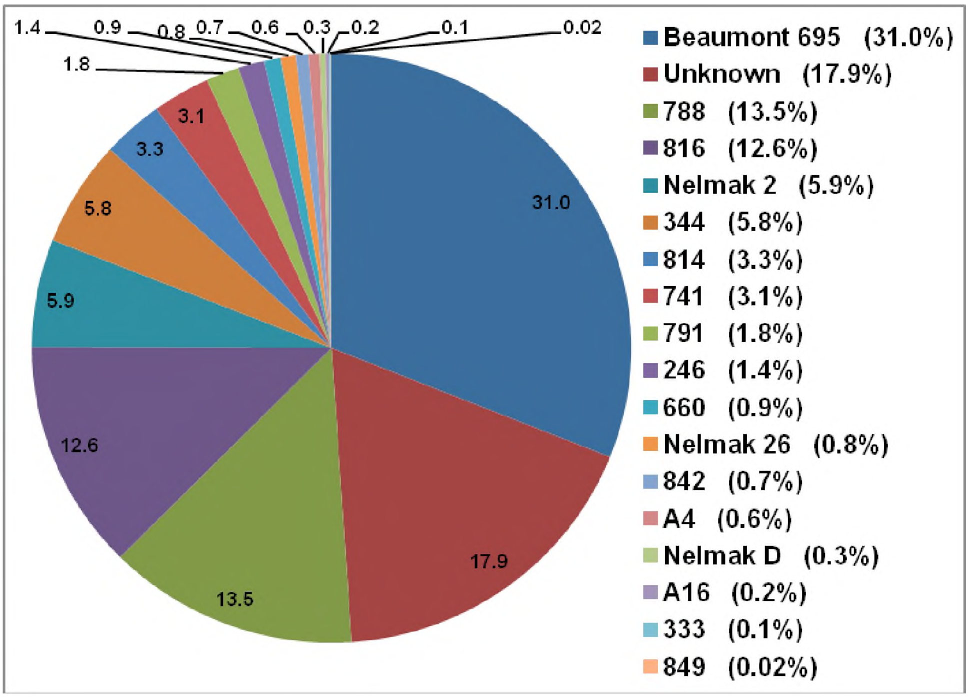


Figure 1.1 Assessment of the most commonly grown macadamia cultivars in South Africa, shown as a percentage (from Subtrop – Anon. 2013a).

1.4 Mpumalanga Province, South Africa

Mpumalanga Province, situated in the north-eastern area of South Africa, covers some 76 495 km² and constitutes 6.3% of South Africa's land area (Statistics South Africa, 2011). It borders Limpopo Province to the north, Mozambique and Swaziland to the east, KwaZulu-Natal and Free State Provinces to the south and Gauteng Province to the west (Fig. 1.2). The region receives summer rainfall.

1.4.1 Biomes and vegetation

Of the nine biomes occurring in South Africa, the three that occur in Mpumalanga: (Grassland, Savanna and Forest), total 874 km^2 (Table 1.1). In 2005 the South African National Biodiversity Institute (SANBI) produced a Revised Vegetation Map of South Africa, Swaziland and Lesotho, and of the three biomes occurring in Mpumalanga, sixty-eight vegetation types are described. There are nine Forest, 28 Grassland and 31 Savanna biome vegetation types (Ferrar and Lötter 2006). Much of the arable land in the province has been transformed (i.e. disturbance or removal of vegetation, as with agriculture, forestry plantations, mining and urban development interventions), which has led to the loss of biodiversity and fragmentation of ecosystems (Ferrar and Lötter 2006).

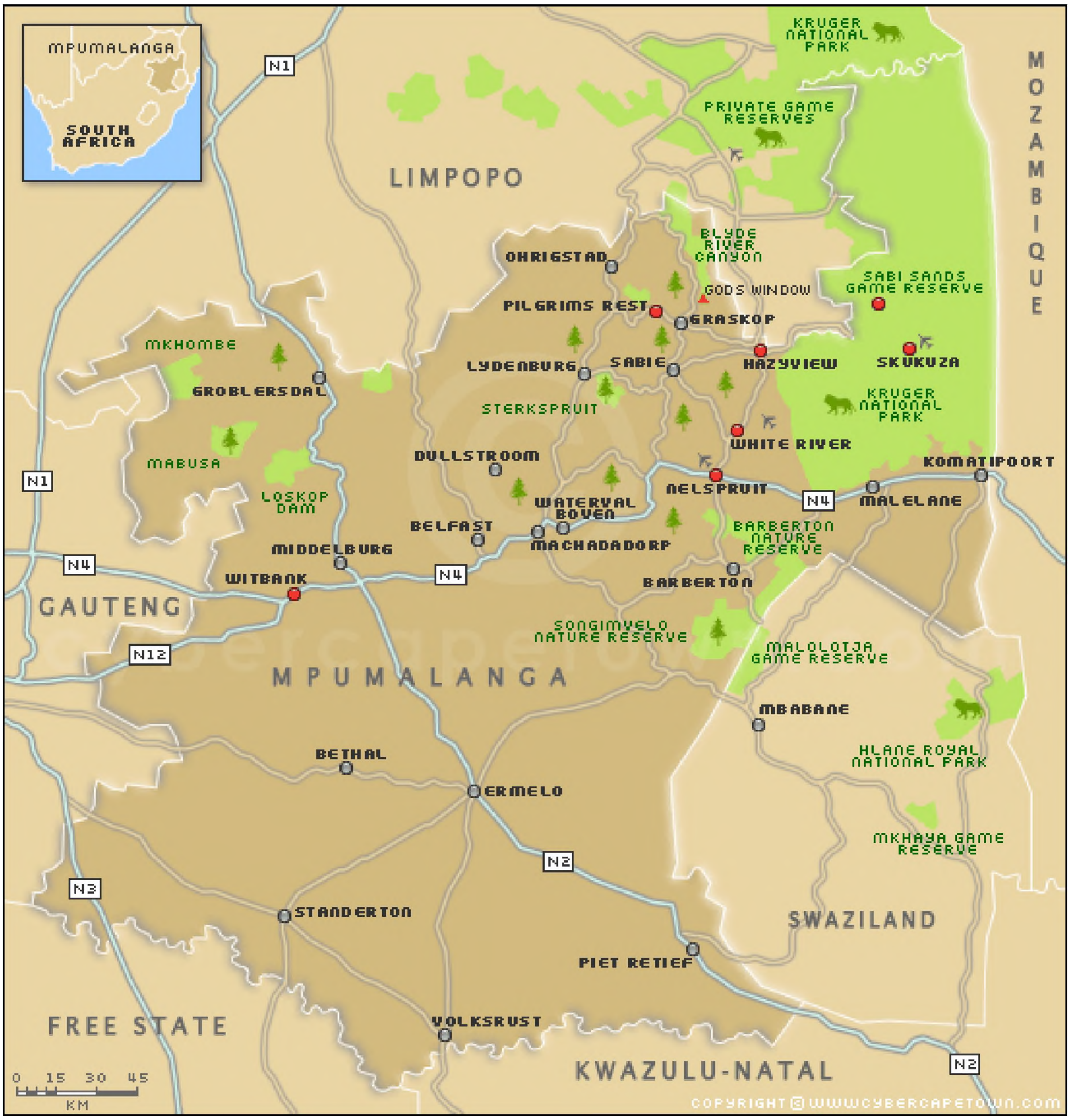


Figure 1.2 Map of Mpumalanga Province, South Africa (From wwwcybercapetown.com Accessed 6 October 2014).

Table 1.1 Extent of the area comprising the three biomes of Mpumalanga Province and the remaining natural vegetation after land transformation has occurred (from Ferrar and Lötter 2006).

Biome	**Total Size (km²)**	**% of Mpumalanga**	**Remaining Natural Vegetation (km²)**	**% Transformed**
Grassland	531	61%	298	44%
Savanna	338	39%	255	25%
Forest	40	0.5%	39	1%
Total	**874**	**100%**	**588**	**36%**

The Grassland biome made up 61% of the vegetation in Mpumalanga and is found in the Highveld and escarpment hills above 1000 m. Grassland occurs over open landscapes which are cool and relatively dry, receiving an annual rainfall of over 500 mm. Thunder storms, frost and hail storms occur frequently. Much of the deep, fertile soils of the Grassland have been transformed for agriculture, livestock production and forestry plantations. An enormous 44% of the original area designated as Grassland has been "transformed" by these man-made intrusions (Ferrar and Lötter 2006).

The Savanna biome is extremely diverse, comprising a typical African mixture of trees, shrubs and grasses occurring at lower altitudes; from tall, dense woodland to open woodland, dense thicket and wooded shrubby hill slopes to grass plains interspersed with trees or clusters of bush. This biome once made up 39% of Mpumalanga's vegetation; 25% of the original Savanna biome has now been transformed. Savanna occurs in the foothills of the escarpment and in the Lowveld. Thunderstorms are frequent during the rainy season and there is a high propensity for flash-flooding, topsoil runoff and soil erosion. During the long, hot dry-season, plants become stressed due to water shortage, which is a limiting factor for agriculture and livestock production in these areas. Only the deeper, more fertile soils are used for cultivation (Ferrar and Lötter 2006). All the sites used in this study are part of the Lowveld bioregion of the Savanna biome.

The Forest biome (comprising indigenous evergreen natural forests), covers 0.5% of Mpumalanga (1% of the original Forest biome has been transformed). The remaining natural forests occur in small scattered patches along the south and east-facing escarpment valleys, mainly on steep slopes and river valleys which are not well suited to cultivation. These areas are normally frost-free and receive high annual rainfall (over 725 mm); through the dry season moisture is supplemented by groundwater from streams and precipitation in the form of mist (Ferrar and Lötter 2006).

1.5 Selection of study sites

The study was conducted over two consecutive growing seasons in the Nelspruit area of Mpumalanga Province, South Africa. During the 2011/2012 season, 13 study sites were chosen after determining the most commonly grown cultivars in the area around Nelspruit; these were surveyed over 33 weeks (8 September 2011 to 10 May 2012). In the second season, 2012/2013, 10 study sites were sampled over 40 weeks (13 July 2012 to 10 April 2013) (Table 1.2). Study sites were chosen based on availability of specific macadamia cultivars, management practices (managed/unmanaged), and locality.

Table 1.2 GPS co-ordinates of the study sites (both managed and unmanaged) used during the 2011/2012 and 2012/2013 macadamia growing seasons.

Location and Study Site	Cultivar	Managed	Tree Age (years)	
			2011/2012	2012/2013
ARC-ITSC Research Station				
25°27'18.8"S 30°58'14.8"E	Nelmak D	No	8	9
25°26'56.2"S 30°58'08.5"E	Beaumont	No	13	14
	A16	No	13	14
	788	No	13	-
	A4	No	13	-
	816	No	13	-
	Nelmak 2	No	13	-
25°27'37.6"S 30°58'22.5"E	Nelmak 2	No	-	43
Friedenheim Research Station				
25°26'53.6"S 30°59'31.4"E	Beaumont	No	6	7
Commercial Farm				
25°29'41.5"S 31°06'58.8"E	Beaumont	Yes	12	13
25°29'42.2"S 31°06'59.2"E	Nelmak D	Yes	12	13
25°29'17.8"S 31°06'29.3"E	Nelmak D	Yes	6	7
25°29'16.3"S 31°06'20.9"E	788	Yes	4	5
25°29'19.0"S 31°06'28.6"E	816	Yes	4	5

Due to the limited number of different cultivar plantings available for research purposes, some of the sites were not orchards but rows (blocks) of a particular cultivar in a mixed-planting cultivar orchard. However, for ease of reference, whether describing an orchard or cultivar block, all are designated as “study sites” in this study.

Some fundamental points arising from the aims of this study needed to be considered when choosing the study sites, as comparisons could then be made.

i. Is there significant variation within the same cultivar, or between cultivars, with regards to thrips damage?
ii. Does thrips damage in unmanaged, unsprayed orchards (referred to as “unmanaged” sites), differ from commercial farming enterprises (referred to as “managed” sites), where good farming practices and chemical spray programmes are undertaken?
iii. Do thrips populations occur more frequently, at higher levels, and over a longer period, at the sites where no chemical applications are made (i.e. the unmanaged sites)?

1.5.1 Commercial (managed) sites

Orchards of Nelmak D, Beaumont, 788 and 816 were located at a commercial farm 20 km east of the other study sites situated at the Agricultural Research Council Institute of Tropical and Subtropical Crops (ARC-ITSC) in Nelspruit (Table 1.2; Fig. 1.3a). Normal commercial farming management practices were applied (i.e. soil and leaf analyses; mineral, trace elements and fertilizer applications; irrigation; pruning; spray applications; *et cetera*). During both seasons, five study sites were located at the commercial farm.

The commercial farm is situated in Malelane Mountain Bushveld (SVI 11: Rutherford *et al.* 2006), with summer rainfall and dry winters. Average annual rainfall is between 600-1100 mm, increasing with altitude. Occasional mist occurs in the mountains and frost is infrequent to occasional at higher altitudes (Rutherford *et al.* 2006). Annual maximum and minimum temperatures are 39.7°C and 4.0°C respectively (Gertenbach 1983).

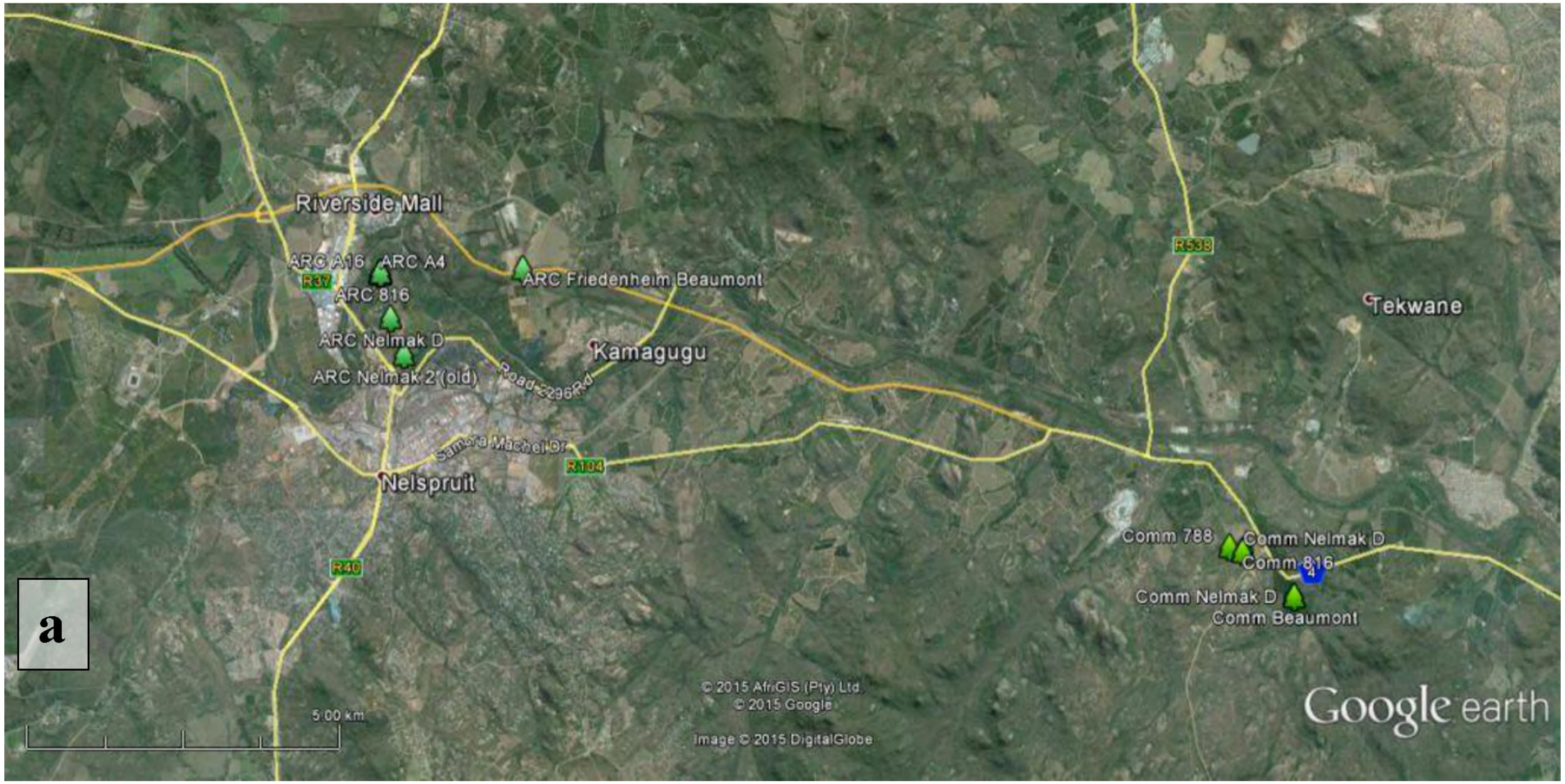


Figure 1.3a Aerial photograph of the ARC and Commercial Farm study sites, Mpumalanga Province, South Africa (Source: Google Earth 2015 AfriGIS (Pty) Ltd).

Figure 1.3b Aerial photograph of the ARC-ITSC Variety Orchard cultivars. (Source: Google Earth 2015 AfriGIS (Pty) Ltd).

1.5.2 Unmanaged sites

The ARC-ITSC in Nelspruit has non-commercial orchards utilized purely for research. Other than some pruning and sporadic irrigation, these orchards are left largely unmanaged. The ITSC main station has orchards of Nelmak 2, Nelmak D and a mixed planting Variety Orchard comprising six different cultivars used in this study (Beaumont, Nelmak 2, 788, A4, 816 and A16) (Table 1.2; Fig. 1.3a-b); some of these sites were however not sampled for both growing seasons as the crop was insufficient.

An additional Beaumont cultivar orchard, located 2 km east of the ARC-ITSC at the ARC Friedenheim Research Station, was included for both seasons. This site is also unmanaged apart from pyrethroid sprays applied during the 2011/2012 season to control *Bathycoelia distincta* (Hemiptera: Pentatomidae), which formed part of another researcher's experiments.

The natural vegetation in proximity to the ARC-ITSC is Legogote Sour Bushveld (SVI 9: Rutherford *et al.* 2006). It is classified as an area with summer rainfall and dry winters; annual precipitation ranges from 700 mm along the bottom of the Mpumalanga escarpment in the east, to about 1150 mm at higher altitudes in the west, where it borders on grassland. The mean maximum and minimum temperatures for Nelspruit are 35.7°C and 1.6°C for October and July respectively (Rutherford *et al.* 2006).

The vegetative type at Friedenheim Research Station is Pretoriuskop Sour Bushveld (SVI 10: Rutherford *et al.* 2006). This area receives summer rainfall of 330-800 mm annually, dry winters, and infrequent frost. The mean annual maximum and minimum temperatures are 37.3°C and 5.2°C for October and July respectively (Rutherford *et al.* 2006).

1.6 Macadamia cultivar comparisons

This study dealt with the variation within and between cultivars. Rigorous comparisons could be made only on the three Beaumont and Nelmak cultivar orchards. Within cultivar comparisons of the two 788 and 816 cultivar orchards, each with one site at the ARC-ITSC and the other at the Commercial Farm, were compromised as the management practices would effect on the results of the analysis.

Orchards for the second season were reassessed and three cultivars at the ARC-ITSC Variety Orchard (Nelmak 2, A4 and 816) were excluded as they did not produce sufficient nuts to give a reasonable representation of the performance of these cultivars. The two remaining cultivars at the ARC-ITSC Variety Orchard (Beaumont and A16) were utilized again during the second season as they had higher yields. This may have been because these two cultivars formed the end rows of the Variety Orchard and, although no management took place, the trees received more sunlight and rain and performed better than the other cultivars. The A4 and 816 cultivars could not be replicated for the second season due to the lack of alternative orchards. Instead, a new orchard, "ARC-ITSC Old Nelmak 2" of 43-year-old trees, was included as an additional Nelmak 2 replicate for comparison (Table 1.2).

1.7 Thrips: pests, predators and pollinators

Many phytophagous thrips (Thysanoptera) species occur worldwide and are recognised as serious, sporadic, or minor pests of numerous agricultural, silvicultural, ornamental and plantation commodities (Childers 1997). Their pest status can differ remarkably from one area to another; as with the South African citrus thrips, *Scirtothrips aurantii* Fauré. For example, since *S. aurantii* was introduced to Australia, it has become established on the mother-of-millions weed, *Bryophyllum delagoense* (Eckl. & Zeyh.) Druce (Crassulaceae), and has not been recorded on citrus or mangoes even though it is highly pestilent on these crops in South Africa (Mound 2005, Morse and Hoddle 2006).

Thrips cause direct and indirect damage. Severe direct damage to leaves, flowers and fruit can cause abscission, as a result the plant may be unable to photosynthesise and produce the necessary resources to develop properly, and damaged tissue may lead to the plant becoming susceptible to pathogens (Childers 1997, Kirk 1997a), all of which result in reduced yield (Morse and Hoddle 2006). Direct damage by thrips also affects the cosmetic quality of produce for fresh marketing causing further economic loss (Childers and Achor 1995, Childers 1997, Lewis 1997a). Indirect damage is caused by certain thrips species that transmit numerous microbial pathogens (viruses, fungi and bacteria) (Ullman *et al.* 1997, 2002, Whitfield *et al.* 2005).

Not all species cause damage: some thrips are beneficial, feeding on other arthropods and mites (Acari); and pollen-feeders could facilitate cross-pollination and ultimately increase crop yield. It has been well documented that thrips augment pollination (Mound 2005, and citations therein).

1.8 Thrips on macadamia in South Africa

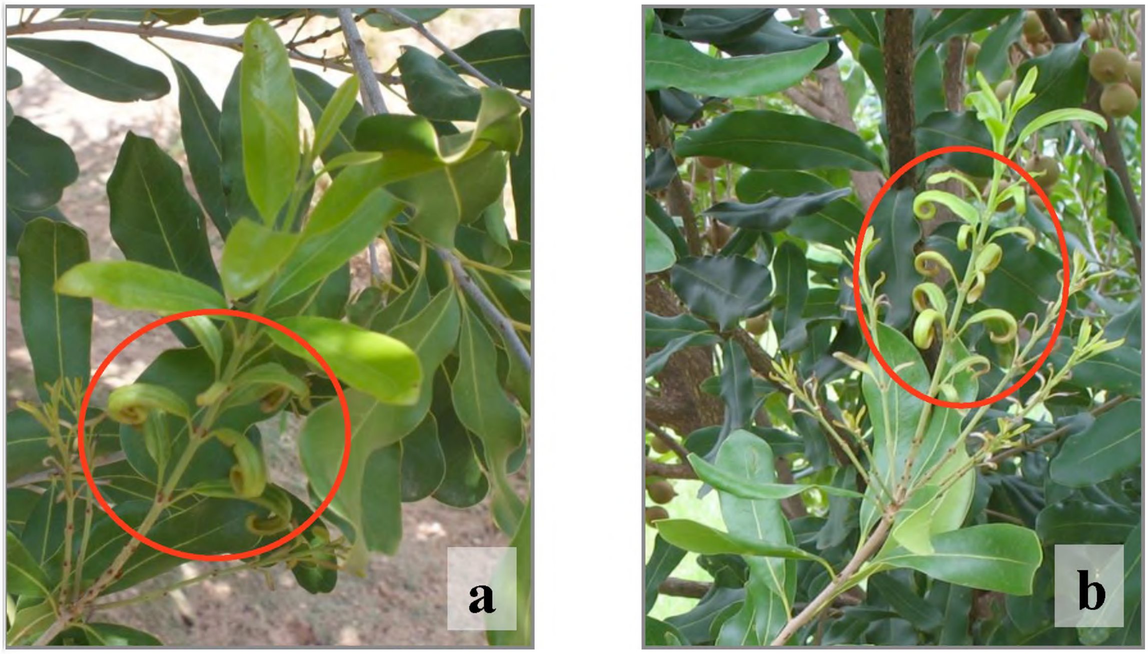
Apart from the study by de Villiers and van den Berg (2003) the Thysanoptera community in macadamia has not been studied. Commercial growers in South Africa wanted research to be conducted as to the extent to which thrips damage affects yields.

Thrips damage on new flush results in shortened terminal growth, malformed leaves, and damage to the husk, known as bronzing, may be partially attributed to mites (Hepburn and Stiller 2012). It has not been established how different cultivars respond to the South African thrips communities, and whether some cultivars are more susceptible or resistant to thrips damage.

1.8.1 Symptoms of thrips damage on macadamia trees in South Africa

Thrips damage at the various phenological stages of macadamias needed to be defined. Determining and identifying what thrips damage looked like to both new flush and the husks (with regards to possible cause of abscission), was crucial in this study.

Damage to new flush causes leaves to become disfigured and curled. In some instances, it was observed that a few weeks later the same shoots subsequently produced new flush with healthy leaves (Fig. 1.4a-b) (Hepburn and Stiller 2013). Terminal growth tips were however stunted after severe thrips damage. Damage to new flush on a single tree was difficult to quantify. Stephenson *et al.* (1986) assessed terminals in the canopy visually, assigning them to either "flush" or "mature" categories as a percentage, giving a clear indication of flushing patterns. Using a method based along these lines, we may be able to determine what percentage of the new flush is "damaged" and extrapolate this loss of leaf-surface area as a percent of overall foliage present. Should the rate of damage to the new flush be unreasonably high, control measures should be implemented.



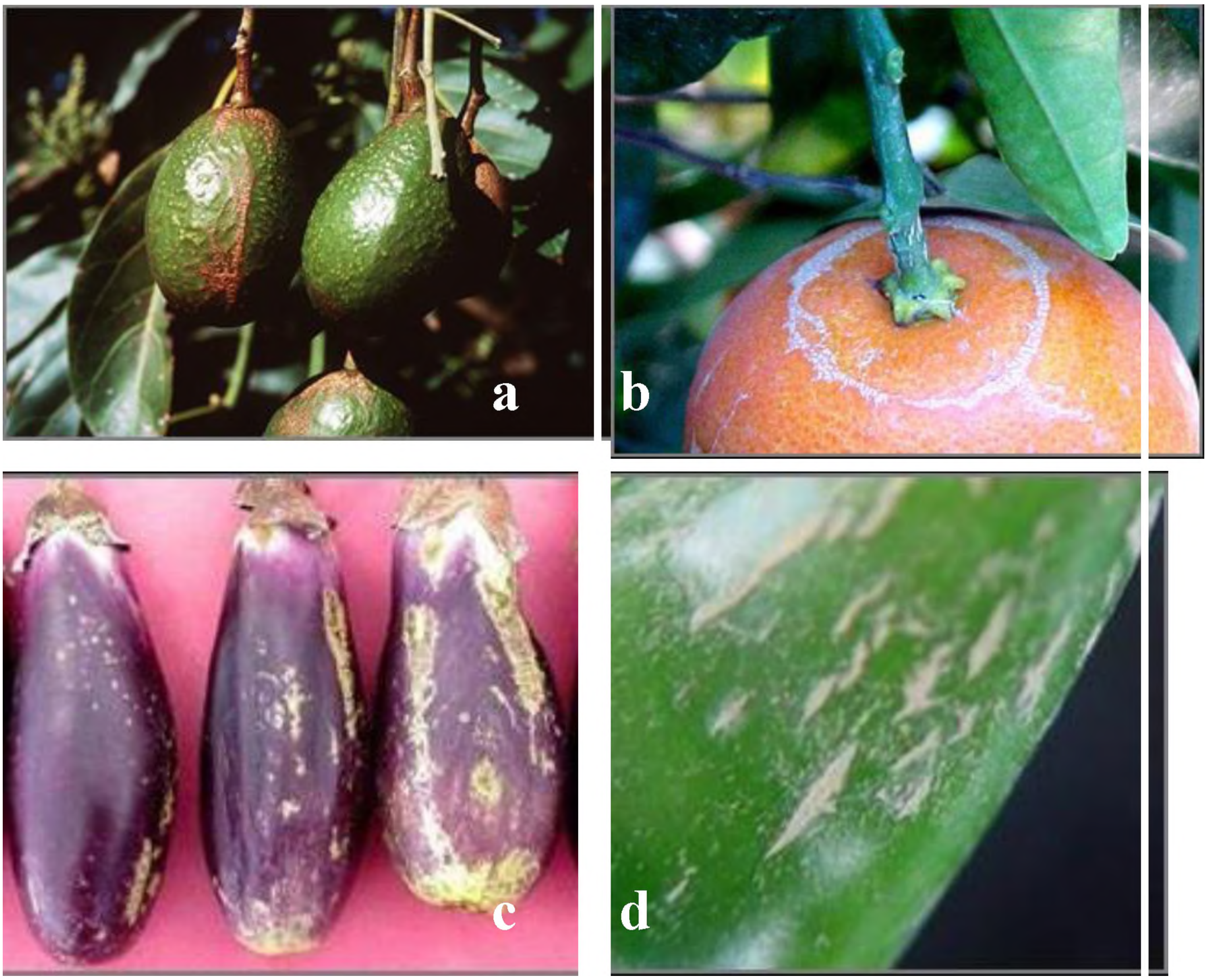
Figures 1.4 a-b Thrips damage to new flush and subsequent new growth with no damage.

Initially it was difficult to quantify thrips damage to husks because all bronzing and browning of husks has historically been attributed to "thrips damage". However different patterns of husk discolouration and markings were observed; some damage lay uniformly over the entire husk and some over only part of the husk (Fig. 1.5a-d). Wind damage resulting in the rubbing of husks against branches was easily identifiable, as the scarring was localized, as was mechanical damage which often cut through the husk. Photographs were sent to colleagues in South Africa and Hawaii for their opinions regarding whether thrips were causing the husk discolouration and markings. Their views were that some of the damage was caused by thrips, some by mites, and other discolouration patterns may also be due to cultivar differences (Hepburn and Stiller 2012).

Figures 1.5a Thrips feeding damage on macadamia husk. **b-c** Mite damage. **d** Natural discolouration of the developing nuts towards maturity in some cultivars.

1.8.2 Determining thrips damage to macadamia in South Africa

In this study, irregular scarring to the outer husk (Fig. 1.5a) was attributed to thrips damage based on intensive visual observations by the author. It was also noted that thrips often fed on the husk of a fruit touching an adjacent fruit. This irregular pattern of "silvering" or "scarring" to the outer skin or rind, which does not affect the entire surface area, is also found on other commercially-grown crops, such as avocado, citrus, aubergine and pepper (Figs. 1.6a-d).



Figures 1.6 Thrips damage to fruits. **a.** avocados (Source: Mark Hoddle, University of California, Riverside); **b.** citrus (Source: University of Arizona); **c.** aubergines (Source: Infonet Biovision); **d.** *Capsicum* pod (Source: Infonet Biovision).

1.9 Thrips on macadamia in Hawaii and Australia

Jones (2002) reported thrips occurring on macadamias in Hawaii, including the red-banded thrips, *Selenothrips rubrocinctus* (Giard), and the Hawaiian flower thrips, *Thrips hawaiiensis* (Morgan). *Selenothrips rubrocinctus* was recorded as an occasional pest, feeding mainly on the outer husk of nuts (Fig. 1.7). However, when populations increased to higher levels of infestation, damage could be seen on underside of recently hardened, young leaves but not on new flush or senescent leaves (Fig. 1.8). *Thrips hawaiiensis* was reported as being rarely a problem, although populations could increase rapidly when conditions were favorable, resulting in damage to flowers and a decrease in fruit-set (Jones 2002).

Ironside (1996) and Gallagher *et al.* (2003) published photographs of macadamia nuts in Australia with husk damage by *Scirtothrips* sp., *Heliothrips haemorrhoidalis* (Bouché) and *S. rubrocinctus*.

Figure 1.7 *Selenothrips rubrocinctus* damage on macadamias (Source: V.P. Jones, Washington State University).

Figure 1.8 *Selenothrips rubrocinctus* damage to the underside of macadamia leaves (Source: V.P. Jones, Washington State University).

Thrips are described as having “punch and suck” mouthparts (Kirk 1997a, 1997b), their feeding on a plant results in collapsed cell walls, which causes discolouration of the substrate over time (Mound 1971, Kirk 1997b, Moritz 1997). Extensive feeding damage on leaves and blossoms would very probably lead to their abscission, but feeding on the outer husk does not seem to affect the growth and maturity of macadamia kernels (Hepburn *et al*. 2014).

Jones (2002) reported that damage to macadamia husks was also caused by broad mite, *Polyphagotarsonemus latus* (Banks) (Acari: Tarsonemidae), and the red-and-black flat mite, *Brevipalpus phoenicis* (Geijskes) (Acari: Tenupalpidae). Discolouration and damage to the husk can be attributed to specific mite species. From the photographs of husk damage brought about by *P. latus*, it appears that the fruit were relatively small when the feeding damage occurred. This could partially explain why the entire surface of the husk is affected. As the fruit increase in size, the rough surface covers a wider expanse of the husk area (Figs. 1.9 and 1.10).

Figure 1.9 *Polyphagotarsonemus latus* scarring to the husk of immature macadamia nuts (Source: V.P. Jones, Washington State University).

Figure 1.10 *Polyphagotarsonemus latus* scarring on mature macadamia nuts discolours the entire husk. By scratching the surface, to show the green of the husk beneath, one can determine that it is *P. latus* damage (Source: V.P. Jones, Washington State University).

In the publications by Ironside (1996) and Gallagher *et al.* (2003), images of mite damage to husks by *P. latus*, and the citrus flat mite, *Brevipalpus lewisi* McGregor (Acari: Tenupalpidae), are also very distinctive.

Damage caused by *B. phoenicis* (Fig. 1.11) is markedly different to other mite damage; some intermittent green patches are still apparent on the husks (Fig. 1.12). Mites have "needle-like" mouthparts that pierce the outer layer of the husk and suck up the cell contents; these empty plant cells die and take on a brown colour as they grow (Jones 2002).

Figure 1.11 *Brevipalpus phoenicis* adult (Source: V.P. Jones, Washington State University).

Figure 1.12 *Brevipalpus phoenicis* damage to mature macadamia nuts (Source: V.P. Jones, Washington State University).

1.10 Species-specific damage to macadamia in South Africa

The appearance of feeding damage by specific species in the thrips community on macadamia trees in South Africa has not been studied; no pattern or markings were evident which could positively be ascribed to a species. With over 15 species of thrips occurring in South African macadamia orchards (Chapter 5), one would be hard pressed to be able to attribute a certain type of damage to a specific species.

If, however, only a couple of thrips species occur in a cropping system, exclusion experiments could be conducted. Preferably these experiments should be conducted in a quarantine-like environment on plants mature enough to bear fruit. This would entail isolating an entire plant or one of the developmental stages in a paper bag or such other material to prevent other thrips species (and mites) gaining entrance. In each enclosure, an unadulterated population of a potentially damaging species should be released. Without setting up experiments such as these, one would be hard-pressed to positively identify specific patterns caused by thrips at a species level and the subsequent effect that this damage has on each developmental stage of the plant. These experiments would show the preferred feeding sites of a particular species, but given the manner in which thrips feed, it is uncertain whether the identification of species-specific damage *per se* could be determined.

2 Macadamia (Proteaceae): Origin, Botany and History of Cultivation in South Africa

2.1 Introduction

To better understand the phenology and commercial cultivation of *Macadamia* (Proteaceae), a literature review was conducted that included the plant's botany and history. An extensive review on the history of macadamia is presented in Annexure I. Most of the early research was undertaken in Hawaii and Australia, so most of the literature is derived from those countries.

2.2 Origin and distribution of Proteaceae

The natural distribution of Proteaceae is mainly in the southern hemisphere, but extends into southern and eastern Asia, central America and western and north-eastern tropical Africa (Weston 2007). The Protea family is almost completely restricted to Gondwanic continental blocks and fragments, and occur in a wide range of habitats; from open grasslands to rain forests, alpine meadows to tropical lowlands. Plants are usually found growing on acidic, nutrient-poor, well-drained soils (Heywood *et al.* 2007; Weston 2007).

Historically, indigenous peoples used Proteaceae as a source of dyes, food, medicines, tannins and timber. The significance of the Proteaceae now is dominated by the commercial production and trade of *Macadamia*, and to a lesser extent the sale of ornamental genera which include *Protea*, *Leucadendron*, *Leucospermum*, *Serruria*, *Banksia*, *Grevillea*, *Telopea* and *Persoonia* (Weston 2007).

2.3 Macadamia botany

Nine species of *Macadamia* are usually recognised (Heywood *et al.* 2007, Weston 2007), but that number alters periodically due to reclassification. *Macadamia integrifolia* Maiden and Betche, *M. tetraphylla* L.A.S. Johnson, *M. ternifolia* F. Muell. and *M. jansenii* C.L. Gross et P.H. Weston, are evergreen, subtropical tree species endemic to the coastal rainforests and adjoining areas of northern New South Wales and southern Queensland, Australia (McConachie 1980, Trueman 2013). Macadamia is the only indigenous Australian tree to be developed commercially as a crop (Gregory 1987, Moncur 1988, Hardner *et al.* 2009). Of the four species of macadamia used for commercial breeding, only *M. integrifolia*, *M. tetraphylla* and their hybrids can be eaten raw; the remaining species of the genus *Macadamia* are inedible or toxic due to cyanogenic glycosides present in the fruit (this includes *M. jansenii* and mature *M. ternifolia* fruit) (Storey 1985 in Trueman 2013, Gross and Weston 1992 in Hardner *et al.* 2009, Dahler *et al.* 1995 in Trueman 2013).

Macadamia ternifolia bears tiny fruit with a bitter flavour (McConachie 1980), and has been used, to a lesser extent than *M. integrifolia* and *M. tetraphylla*, in three-way crossing cultivar trials. High levels of cyanogenic glycosides are also present in *M. integrifolia* embryos prior to shell hardening, but decline with maturity (Hardner *et al.* 2009). Dahler *et al.* (1995 in Trueman 2013) and O'Neill (1997 in Hardner *et al.* 2009) found extremely high levels in germinating seeds and tissue of young seedlings of *M. integrifolia*, *M. tetraphylla*, and *M. ternifolia* and suggested that this may be an adaptation by the plant to reduce herbivory.

2.3.1 Propagation

Macadamias are propagated vegetatively, as are most commercially grown nut trees, which ensures that the characteristics of the "mother trees" are passed on and that uniformity throughout the orchard is maintained (Froneman 2003). Macadamias can be propagated in a number of ways; from cuttings and clonal rootstocks (Stephenson 1990 in Hardner *et al.* 2009, Trochoulias 1992 in Hardner *et al.* 2009, Wiid and Hobson 1996, Froneman 2003), grafting scions onto seedling rootstock (Stephenson 1990 in Hardner *et al.* 2009, Nagao and Hirae 1992 in Trueman 2013, Froneman 2003), and through tissue-culture (Xiao *et al.* 2002a in Hardner *et al.* 2009, Bhalla and Mulwa 2003, Mulwa and Bhalla 2007, Garcia *et al.* 2013).

Cuttings entail taking leafy twigs and rooting them in a mist bed to propagate rootstock which is genetically identical to the (mother tree) plant material chosen for its superior production traits.

To produce suitable rootstock for grafting, *M. integrifolia* or *M. tetraphylla* seed are planted. In Hawaii *M. tetraphylla* hybrids, such as Beaumont, grow faster and more uniformly than *M. integrifolia* seedlings (Froneman 2003). In South Africa, the seed of two cultivars, Nelmak 2 and Beaumont, have a high germination success; after 15 to 18 months the seedlings are ready for grafting (Froneman 2003).

Graftwood should ideally be about a year old before it is cut from the mother tree. In grafting a long sloping cut is made on the rootstock and a similar cut is made to the scion to match the edges together. The scion is tightly tied to the rootstock, cut edges joined, with Parafilm® grafting tape. Once the buds begin to swell, after about 2 weeks, the tape is slit just above the buds. After more vegetative growth, a strong, straight shoot is chosen as the central leader, the other shoots are pruned accordingly. Trees propagated by grafting usually begin bearing a crop between 3 and 6 years (Stephenson 1990 in Hardner *et al.* 2009, Nagao and Hirae 1992 in Trueman 2013, Oosthuizen 1992). Budding is another method of vegetative propagation when limited material is available, it uses the same basic principles as grafting but only a single bud and small amount of bark are propagated.

Research into propagating both *M. integrifolia* (Garcia *et al.* 2013) and *M. tetrophylla* (Mulwa and Bhalla 2007, Xiao *et al.* 2002b in Hardner *et al.* 2009) by in vitro tissue-culture is becoming an additional way of macadamia propagation (Bhalla and Mulwa 2003).

2.3.2 Root system

Macadamias' root systems are adapted to extract moisture and nutrients from organic matter and phosphorus-deficient, acidic, poor soils in their native Australian rainforests. The root system comprises surface feeder roots, a proliferation of lateral fibrous root hairs which form nodules (Wiid-Hobson 2003a, Weston 2007), and about three minor tap or "dropper" roots which extract moisture from up to 1.6 m beneath the surface (Wiid-Hobson 2003a, Carr 2013). The lateral roots form an extensive shallow radius and extend the root surface area to utilize nutrients from decomposing organic matter in the leaf litter and soil layers. The roots exude carboxylates which make phosphorus available for absorption by the plant (Wiid-Hobson 2003a). The lateral roots usually shrivel at the end of the growing season and re-grow the following season. The adaptation of the root system however has also made macadamia trees more intolerant of fertilizers and vulnerable to die-back caused by the fungal disease *Phytophthora*.

It takes at least 10 years for a macadamia tree to establish maximum canopy cover, during which time soil management is crucial (Wiid-Hobson 2003a). To ensure healthy growth and productivity of macadamia trees, organic matter should always be available, especially over periods of high temperatures so as not to cause stress to the root system. Just as hot, dry conditions stress the roots, so do waterlogged, wet conditions. Soil pH also needs to be checked regularly as the tree grows; there are periods of intense leaching and the acidifying effects of fertilizers which cause the pH to change. This in turn can lead to nutrient deficiencies or precipitate heavy metal toxicity in the tree (Wiid-Hobson 2003a).

2.3.3 Leaves and new flush

The leaves of different Proteaceae species are highly variable although most mature leaves are very thick and leathery with the venation emanating from a central axis. Leaves can be toothed, lobed and toothed, or simple, and variation between shapes during development is a prominent trait of some rain forest Proteaceae species (Weston 2007). *Macadamia integrifolia* and *M. ternifolia* form three leaves in a nodal whorl, whereas *M. tetraphylla* forms four-leaf whorls (Wiid-Hobson 2003a, Orwa *et al.* 2009, Trueman 2013). The new flush of *Macadamia integrifolia* is light green and *M. ternifolia* and *M. tetraphylla* both have pink or red new flush (Hardner *et al.* 2009).

Macadamias produce carbohydrates that are stored as reserves to meet the high-energy demand required for producing the oil-rich nuts. New flush not only increases the accumulation of carbohydrates through photosynthesis, but develops into shoots and future nut-bearing wood. In Australia, the main new flush peaks occur in late summer and early spring (Stephenson *et al.* 1986). It has been shown that the summer flush is the major event between the two, producing up to ten times the new growth of the spring flush (Stephenson and Gallagher 1983, Stephenson *et al.* 1986).

2.3.3.1 Effects of temperature and rainfall on new flush

In cultivating macadamia, it is vital that the balance be maintained between resources used for vegetative flush and those for yield; good farming practices, such as pruning, help to maintain long-term productivity in an orchard. To be able to produce the necessary reserves for the next season's crop, new growth needs to be encouraged, yet controlled, as excessive vegetative growth will compete with developing nuts for these resources (Stephenson *et al.* 1986). New growth is regulated by both minimum and maximum temperatures, the optimum temperatures being 16-25°C. Temperatures below 10°C restrict vegetative growth, and those above 30°C have an abnormal effect (Trochoulias and Lahav 1983, Stephenson *et al.* 1986), substantially lowering the rate of photosynthesis in the leaves (Allan and de Jager 1978).

Temperature is a significant factor in determining when flushing events occurred (Stephenson *et al.* 1986). No correlation was found between the presence of flush and rainfall; however, the amount of rainfall did influence the amount of flush produced.

In Hawaii, however, macadamia trees are not synchronous and new flush on young shoots occurs throughout most of the year. The spring and autumn new flush produced most of the racemes for nut-set and subsequently the annual crop (Nagao *et al.* 1994).

2.3.4 Flowers

Flowers of most of the genera making up the Proteaceae are used as a diagnostic key for identification; the racemes are often impressively large and consist of a collective cluster of many small flowers, either packed closely together forming a "head" or along an axis. Botanically, macadamia flowers are known as "perfect flowers" or "bisexual", which means they contain functional reproductive organs (both female carpels and male stamens); the genus is hermaphroditic (Scholefield 1982). The floral anatomy and morphology of *M. ternifolia* was described in 1938 by Kausik (cited in Scholefield 1982), and in 1954 by Urata; the developmental stages and opening of the flowers was described by Vogel in 1957 (Scholefield 1982).

Three floral buds form longitudinally in the axil of each leaf in a whorl, but usually only the top bud shoots to produce a raceme (Storey 1985 in Trueman 2013, Orwa *et al.* 2009, Wilkie *et al.* 2009), which is attached to stems or branches on wood that is usually two or more years-old (Wiid-Hobson 2003a, Trueman 2013). These racemes are pendulous, and 10-45 cm long. Bud growth is protracted for 50-96 days after initiation (Moncur *et al.* 1985). Between 100 and 300 flowers develop on a single raceme (Urata 1954, Ito 1980, Trueman 2013). Hardner *et al.* (2009) reported mature trees, over 15 years old, produced approximately 10,000 racemes. Only between 0.3% (Ito 1980) and 0.6% (Sakai and Nagao 1985) of these blossoms set nuts and reach maturity (Moncur 1988).

Macadamia integrifolia bears white inflorescences and *M. tetraphylla* pink, white or cream; hybrids of these two species produce white and pink inflorescences (i.e. 695 (Beaumont) and Nelmak 1 pink, and Nelmak 2 white). Flower initiation begins with the shortening of day length (autumn/winter) and night temperatures between 11°C and 15°C (Wiid-Hobson 2003a, Trueman, 2013).

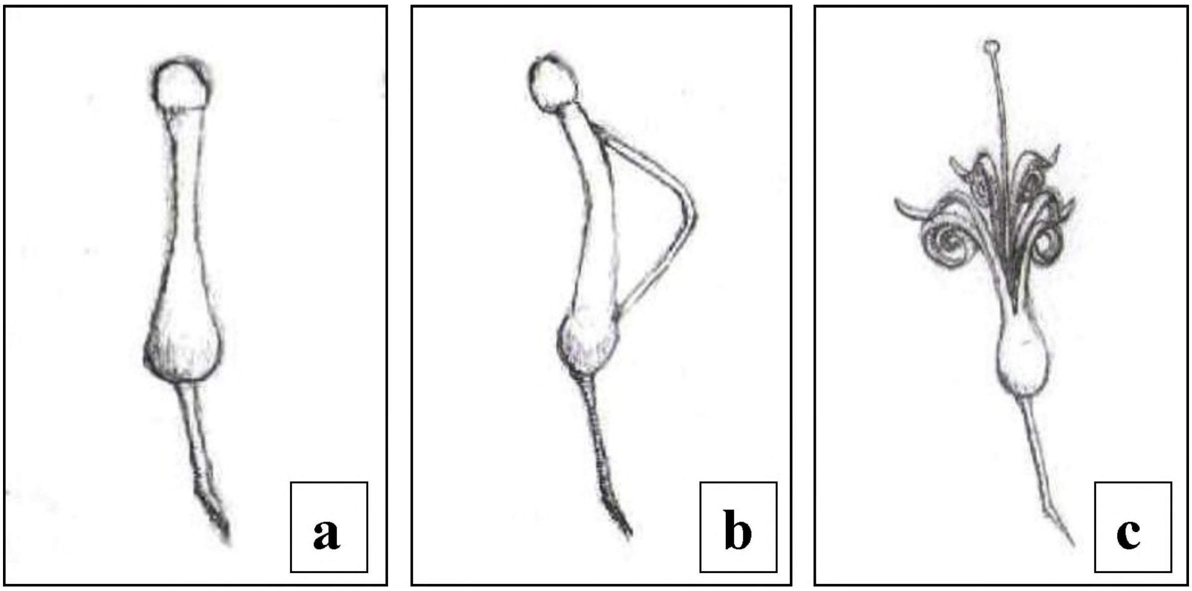
2.3.4.1 Flower morphology

The outermost structure enveloping the sexual organs of a flower, comprising the calyx (sepals) and corolla (petals), is known as the perianth (Barth 1991). In macadamia, the perianth is uniseriate, with the four petal-like segments, the tepals, fused together forming a single, long, narrow whorl around the stamens and pistil with a closed "cup" at the tip (Scholefield 1982, Storey 1985 in Trueman 2013, Tavares 2013, Trueman 2013). The botanical term "tepal" is used when there is no distinction in the colour, shape or other characteristics, by which one can separate the sepals and petals except by their position (Tavares 2013). The filaments of the four stamens are joined to each of the four tepals; the pollen-producing anthers are therefore also enclosed within the apical cup.

With the development of the flower, the pistil grows rapidly, passing through the perianth tube. Styles begin elongating 6-7 days before anthesis (when the flower becomes fully open, produces nectar and is mature). Once the style tip reaches the "cup" within, the perianth and can progress no further, it bends, pressing against the perianth which then splits along one of the tepals' "fused seams" (Scholefield 1982); this takes place 2-5 days before anthesis (Urata 1954, Sedgley *et al.* 1985) (Figs. 2.1 a-c). Separation of the tepal segments occurs from the tip; these curl outwards exposing the four anthers joined at their apex and the pistil. The tip of the style terminates in a small, club-shaped stigma, covered with papillae that extend down a furrow in the style, and to which the pollen adheres (Kausik 1938 in Scholefield 1982).

The stigma functions as a "pollen-presenter", another common, highly specialized trait among most of the genera in the Proteaceae (Scholefield 1982, Tavares 2013). Thus, insects foraging for pollen come into contact with the pollen-presenter, as do those in search of nectar, thereby also facilitating pollination. A few days after pollination only the ovary, style and stigma remain attached to the raceme, the tepals and other sections of the flower have dried and abscised.

Anthesis usually takes place during the morning and the open flowers remain receptive for a few days (Wiid-Hobson 2003a, Tavares 2013). The anthers dehisce 1-2 days prior to anthesis, depositing their tetrahedral-shaped pollen in clumps on the stigma and upper style (Sedgley *et al.* 1985, Moncur 1988, Trueman 2013). Maximum pollen germination and pollen tube growth occurs when the flower is 3 days old, and the stigma becomes fully receptive 2 days after anthesis (Sedgley *et al.* 1985, Moncur 1988, Trueman 2013).



Figures 2.1 Macadamia **a.** closed bud; **b.** flower at anthesis; **c.** fully open flower. (Courtesy of K.J. van Zuydam*)*.

Protandry is the term used when pollen ripens before the stigma becomes mature (Barth, 1991); macadamia flowers are therefore protandrous (Orwa *et al.* 2009, Tavares 2013). Fertilization takes place within 1 week of anthesis (Ito 1980, Sedgley 1983) and usually only one of the two ovules is fertilized (Sedgley 1981, Trueman and Turnbull 1994a in Trueman 2013). Anthesis progresses basipetally along the racemes (Urata 1954), but can also start at the centre or from both end points of the raceme depending on cultivar and environmental conditions (Trueman 2013).

The rapid abscission of infertile flowers occurs around two weeks after anthesis. Urata (1954) reported that >90% of the flowers abscise; these were mostly pollinated but remained infertile (Sakai and Nagao 1985). Initial nut-set can be observed 1-3 weeks post-pollination as the swelling of the ovary becomes evident (Trueman 2013).

2.3.4.2 Effects of temperature and rainfall on flowering

Moncur *et al.* (1985) stated that temperature changes in sub-tropical regions are usually of greater significance than rainfall and moisture components; even though these two factors generally provide the major stimuli to plants found in tropical latitudes. The authors reported that, after a rise in temperature and some rainfall, raceme elongation began and bud dormancy in macadamia broke. During their study, it was noted that raceme elongation began at the coolest sites first, suggesting that cooler temperatures may be required for floral development (Moncur *et al.* 1985). During the flowering period, water stress can cause desiccation to the perianth (the outer part of the flower) and as a result pollination may fail (Stephenson and Trochoulias 1994).

The initiation of lower temperatures to break bud dormancy and promote flower development has been reported for other crops: *Coffea* L. (Mes 1957); jojoba, *Simmondsia chinensis* (Link) (Dunstone 1980 in Moncur *et al.* 1985); and mango, *Mangifera indica* L. (Ravishankar *et al.* 1979). Browning (1977 in Moncur *et al.* 1985), suggested that rainfall operates as a flowering stimulus in *Coffea arabica* by lowering the temperature of the plant.

2.3.4.3 Anthesis

In the main growing areas in Australia anthesis occurs over approximately five weeks (Moncur *et al.* 1985, Boyton and Hardner 2002) depending on cultivar. In Hawaii, the flowering period alone may be prolonged and last up to 30 weeks in total (November through May), with three distinct peaks occurring late January to early April (Nagao and Sakai 1988 in Trueman 2013, Nagao and Sakai 1990 in Trueman 2013, Nagao *et al.* 1992 in Hardner *et al.* 2009, Nagao *et al.* 1994). This protracted flowering period of macadamia in Hawaii, which extends over several months, bears a marked difference to macadamias grown in the southern hemisphere, where the timing of developmental stages is very similar both in South Africa and Australia. In South Africa, fruit development in macadamia from full flowering (anthesis) usually around September/October, to kernel maturity and harvest (April/May), takes approximately 30 weeks (Wiid-Hobson 2003a) (Chapter 4). When anthesis is protracted or late, as in Hawaii, this results in an overlap of the flowering period and the time at which the photosynthesis rate in the leaves is high. With the excessive production of flowers by the tree, these lost resources could have a negative impact on overall production and yield (Moncur *et al.* 1985).

2.3.5 Pollination

Macadamia are protandrous which diminishes the chances of self-pollination and increases the potential for out-crossing. As the “pollen presenter” of the stigma is fairly small, and the pollen grains adhere to the papillae, it is thought that wind pollination is somewhat limited (Urata 1954, Scholefield 1982). The excessive production of flowers, floral display, and the presence of nectaries strongly signifies that insects are the principal agents of pollination (Urata 1954, McGregor 1976 in Scholefield 1982, Heard 1994).

The duration of the flowering period has implications for cross-pollination which are caused by genetic variation and environmental effects (i.e. rainfall and temperature). Certain macadamia cultivars are early-bearing and others late-bearing (Hardner *et al.* 2009). According to Nagao and Hirae (1992 in Trueman 2013), variability of the commencement of flowering (within and between trees of a cultivar orchard) is more inconsistent than that among different cultivar orchards (Trueman 2013). In their study on the phenology of flowering and nut production in macadamia, Boyton and Hardner (2002) found significant genetic variation in the initiation and duration of flowering, nut-set and the commencement of nut-drop, but only a small genetic variation with respect to the duration of nut-drop. They reported that the most variation between all traits was recorded among racemes within the same tree; this variance was even greater than that between trees of different cultivars. The trait most influenced by genetic control was the onset of flowering. The trees flowered over a period of 33 days; racemes took, on average, 3.2 days between when the first flowers started to open until all the flowers were fully open.

Research into the cross-pollination of macadamia has shown significant results for initial nut-set (Sedgley *et al.* 1990 in Trueman 2013), and improved yield (Ito and Hamilton 1980 in Scholefield 1982, Trueman and Turnbull 1994a in Trueman 2013, McConchie *et al.* 1996, Wallace *et al.* 1996 in Trueman 2013). Urata (1954) first reported that some cultivars are, to a degree, self-incompatible; this was later corroborated by Ito and Hamilton in 1980 in Scholefield 1982. In orchard studies, Sedgley *et al.* (1990 in Trueman 2013) found *M. integrifolia* to have a "partial gametophytic self-incompatible" reproductive system, which would promote out-crossing and limit self-fertilization in natural populations. The progeny were almost entirely as a result of out-crossing; no "selfing" (self-pollination) or biparental inbreeding occurred. Research on wild populations of *M. integrifolia* found no optimal crossing distance or effect of genetic relationship including "selfing" on nut-set (Neal 2007 in Hardner *et al.* 2009). This suggests nut-set in wild populations is more likely to be resource-limited rather than pollen-limited (Neal 2007 in Hardner *et al.* 2009). Some cultivars are however self-compatible, and produce fruit through self-pollination (Scholefield 1982, Tavares 2013).

Of the insects pollinating macadamias, the European honeybee, *Apis mellifera* L., (Hymenoptera: *Apis*) is the major pollinator (Urata 1954, Heard 1994, Heard and Exley 1994, Wallace *et al.* 1996 in Trueman 2013, Wiid-Hobson 2003a, Tavares 2013). *Apis mellifera* workers are able to forage over kilometres; studies on pollen-flow have shown cross-pollination to occur over hundreds of meters and across rows in orchards (Vithanage *et al.* 2003), and distances of several kilometres were substantiated by paternity analyses (Neal 2007 in Hardner *et al.* 2009). Urata (1954) observed honeybees to have a preference for macadamia pollen, and fruit-set measured 15-20 days after anthesis, was higher on open-pollinated racemes than racemes bagged to prevent insect pollination (Trueman 2013); syrphid flies were also observed pollinating macadamias (Urata 1954). In Australia, the indigenous stingless bees (*Tetragonula* spp. formerly *Trigona* spp.) commonly pollinate macadamias (Neal 2007 in Hardner *et al.* 2009, Tavares 2013, Trueman 2013).

The facultative nature of out-breeding and the apparently excessive production of racemes, of which the majority abscise, pose challenging opportunities for the development of macadamias cultivars for commercial cropping.

2.3.6 Fruit

The macadamia fruit is described in botanical terms as a "follicle"; the dry outer casing enveloping a seed formed from a single carpel, with a longitudinal line of dehiscence (Strohschen 1986). The fruit contains a small subglobose embryo (kernel), two semiglobose cotyledons enclosed in a hard, woody outer testa (shell) and a fibrous outer dehiscent pericarp (husk) (Strohschen 1986, Trueman 2013). *Macadamia integrifolia* is known as the "smooth-shelled" macadamia, whereas *M. tetraphylla* is termed "rough-shelled".

Fruit retention is strongly correlated to the available carbohydrate levels in the tree, and abscission may be attributed to the plant adjusting to the crop load prior to biomass accumulation (Trueman and Turnbull 1994b in Trueman 2013). Depending on site and cultivar, immature fruit-drop can continue up until 15 weeks after anthesis (Trueman 2013). From around 2-3 weeks post-anthesis, small developing fruit abscise at an excessively high rate, >80% (Urata 1954); the second occurrence of high abscission is at weeks 5-7, then again at week 10. Thereafter only a moderate rate of abscission occurs, which may be due to insect pressure or disease (Sakai and Nagao 1985, Trueman and Turnbull 1994b in Trueman 2013).

The fruit continues to develop in diameter until 15-16 weeks after anthesis (Sakai and Nagao 1985, Nagao and Hirae 1992 in Trueman 2013, Trueman and Turnbull 1994b in Trueman 2013); biomass accumulation is from 13-24 weeks, by which time the fruit would have reached optimal size and the shell has hardened (Jones W.W. 1937, 1939, Jones V.P. 1994, Trueman and Turnbull 1994b in Trueman 2013). Until 12-15 weeks the oil content of the developing embryo is low; but then oil accumulates rapidly until 23-25 weeks (Jones W.W. 1937, 1939, Baigent 1983 cited in Hardner *et al.* 2009, McConchie *et al.* 1996, Trueman *et al.* 2000 in Trueman 2013), and the fruit mass increases until around week 24 (Trueman and Turnbull 1994a in Trueman 2013, McConchie *et al.* 1996, Trueman 2013). The fruit mature six to nine months after initial fruit-set.

Initially it was thought that the dehiscence of the husk indicated maturity of the fruit (Cheel and Morrison 1935 in Hardner *et al.* 2009, Wills 1939 cited in Hardner *et al.* 2009, Leverington 1958 cited in Hardner *et al.* 2009). Later studies have shown that dehiscence occurs well after maximum oil content of the kernel has been reached, generally once the fruit has abscised from the tree (Trueman *et al.* 2000 in Trueman 2013). In Australia, mature fruit-drop occurs approximately 24 to 46 weeks after anthesis, between March and July. Fruit abscission in Hawaii happens over an extended period, August and April (Ito 1984 in Scholefield 1982, Nagao and Hirae 1992 in Trueman 2013); combined with the prolonged flowering period, this results in flowers and fruit at various developmental stages being simultaneously present on the same tree (Hardener *et al.* 2009). Under these conditions this is not only problematical with regards to normal farming practices (i.e. pruning, application of chemicals, costs of harvesting, *et cetera*), but also the continual presence of various plant phenological stages increases pest pressure (Stephenson and Gallagher 2000 in Trueman 2013).

The fruit of most cultivars abscise at maturity; but there are some cultivars which are “stick tights” and need to be harvested by hand, the most well-known being 695 (Beaumont) (Wiid-Hobson 2003b). Fruit-drop can be induced by applying an ethylene-generating compound, (2-chloroethyl) phosphonic acid (Ethaphon), or using mechanical shakers (Nagao and Hirae 1992 in Trueman 2013, Trueman *et al.* 2002 in Trueman 2013). Salter *et al.* (2003) showed significant leaf loss between cultivars when Ethaphon was applied to different cultivars.

Mature fruit that abscised are collected from the orchard floor at regular intervals. The nuts are then mechanically de-husked and the nut-in-shell dried to around 1.5% kernel moisture content at low temperatures. Once dried, nuts are cracked and their kernel extracted and graded (Trueman 2013).

2.4 Historical background of macadamia cultivation in South Africa

South African germplasm can be traced back to importations from Hawaii, Australia and California (Hardner *et al.* 2009). In 1931 macadamia seeds were imported from Hawaii to South Africa (McConachie 1980, Peace *et al.* 2005 in Hardner *et al.* 2009). The next recorded introduction was by the Reim family of Hillcrest, KwaZulu-Natal; *M. integrifolia* and then *M. tetraphylla* seed was imported from Australia in 1935 (Reim 1991). A further supply of *M. tetraphylla* seed was imported and it is from these that the Reim family's original orchards were established; seeds from the initial yields were used to extend the orchards. The Reim family established a macadamia nursery, selling macadamia seedlings and distributing over 60,000 plants to other parts of the country (Reim 1991). Macadamias have only been grown since the 1960s and 1970s along the south coast of KwaZulu-Natal (Garlick 1991).

In 1968 the Beaumont (695) cultivar was introduced to South Africa from California (Wiid and Hobson 1996). During 1969 graft-wood of the older Hawaiian cultivars introduced to South Africa became available (Allan 1995 in Hardner *et al.* 2009). In the 1970s newer cultivars and selections were introduced (Hardner *et al.* 2009). As was reported in Australia, the early Hawaiian cultivars did not perform well in South Africa either. It has been suggested that *M. integrifolia* cultivars do not adapt as well to the cooler subtropical conditions of South Africa as the cultivars of hybrid origin (Wiid and Hobson 1996, McCubbin and Lee 1996, Allan *et al.* 1999). Professor Peter Allan of the Horticultural Science Department, Natal University, Pietermaritzburg, Kwa-Zulu Natal has, over a period of thirty years, been instrumental in the importation of cultivars from Hawaii and Australia and selection trials to scientifically evaluate performance under South Africa conditions (Anon. 2011).

The first three South African hybrid cultivars were developed in the 1970s; Nelmak 1, Nelmak 2 and Nelmak 26 were derived from natural and artificially cross-pollinated *M. integrifolia* and *M. tetraphylla*, and released by the Agricultural Research Council Institute of Tropical and Subtropical Crops (ARC-ITSC) in Nelspruit (Wiid-Hobson 2003b). Of these, only Nelmak 2 performed well with good yields and kernel recovery. During 2002 a new South African cultivar, Nelmak D, was registered with improved characteristics of the Nelmak 2 cultivar (Wiid-Hobson 2003b). In 2013 Nelmak 2 plantings constituted 5.9% and Nelmak D 0.3% of the most commonly grown cultivars in South Africa (Anon. 2013a); the two-remaining hybrid Nelmak cultivars represent a small fraction of the cultivars commercially grown (Chapter 1, Fig. 1.1).

In Limpopo Province, the earliest plantings in Levubu date back to the late 1950s and early 1960s (Ahrens 1991). Seedlings were acquired from the Reim family and introduced in the Letaba (Tzaneen) area (Hobson 1991). In Vhembe, there is an increasing number of macadamia growers; this is an emerging "growth point" in South African production. The Subtrop Census for 2012 reported that the trees in Vhembe accounted for 6% of the total number of trees planted, and 10% of the total area under macadamia cultivation (Anon. 2013a). Mpumalanga Province is the largest macadamia growing area in the country, although macadamias only became a key commercial crop around 1970; before this it was a major tobacco producing region, which was very lucrative (Schormann, 1991).

South Africa was ranked first in the estimated 2014/2015 world macadamia production and export of both nut-in-shell (NIS) and on a kernel production basis (Tables 2.1 and 2.2) (Subtrop 2013, Anon. 2014, Henning 2014).

Table 2.1 Estimated world macadamia production and exports for 2013/2014 and 2014/2015 (nut-in-shell (NIS) at 10% moisture content) in metric tons (from Henning 2014 and International Fruit & Nut Council – Anon. 2014).

Country	2013/2014 NIS Production	2013/2014 NIS Exports	2014/2015 NIS Production	2014/2015 NIS Exports
South Africa	39,785	12,000	46,237	26,000
Australia	35,200	4,000	40,000	8,000
Guatemala	7,800	-	8,400	-
USA (Hawaii)	18,900	-	18,900	-
China*	5,000	-	5,000	-
Kenya	22,320	1,250	23,436	5,000
Malawi	4,946	-	5,948	-
Brazil	4,800	-	5,000	-
Others	5,629	-	5,710	-
World Total	**144,380**		**158,631**	

* Processing country – No individual data

Table 2.2 World macadamia exports (kernel equivalent basis) 2012 and 2013/2014 and 2014/2015, in metric tons (from Subtrop 2013, and International Fruit & Nut Council – Anon. 2014).

Country	2012 Estimated Kernel Production	2012 Kernel Exports	2013 Estimated Kernel Production	2013 Kernel Exports	2014 Estimated Kernel Production
South Africa	9,980	9,680	10,187	6,339	14,100
Australia	12,090	6,680	10,500	5,470	13,146
Guatemala	2,260	1,793	1,460	1,453	1,650
USA (Hawaii)	6,898	1,743	6,510	1,475	3,600
China*	-	6,598	1,200	2,148	1,540
Kenya	6,123	-	4,940	-	5,448
Malawi	1,619	-	1,847	-	1,813
Others	3,640	7,277	1,307	3,474	2,907
World Total	**42,150**	**35,288**	**37,951**	**20,359**	**44,204**

* Processing country – No individual data

2.5 Macadamia cultivation in South Africa

Macadamia tetraphylla originated in the cooler regions of New South Wales (2500 heat units), and *M. integrifolia* (2900 heat units) in the warmer areas of Queensland. Plants are able to survive low temperatures but the cut-off temperature for growth is around 10°C (Trochoulias and Lavhav 1983 in Stephenson *et al.* 1986, Wiid-Hobson 2003a). An assessment can be made of suitable climatic areas in South Africa in which to grow macadamia by considering heat units and cultivar requirements. Heat units are calculated using the number of degrees the daily mean temperature is over the minimum growth temperature (12.5°C), for each day of the growing season (maximum + minimum temperature ÷ 2 – threshold temperature 12.5°C = heat units) (Moncur *et al.* 1985, Wiid-Hobson 2003a).

The areas of origin in Australia share the same 25°C to 29°C-zone latitude as the KwaZulu-Natal north coast and the south-east Mpumalanga Lowveld in South Africa. The macadamia growing areas extend from the KwaZulu-Natal coast, Port Shepstone to Richards

Bay, moving inland through KwaZulu-Natal, Swaziland and Nelspruit in eastern Mpumalanga, up to Tzaneen and Louis Trichardt in Limpopo. Plantings of macadamias have also been made in the Eastern Cape through to Mossel Bay (34°S) in the Western Cape (Wiid-Hobson 2003a). In areas where frost occurs, *M. tetraphylla* and crosses of *M. tetraphylla* and *M. integrifolia* are hardier than *M. integrifolia* and the Hawaiian *M. integrifolia* cultivars (Wiid-Hobson 2003a).

2.5.1 Most commonly grown cultivars in South Africa

The tree census conducted in 2013 gathered a lot of extremely important data (Anon. 2013a). One of the factors investigated was the most commonly grown cultivars in South Africa (Chapter 1, Fig. 1.1). Importation of seeds, scions, bud-wood *et cetera* has occurred in South Africa over the past eighty years. As with any introduced plant, the imported cultivars needed to adapt to the environmental conditions and resources of the adoptive country to reach their full yield potential. Many selections have been tested to ascertain which cultivars are the most productive under South African conditions. Presently the cultivar which makes up 31% of the total plantings in South Africa is 695 (Beaumont), which seems to adapt more readily to the climatic and environmental conditions.

2.6 Production in South Africa

An overview of the macadamia industry reports that since macadamias were first grown commercially during the 1960s, South Africa has become a major member, competing with Australia as the leading producer worldwide (Anon. 2013a).

There are approximately 450 macadamia growers in South Africa and new plantings have increased the number of trees from around 1 million in 1996 to close on 5.4 million in 2013; covering an area of 17 821 hectares (Table 2.3). Macadamias are arguably the fastest growing tree crop industry in South Africa; production having increased more than 23-fold during the past 20 years (Nortjé 2012, Anon. 2013a).

Table 2.3 Hectares (17,821) planted to macadamias in South Africa, shown by Province (Nortjé 2012).

Province	Hectares planted to macadamias
Limpopo	4,758
Mpumalanga and Swaziland	8,024
KwaZulu-Natal	3,701

Eastern Cape	302
Emerging Growers (Vhembe)	1,036
Total:	**17,821**

Throughout the growing regions, a number of young plantings have been made which are as yet too young to produce much of a yield. The South African macadamia industry is steadily expanding, and these young plantings will ensure an increase in production in the years to come (Table 2.4) (Nortjé 2012; Anon. 2013a).

Table 2.4 Number of macadamia trees in South Africa shown by Province (Nortjé 2012).

Province	**Number of Trees Planted**
Limpopo	1,441,674
Mpumalanga and Swaziland	2,431,272
KwaZulu-Natal	1,121,403
Eastern Cape	91,506
Emerging Growers (Vhembe)	313,908
Total:	**5,399,763**

The cash value of the annual product increased from R32 million in 1996 to over R1.25 billion in 2014. More than 95% of the annual crop is exported internationally; the main markets are in the Far East, Europe, the USA, Canada and the Middle East (Anon. 2013b, 2014, Henning 2014).

According to the International Fruit and Nut Council (INC), South African edible kernel exported from South Africa in 1992 was 413 metric tons; this increased to 9,680 metric tons in 2012 (Table 2.2) (Anon. 2013b, 2014).

2.7 Conclusion

From the first plantings in Hawaii 134 years ago, macadamias are becoming a much sought after product worldwide with demand being higher than supply. In terms of world production on a kernel basis, macadamia is ranked seventh, after almonds, walnuts, pistachios, cashews, hazel nuts and pecans. Statistics provided by the International Nut and Dried Fruit Council (INC) for 2014 show macadamia production rose to 44,204 (kernel basis) metric tons, which only accounts for 1.2% of the total worldwide tree nut production (Buthelezi 2015). Production is presently increasing on a basis of 10% annually (Buthelezi 2015). With major annual growth in the industry and high consumer demand, the cultivation and production of macadamias in South Africa looks extremely positive.

3 Thrips (Thysanoptera): Their Biology and a Review of Thrips in Tropical and Subtropical Crops in South Africa

3.1 Introduction

More than a century ago, many of the early applied entomologists worked on larger, more obvious insect pests; very few specialized in studying thrips (Thysanoptera). Perhaps this was because of the insects' size and fragility, the extreme care with which specimens need to be handled, and the time involved in preparing specimens for identification (Lewis 1997a). Around 1900 interest in studying thrips increased, with researchers describing and naming many species in the 1920s and 1930s (Lewis 1997a). Since Pittman's discovery in 1927 that some thrips species transmit a "spotted wilt" disease to plants, extensive research has been initiated on thrips as vectors of plant virus diseases (Lewis 1997a).

As commercial food production and worldwide trade patterns change over the years, the spread of endemic and exotic thrips species has escalated; endemic species adapting to new host plants and exotic species exploiting new areas (Mound 1983). A catalogue of South African thrips species published by zur Strassen in 1960 was later updated by him in 2006, increasing the number of thrips species known for South Africa to 280 (zur Strassen 1960, 2006). Further extensive taxonomic studies have been conducted on species of the genus *Thrips* Linnaeus from the Afrotropical Region (Mound 2010) and the genus *Scirtothrips* from Africa (Mound and Stiller 2011), increasing the number of thrips species to 284.

Thysanoptera is currently divided into two suborders, Terebrantia which consists of eight families, and Tubulifera of one family (Mound, 2013a); these comprise an estimated 8000 extant species (Lewis 1997a, b), of which just over 6000 species have been described (Mound 2013a). Most of the species in the Terebrantia (95%) are associated with vascular plants or are predatory, whereas the Tubulifera species are mainly fungivorous (60%), feeding on fungi, mosses, lichens, ferns, gymnosperms or cycads (Mound and Teulon 1995, Mound 1997, 2005, 2013b, Izzo *et al.* 2002). Scarcely 1% of thrips species are recognized as serious agricultural pests (Morse and Hoddle 2006). Some thrips species are beneficial; *Liothrips urichi* Karney was used as a biological control agent to control *Clidemia hirta* (Melostomaceae), an invasive tropical shrub, in Fiji (Lewis 1973). *Aleurodothrips fasciapennis* (Franklin) proved to be the primary predator of *Aonidiella aurantii* (Maskell), citrus red scale, in China (Beattie 1985 in Palmer *et al.* 1989). Thrips are also effective pollinators; some species are specialist, host-specific pollinators of plant species within the families Euphorbiaceae, Moraceae and Zamiaceae, whilst other thrips pollinators may be polyphagous species such as those pollinating Monimiaceae species in Australian subtropical rainforests (Mound 2005).

3.2 Thrips biology

Comprehensive studies on the morphology, biology and ecology of Thysanoptera have been documented by Lewis (1973), Moritz (1997), Mound and Walker (1982 in Mound 2005), Ananthakrishnan (1993), Kirk (1984, 1985), Palmer *et al.* (1989), Palmer (1990), Mound and Teulon (1995) and Mound (2005).

3.2.1 Morphology

The name of the order Thysanoptera is derived from the Latin, “thysanos” meaning fringe and “ptera” wings. Thrips are minute, slender-bodied insects, 0.5 to 2 mm long; some tropical and subtropical species of the suborder Tubulifera may grow to 15 mm. These insects are “torpedo” shaped, their body dorsoventrally flattened. Body pigmentation varies from white, yellow, brown, dark brown and black.

In adults, the antennae project forwards from the head, which is attached to a prothorax, a fused pterothorax, and an 11-segmented abdomen. Species of both the suborders, Terebrantia and Tubulifera, share a unique structural characteristic: only the left mandible is fully developed, and the right mandible degenerates during embryogenesis and is reabsorbed by the embryo (Hemming 1993 in Mound 2005, Kirk 1997a, Moritz 1997, Mound 2005).

A characteristic which distinguishes females of the two suborders is the structure of the ovipositor. Terebrantia females normally have an external, well-developed, saw-like ovipositor; Tubulifera have an elongate, tube-shaped abdominal segment X and females have internal, chute-like ovipositors (Palmer 1990, Moritz 1997).

Thrips are pterygote insects, although wings are reduced or absent in some species (Mound 2005). In the winged species, two pairs of fringed wings are attached to the pterothorax. The fore and hind wings have coupling adaptations which link the wings whilst at rest and in flight so that they beat synchronously; the ciliary fringes functionally increase the wing surface area (Moritz 1997).

Another feature of the winged species is that, in addition to a pair of multi-faceted compound eyes, three ocelli are situated dorsally on the head in a triangular configuration between the compound eyes (Moritz 1997).

Thrips have "punch and suck" mouthparts formed into a ventral mouth cone (Kirk 1997a, 1997b). Thrips puncture the substrate with a sharp downward movement of their head, thrusting the solitary left mandible into the food source. The maxillary stylets are then inserted through the aperture and stab the epidermal, palisade and spongy mesophyll cells, facilitating a steady uptake of liquids, leaving collapsed cell walls (Mound 1971, Wiesenborn and Morse 1988, Kirk 1997b, Moritz 1997). The cibarial muscles create sufficient suction to draw the plant cell liquid up the feeding tube; this is alternated with the salivary pump injecting saliva into the plant tissue through the feeding tube (Mound 2005). The feeding tube structure is the same in larvae and adults. Species of the Idolothripinae have broader stylets, creating a wider feeding tube and enabling them to ingest whole fungal spores (Mound 2005).

Thysanoptera adults have characteristic pretarsi where a bladder-like protrusion, the arolium, is located. Whilst walking, these are in contact with the substrate, enabling thrips to adhere even to smooth surfaces without being dislodged.

3.2.2 Reproduction

In most species the sex ratio is more or less equal (Palmer 1990). However, parthenogenic reproduction is common in thrips species; offspring arising from unfertilized eggs, females through thelytoky and males through arrhenotoky. In a few species, obligate parthenogenesis occurs resulting in mostly all-female progeny, rarely males, which is known as deuterotoky (Moritz 1997).

Most thrips are oviparous (eggs hatch after they have been laid), although a few of the larger species are ovoviviparous (eggs hatch within the female's body), or even viviparous (bring forth live young) (Palmer 1990). In the Terebrantia only a single egg develops at a time. The female uses her saw-like ovipositor to make an incision into the plant tissue where she lays the egg. In the Tubulifera, several eggs develop simultaneously; the female lays these eggs in succession which are adhered to the substrate of the plant, in crevices or under bark.

3.2.3 Life cycle

Metamorphosis in Thysanoptera is complex; the egg is followed by two larval stages with no external wing development, the propupa(e) and pupal stages with external wing bud formations present, followed by the eclosion of the adult. Thus, the life cycle of thrips is a permutation of both holometabolous (complete) and hemimetabolous (simple) metamorphosis (Nakahara 2005). Following the egg stage, the two active, feeding larval instars are followed by two (in Terebrantia) or three (in Tubulifera) pupal instars, and finally an adult. The propupa(e) are relatively inactive and do not feed, their wing buds start to develop and the antennae form short, horn-like protrusions on the head. The pupae are also non-feeding and quiescent, the wing buds are longer and the antennae are folded back against the head. Pupation sites are normally situated close to the feeding sites; flower-dwelling species usually pupate in the soil beneath the host plant.

Life cycle duration varies considerably between species and are strongly linked to climatic conditions and season. Humidity and, in particular, ambient temperatures, effect developmental time; during cooler temperatures thrips take considerably longer to develop than in warmer conditions. Lewis (1973) reported on the developmental times for a number of species. A very rough approximation of development at a mean temperature of around 27°C would be 19 days to complete the full cycle, egg to egg: the egg - 5 days, larva I - 2 days, larva II - 5 days, propupa - 2 days, pupa - 3 days and adult female pre-oviposition - 2 days. Adult longevity is around 38 days, longer in cooler months, and the number of eggs a female lays within this time is around 70.

3.2.4 Feeding

The Thysanoptera comprises carnivorous (arthropod and Acari predators), herbivorous (plant), mycophagous (fungi), saprophytic (dissolved organic material) and sporophagous (spore and decaying organic matter) feeding groups (Palmer *et al.* 1989, Palmer 1990, Lewis 1997a, Mound 2005). Many species have specific feeding sites; some live in flowers feeding on pollen and plant tissue (Kirk 1984), others on buds or new flush, and some prefer mature, hardened-off leaves where they feed on mesophyll cell sap (Lewis 1973). The flower-living species can be important pollinators, but when their populations increase exponentially they can cause serious economic damage to crops (Palmer 1990).

Palmer *et al.* (1989) compiled a list of thrips genera found in the Afrotropical region, including a brief description of their host plants, feeding habits and transmission of microbial pathogens (Table 3.1). Because this initial study concentrates on thrips species in Mpumalanga province, South Africa, different species may very well occur on macadamia in other regions of the country, therefore the entire list has been included here and not added as an Appendix.

Table 3.1 The most comprehensive list of thrips genera, specifically of the Afrotropical region, and damage caused was published by Palmer *et al.* 1989.

Plant-feeding species:

Family - Thripidae
Subfamily - Panchaetothripinae Adults cause leaf markings, and larvae cause the most damage by their sticky excrement on leaves which attracts fungal spores.

Subfamily - Thripinae
Tribe - Dendrothripini
Dendrothrips In the Afrotropics; feed on leaves of various herbs, shrubs and trees, particularly Oleaceae.

Tribe - Sericothripini
Scirtothrips In the Afrotropics; transmits brown spot disease.
Sericothrips Widespread distribution, mostly in legume flowers and cashew leaves and flowers in the Afrotropics.

Tribe - Chirothripini
Chirothrips Widespread distribution; found on flowers of grain crops and grasses causing seed loss.

Tribe - Thripini
Anaphothrips Found on many plants worldwide particularly grasses including sugarcane and grain crops.
Aptinothrips Feed on leaves of temperate grasslands and grain crops.
Bolacothrips In the Afrotropics; feed on grasses including sugar cane, maize and rice.
Chaetanaphothrips In the Afrotropics; transmits banana rust.
Florithrips In the Afrotropics; feed on flowers and leaves of Acacia, maize, rice, sugarcane, sorghum and grasses.
Frankliniella Flower feeders causing poor fruit-set, some species are also virus vectors. In the Afrotropics; transmits Tomato Spotted Wilt Virus (TSWV).
Mycterothrips In the Afrotropics; feed on leaves.
Thrips Worldwide distribution; feed on flowers and leaves of many plants, often polyphagous, cosmopolitan and vectors particularly of TSWV.

Family - Phlaeothripidae
Subfamily - Phlaeothripinae
Gigantothrips In the Afrotropics; causes leaf curl in figs.
Gynaikothrips Cosmopolitan; cause leaf curl and galls on many trees and shrubs, particularly fig species.
Haplothrips Cosmopolitan; polyphagous flower feeders and some leaf feeders.

Hoplandrothrips Worldwide distribution; found on dead leaves and the wood of many trees. In the Afrotropics; causes leaf margins to curl on coffee.
Liothrips Worldwide distribution; causes the rolling-up of leaf margins on many trees and shrubs.

Fungi-feeding species:

Family - Phlaeothripidae
Subfamily - Phlaeothripinae
Haplothrips Worldwide distribution; polyphagous, some species possibly feed on fungal hyphae.
Hoplandrothrips Worldwide distribution; usually feeds on fungal hyphae.

Family - Phlaeothripidae
Subfamily - Idolothripinae
Bactrothrips In the Afrotropics; feed on spores on dead leaves, mainly oak, coffee and cocoa.
Elaphrothrips Recorded in the Afrotropics; feed on spores.
Nesothrips In the Afrotropics; feed on spores, grasses and sedges.

Predatory species:

Family - Aeolothripidae
Aeolothrips In the Afrotropics; feed on mites.
Franklinothrips Recorded in the Afrotropics; in other parts of the world feed on other thrips species, mites and whitefly.

Family - Thripidae
Subfamily - Thripinae
Scolothrips Feed on tetranychid mites.

Family - Phlaeothripidae
Subfamily - Phlaeothripinae
Aleurodothrips Recorded in the Afrotropics; in other parts of the world a primary predator on citrus pests (i.e. coccids, mites, whitefly and red scale).
Haplothrips Worldwide distribution; sometimes thought to be predatory.
Karnyothrips Worldwide distribution; feed on coccids and possibly also whitefly and mites.
Podothrips In the Afrotropics; usually found in grasses, predatory on coccids.

3.2.5 Ecology

Thrips synchronize their life cycle characteristics quickly after introduction to a new region adapting to recently colonized ecosystems (Morse and Hoddle 2006). Thrips species often lack obligate diapause, so populations are continually active. Thrips are multivoltine, and have a high fecundity with short generation times, depending on ambient temperatures (Mound and Teulon 1995, Mound and Marullo 1996, Mound 1997, Worner 2002, Kirk and Terry 2003, Shelton *et al.* 2003, Morse and Hoddle 2006).

3.3 Damage to crops

Many thrips species are polyphagous, moving between host plants seasonally to feed and breed. The species richness within a crop can also greatly vary. Plants infested with thrips may not be able to photosynthesize properly, can lose a significant amount of water and dehydrate, and may become prone to pathogens through exposed damaged tissue. Many cultivated plants are severely affected by thrips, causing plant damage and a reduction in yields (Morse and Hoddle 2006). Thrips damage also impacts on the cosmetic quality of a number of commodities, causing further economic loss (Childers and Achor 1995, Childers 1997, Lewis 1997a).

3.3.1 Thrips – vectors of microbial pathogens

Fungi

Some thrips species are also vectors of numerous microbial pathogens, facilitating the mechanical dissemination of fungal spores and bacteria causing mildews, moulds and rusts (Ananthakrishnan and Suresh 1984, Palmer 1990, Elmer and Michailides 2004). Research in South Africa on thrips species, which may be vectors of microbial pathogens in macadamia, has not been conducted. By reviewing the literature from other macadamia growing countries, future studies could determine which species are vectors and see whether the same interaction occurs in South Africa. Fungi recorded on macadamia in South Africa are listed in Table 3.2 (Manicom 1997, 2003; Serfontein *et al.* 2007).

Table 3.2 Fungi recorded on Macadamia in South Africa (from Manicom 1997, 2003 and Serfontein *et al.* 2007).

Alternaria sp.
Armillaria sp.
Botryosphaeria sp.
Botrytis cinerea
Cladosporium cladosporioides

Colletotrichum gloeosporiodes
Cylindrocladium sp.
Ganoderma
Pestalotia sp.
Phytophthora sp. - including *P. cinnamomi*
Pythium sp. - including *P. irregulare*, *P. ultimum* var. *sporangiiferum*, and *P. vexans*.
Rhizoctonia sp.

A number of fungi have been recorded in the New South Wales and Queensland Herbarium Records, Australia, on *Macadamia integrifolia* (Fitzell 1994) (Table 3.3). Research on New Zealand flower thrips, *Thrips obscuratus* (Crawford), showed that whilst feeding on kiwifruit petals, *T. obscuratus* pick up *Botrytis cinerea* fungal spores which they then inadvertently transmit to different parts of the plant and to other plants (Elmer and Michailides 2004). Extensive research on the taxonomy and distribution of mycophagous thrips has been conducted (Ananthakrishnan 1973 in Ananthakrishnan and Suresh 1984, Mound 1974a, 1974b in Ananthakrishnan and Suresh 1984, Palmer and Mound 1978 in Ananthakrishnan and Suresh 1984, Mound and Palmer 1983 in Ananthakrishnan and Suresh 1984). Mycophagous and sporophagous thrips species are associated with drying and decaying leaf litter, dead and decaying twigs/branches and loose bark; plant pathogenic fungi groups Ascomycetes, Coelomycetes, Hyphomycetes, Basidiomycetes and Zygomycetes are associated with litter-thrips-fungus interactions (Ananthakrishnan and Suresh 1984).

Table 3.3 Fungi recorded on *Macadamia integrifolia* in Australia (from Fitzell 1994).

Alternaria alternate
Armillaria sp.
Asterina sp.
Botrytis cinerea
Colletotrichum gloeosporioides var *minor*
Cylindrocladium quinqueseptatum
Cytosphaera mangiferae
Dothiorella sp.
Fusarium decemcellulare

Kretzschmaria cetrarioides
Lasiodiplodia theobromae
Microsphaeropsis sp. *Mucor racemosus*
Penicillium brevicompactum
Pestalotiopsis sp.
Phomopsis sp.
Physalospora sp.
Phytophthora cinnamomi
Pseudocercospora sp.
Pythium sp.
Septobasidium sp.
Sporidesmium sp.
Stilbella cinnabarina

In the study by Ananthakrishnan and Suresh (1984) scanning electron microscopy (SEM) was used to show that, in *Loyolaia indica* Ananthakrishnan, sensory areas and oral pads of the mouthparts were used for spore selectivity. Pathogenic fungi spores are highly variable in appearance, having adapted to different types of dissemination; the SEM study showed spores of *Aspergillus* spp. to have surface ornamentations, *Pestalotia* spp. external appendages, *Lasiodiplodia theobromae* "sticky" surfaces, and *Fusarium, Polyporus* and *Penicillium* spp. smooth surfaces.

Mycophagous and sporophagous thrips species can be mechanical vectors, facilitating the dissemination of plant pathogenic fungal spores inadvertently, carrying spores on various parts of their body, either singularly or in clusters, whilst moving within or between habitats. The physiology of the fungal spores helps with the adherence to setae, antennae, legs, wings and the body surface of thrips (Ananthakrishnan and Suresh 1984). Due to the close thrips-fungus affiliation, dispersal of fungal propagules is made to nearby uninfected live host plants.

Viruses

Thrips are vectors of a number of viruses causing indirect damage by their transmission (Ullman *et al.* 1997, 2002, Whitfield *et al.* 2005) (Table 3.4). Plant viruses in the genera Tospovirus, Ilarvirus, Carmovirus, Sobemovirus and Machlomovirus are transmitted by thrips species of the family Thripidae, subfamily Thripinae (Jones 2002). Transmission of Ilarviruses by thrips involves the physical movement of virus-carrying pollen from one plant to another and its introduction into the plant through feeding wounds. Thrips in the genera *Frankliniella*, *Microcephalothrips* and *Thrips* have been implicated in the spread of Ilarviruses (Jones 2002).

There has been one report of transmission of a Carmovirus by thrips utilizing the same mechanism as for Ilarviruses. One Sobemovirus can also be transferred with pollen by thrips and plants are subsequently infected during feeding. This virus can also be carried from one plant to another on the mouthparts of thrips. One Machlomovirus is also thought to be thrips-transmitted, but the mechanism is unknown (Jones 2002).

Table 3.4 Recognised Tospovirus species and their vectors (from Whitfield *et al.* 2005).

Tospovirus species	**Thrips vectors**
Capsicum chlorosis virus	*Ceratothripoides claratris*
Chrysanthemum stem necrosis virus	*Frankliniella occidentalis* *F. schultzei*
Groundnut bud necrosis virus	*F. schultzei* *Thrips palmi* *Scirtothrips dorsalis*
Groundnut ringspot virus	*F. occidentalis* *F. schultzei*
Impatiens necrotic spot virus	*F. occidentalis*
Iris yellow spot virus	*T. tabaci*
Melon yellow spot virus	*T. palmi*
Peanut chlorotic fanspot virus	*S. dorsalis*
Peanut yellow spot virus	*S. dorsalis*
Tomato chlorotic spot virus	*F. intonsa* *F. occidentalis* *F. schultzei*
Tomato spotted wilt virus	*F. bispinosa* *F. fusca* *F. intonsa* *F. occidentalis* *F. schultzei* *T. setosus* *T. tabaci*
Watermelon bud necrosis virus	*T. palmi*
Watermelon silver mottle virus	*T. palmi*
Zucchini lethal chlorotic virus	*F. zucchini*

3.4 Chemical control

In general, the newer chemicals developed by chemical companies are not as harsh and are more target-specific, meaning a lower impact on the environment, natural enemies, parasitoids and pollinators. Most of the broad-spectrum insecticides, such as the organophosphate-based chemicals, are being phased out. Because some of the newer chemicals may have a lower persistence, this means that additional, careful scouting and monitoring of pest populations are required so that treatments can be timed optimally. These newer chemicals cannot be applied prophylactically in advance, as was the case with the older, broad-spectrum chemicals (Morse and Schweizer 1996; Hepburn and Stiller 2012).

Immaraju *et al.* (1990) and Morse and Schweizer (1996) have suggested that a rotation strategy of chemical applications and alternative means of control be used to manage pesticide resistance of citrus thrips, *Scirtothrips citri*. The over-utilization of chemical sprays also leads to the resurgence of other insect pests (i.e. mealy bug, mites, and scale insects). Timing of spray applications is vital in attaining maximum control, and growers should be made aware of the possibility of cross-resistance arising when using chemical control against other pests in the orchards (Hepburn and Stiller 2012).

One of the major obstacles arising from trying to control damage caused by thrips in various cropping systems is that non-target populations have built up resistance to most of the insecticides used (Morse and Brawner 1986, Immaraju *et al.* 1990, Arcamonte 1995, Grout *et al.* 1996, Morse and Schweizer 1996, Grové *et al.* 2000a). In addition, many of the chemicals previously used to control pests have been banned to meet international export regulations, or reduced to comply with Maximum Residue Levels (MRLs). In 2011 an updated list of registered products for insect control on macadamias in South Africa was published (Anon. 2011); no products were registered for the control of thrips (Hepburn and Stiller 2012). One product was registered in 2013 for the control of thrips populations; the active ingredient is spinetoram (Anon. 2013). It was recommended that a light, but thorough, cover spray be applied when thrips presence was observed and to repeat the application when necessary (Anon. 2013).

Extensive research has been conducted on thrips resistance and cross-resistance in citrus, both in South Africa and in California, United States of America (Georgala 1982, Morse and Brawner 1986, Immaraju *et al.* 1990, Arcamonte 1995, Grout *et al.* 1996, Morse and Schweizer 1996). In America, *Scirtothrips citri* populations develop resistance rapidly to an increasing number of pesticides; pyrethroids in particular. It has been shown that by applying one chemical spray for citrus thrips per season, the population quickly returned to a normal level and efficacy of the spray is still high the following season (Morse and Schweizer 1996). Low-level resistance of *S. citri* to pyrethroids appears to regress in the absence of chemical treatments (Morse and Schweizer 1996).

Resistant genes generally have a detrimental side-effect, that of lower general fitness, resulting in higher mortality or reduced fecundity. This collateral handicap allows non-resistant members of the population to outbreed the resistant ones in the absence of the pesticide, thus gradually displacing the resistance gene from unsprayed populations. One explanation for the handicap may be that resistance is generally linked to some form of biological disadvantage that essentially means diverting resources from growth into maintenance. In the absence of selection pressure from chemical treatments, the tolerant individuals are less fit than the susceptible forms, and selection acts against them (Grout *et al.* 1996). This, coupled to the fact that multiple thrips generations occur per year, indicates that it may be in our best interests to severely limit the number of chemical sprays, thereby reducing the rate of resistance evolution in thrips. It is important to break the cycle of resistance, because with each chemical that is “lost” to resistance, we also lose the flexibility to make pest management more reliable, effective and economical (Morse and Schweizer 1996, Hepburn and Stiller 2012).

3.5 Natural enemies, predators and biological control agents

A few *Scirtothrips aurantii* predators were recorded on citrus by Bedford (1943a) and Wentzel *et al.* (1978). Milne (1977) posited that predacious ground mites may inhibit *S. aurantii* populations by preying on the soil-dwelling pupal stage. *Euseius addoensis* (van der Merwe and Ryke), *Euseius citri* (van der Merwe and Ryke) and *Euseius pafuriensis* (van der Merwe) (Phytoseiidae) are the three, dominant species of predatory mites throughout South Africa (Grout 2011). Thrips natural enemies are mostly generalist predators including predatory species of anthocorid bugs, thrips, mites and parasitic nematodes (Table 3.5) (Butt and Brownbridge 1997, Loomans *et al.* 1997, Lim *et al.* 2001, Hoddle and Robinson 2004, Hoddle *et al.* 2004, Morse and Hoddle 2006, Grout 2011).

Table 3.5 Natural enemies, predators and biological control agents of thrips (from Butt and Brownbridge 1997, Loomans *et al.* 1997, Grout 2011, Lim *et al.* 2001, Hoddle and Robinson 2004, Hoddle *et al.* 2004, Mound 2005, Morse and Hoddle 2006, Dreistadt *et al.* 2007).

Class	Family	Species
Insecta		
Heteroptera	Anthocoridae	*Orius* spp. *Macrotracheliella nigra*

Class	**Family**	**Species**
Thysanoptera	Aeolothripidae Phlaeothripinae	*Franklinothrips orizabensis* *Haplothrips* spp.
Neuroptera	Chrysopidae	*Chrysopa* and *Chrysoperla* spp.
Hymenoptera	Chalcidae	*Tetrastichus* spp. *Pedobius* spp.
	Trichogrammatidae	*Megaphragma* spp. (egg parasitoid) *Megaphragma mymaripenne* (egg parasitoid)
	Eulophidae	*Ceranisus* spp. (larval parasitoids) *Thripodius semiluteus* (larval entoparasitic wasp) *Goetheana incerta*
Arachnida		
Acari	Phytoseiidae	*Euseius* spp.
	Tarsonemidae	
	Erythraeidae	
	Phytoseiidae	*Amblyseius* *Euseius tularensis* *Noeseiulus* spp.
	Anystidae	*Anystis agilis*
Sordariomycetes		
Entomopathogenic Fungi	Clavicipitaceae	*Beauveria bassiana* *Metarhizium anisopliae*
	Neozygitaceae	*Neozygites* spp.
	Trichocomaceae	*Paecilomyces fumosoroseus*
	Hypocraeceae	*Verticillium* spp.
Nematoda		
Nematodes (Parasitic)	Allantonematidae	*Thripinema* spp.

Control of thrips species using beneficial insects as biological control agents is limited (Parrella and Lewis 1997a, Neuenschwander and Markham 2001, Hoddle *et al.* 2002, Hoddle and Robinson 2004, Morse and Hoddle 2006). Loomans *et al.* (1997) and Lim *et al.* (2001) reported that although parasitic nematodes specializing on thrips, *Thripinema* spp. (Tylenchida: Allantonematidae), delay oogenesis in females, growth rates did not alter, and it is uncertain whether control of field populations could be achieved. No viral diseases of thrips are known (Morse and Hoddle 2006). Entomopathogenic fungi, *Neozygites* spp. (Neozygitaceae) and *Verticillium* spp. (Hypocraeceae), rarely control thrips populations (Butt and Brownbridge

1997). Thrips are susceptible to microsporidian (*Mrazekia* sp.) and fungal infections caused by *Entomophthora thripidum* (Ananthakrishnan 1993).

Even though the effect of natural enemies and pathogens seems limited on thrips, we cannot afford to ignore any possible means of control, no matter how small. No part of an Integrated Pest Management (IPM) programme is a 'stand-alone' component; by augmenting and ensuring conditions are favourable to establishing these natural means of control, a multi-pronged offence against thrips on macadamias in South Africa can be incorporated within an IPM framework.

3.6 Thrips research on tropical and subtropical crops in South Africa

It is well documented that insects, mites and pathogens endemic in particular area have moved from their natural host plants in indigenous vegetation to crops introduced to the region. This 'new association' effect was described by Hokkanen and Pimentel in 1989. It is important to understand the plant-insect interactions between the South African thrips species community and how these populations affect macadamias grown outside their native range. Macadamias are introduced to South Africa, where they are exposed to thrips that are also found in their native range, but also to thrips species, predators and parasitoids which do not occur in Australia.

As in-depth research was yet to be conducted on interactions between the South African communities of thrips inhabiting macadamia cultivars grown here, the insects' pest statuses on this crop were not well understood. Historically, the South African citrus thrips, *Scirtothrips aurantii* Fauré (Thripidae) and the greenhouse thrips, *Heliothrips haemorrhoidalis* (Bouché) (Thripidae) were the only species recorded on macadamias (de Villiers and van den Berg 2003). *Heliothrips haemorrhoidalis* was usually of little economic importance, except occasionally in nurseries, and *S. aurantii* fed on small nuts and leaves (which could be problematic in nurseries), but damage in orchards was usually not serious (de Villiers and van den Berg 2003).

Research on thrips populations on various tropical and subtropical crops grown in South Africa goes back to Fauré's (1929) work on *Scirtothrips* species. Of these crops, citrus (*Rutaceae*), mango (*Anacardiaceae*) and avocado (*Lauraceae*) have been the most extensively studied. Because very little was known about the thrips species communities in macadamia, a comprehensive literature research was undertaken to determine both endemic and invasive thrips species in the other tropical and subtropical cropping systems in South Africa (Table 3.6).

Table 3.6 Publications on thrips in tropical and subtropical crops grown in South Africa.

Crop	Thrips species	Source
Avocado	*Heliothrips haemorrhoidales* (Bouché)	Dennill and Erasmus 1992; de Villiers 1990; de Villiers and van den Berg 1987; Erichsen 1996; Fauré 1929; Grové 2001; Milne 1973; Steyn 1991, 2001a.
	Scirtothrips aurantii Fauré	Grové 2001; Steyn 2001b.
	Selenothrips rubrocinctus (Giard)	de Villiers 2001.
	Heliothrips sylvanus Fauré	de Villiers 2001.
Banana	*Hercinothrips bicinctus* (Bagnall)	de Jager and de Villiers 1993a, 1993b; de Villiers and de Jager 2001a; Malan and Thomas 1963; Wentzel 1973.
	Thrips exilicornis Hood	de Villiers and de Jager 1993b, 2001b.
Citrus	*Scirtothrips aurantii* Fauré	Annecke and Moran 1982; Bedford 1943a, 1943b, 1968; Bedford and du Toit 1993; Bedford *et al.* 1985; Fauré 1929, 1956; Gilbert 1986, 1990, 1992; Gilbert and Bedford 1998; Grout 1994; Grout and Richards 1990, 1992; Grout and Stephen 1993, 1994, 1995; Grové 2001; Kamburov 1986, 1991; Milne 1977; Mound and Palmer 1981; Samways 1986; Samways *et al.* 1986; Schwartz 1983; Wentzel *et al.* 1978.

Crop	**Thrips species**	**Source**
Guava	*Heliothrips haemorrhoidales* (Bouché)	de Villiers 1990; Steyn 2001a.
	Heliothrips sylvanus Fauré	de Villiers 2001.
	Scirtothrips aurantii Fauré	Grové 2001; Steyn 2001b.
	Selenothrips rubrocinctus (Giard)	Steyn 2001b.
Litchi	*Scirtothrips aurantii* Fauré	Fauré 1929; Grové 2001.
Macadamia	*Heliothrips haemorrhoidales* (Bouché)	de Villiers 1990; de Villiers 1993; de Villiers and van den Berg 2003; Steyn 2001a.
	Scirtothrips aurantii Fauré	Grové 2001; Wentzel 1971; Wentzel *et al.* 1978
Mango	*Heliothrips haemorrhoidales* (Bouché)	Grové 1999; Grové *et al.* 2001; Steyn 2001a.
	Scirtothrips aurantii Fauré	Annecke and Moran 1982; Brink 1993; Brink and Maritz 1995; Fauré 1929, Grové 1999, 2001; Grové and Pringle 2000; Grové *et al.* 2000a, 2000b, 2000c, 2000d, 2001, 2003.
	Selenothrips rubrocinctus (Giard)	Steyn 2001b.
Pineapple	*Frankliniella schultzei* (Trybom)	Carter 1939; Malan 1954; Petty 1978, 2001a.
	Thrips tabaci (Lindeman)	Carter 1939; Malan 1954; Petty 1978, 2001b.
Sugarcane	*Fulmekiola serrata* (Kobus)	Leslie 2005; Way 2006.
Tea	*Heliothrips haemorrhoidales* (Bouché)	Steyn 2001a.
	Scirtothrips aurantii Fauré	de Rooster *et al.* 1985; Grové 2001.
	Selenothrips rubrocinctus (Giard)	Steyn 2001b.

4 Phenology of *Macadamia* Cultivars in Southern Mpumalanga, South Africa

4.1 Introduction

Research on macadamia phenology conducted in Australia and Hawaii gives an overview of how cultivars perform under different conditions, in different hemispheres and in these countries. However, this information can only be used as a guideline and studying the cultivar phenology and performance under local conditions will give more accurate idea of macadamia production in South Africa. Carefully looking at how cultivars perform here may also reveal which phenological characteristics are universal, thereby showing which varieties may have strongly inherited genetic traits and adapt more readily to different environments.

Insect pest populations are sometimes synchronised with specific host plant growth stages, so it is necessary to include the seasonal occurrence of the thrips communities during the study period in this chapter. From this preliminary study, a pattern of thrips species present at specific growth phases of the plant could indicate feeding preferences (i.e. pollen, flowers, new growth), and their ability to reproduce on the host plant as seen from the increasing number of nymphs occurring in the samples collected (Chapter 5).

Based on literature reviewed, a general phenology of macadamia in Australia is shown in Figure 4.1. Given that South Africa is also in the southern hemisphere, it is interesting to see how the general phenology will compare to that in Australia.

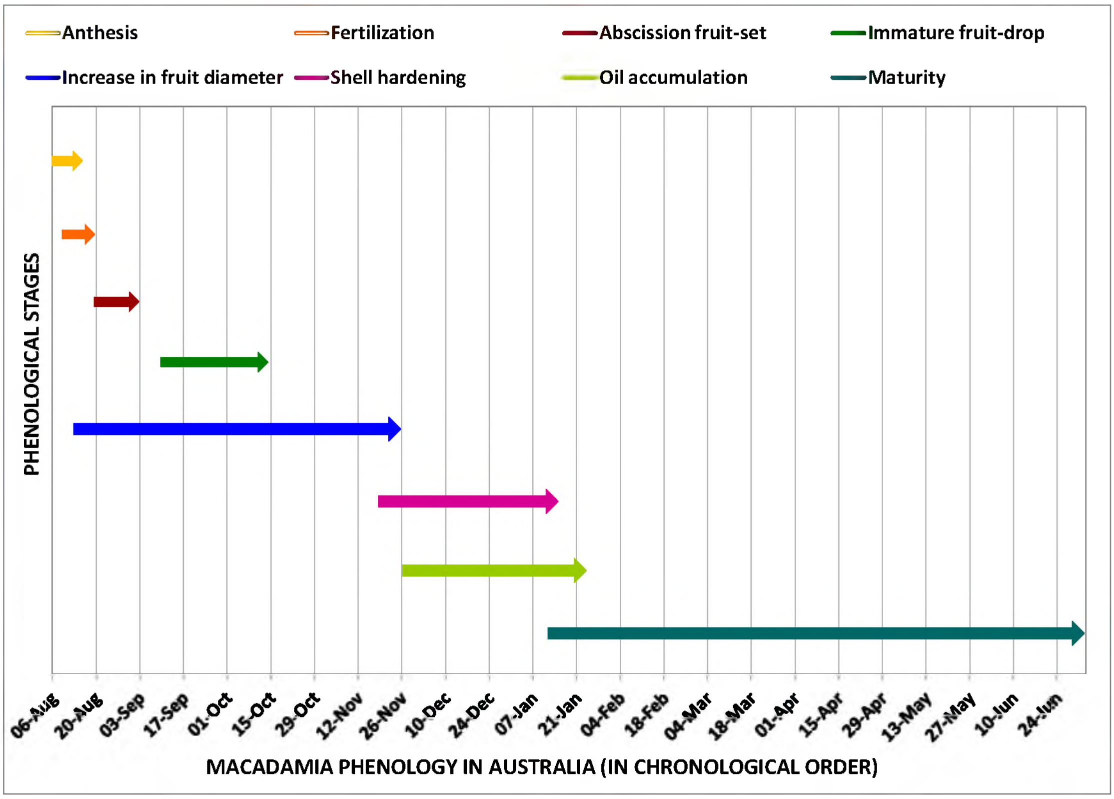


Figure 4.1 Macadamia phenological stages shown over time from anthesis to maturity in Australia (from Moncur *et al*. 1985, and Trueman 2013).

Comprehensive studies on macadamia phenology conducted in Hawaii include those by Jones (1939), Urata (1954), Shigeura and Ooka (1984 in Hardner *et al*. 2009), Sakai and Nagao (1985), and Nagao *et al*. (1994). Because the various developmental stages occur year-round, the general phenology of macadamia is presented by weeks post-anthesis in Figure 4.2.

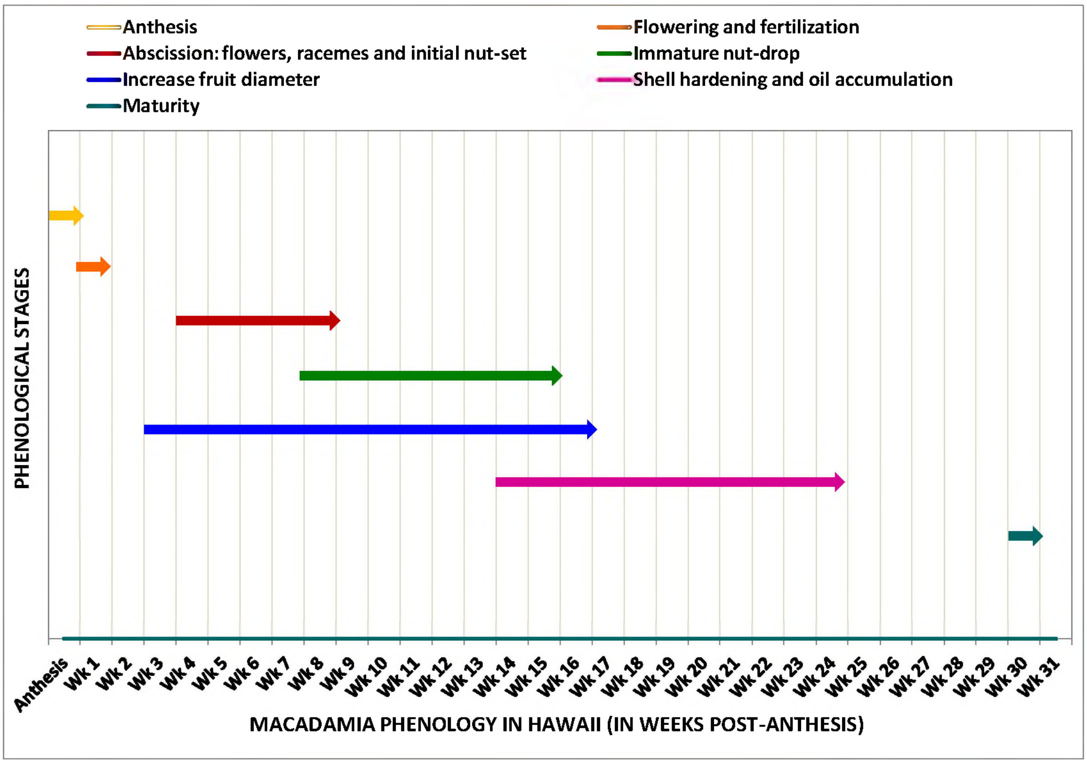


Figure 4.2 Macadamia phenology, (reflected in weeks post-anthesis), in Hawaii (from publications by Nagao and Sakai 1985, Sakai and Nagao 1985, and Urata 1954).

Although Hawaii is in the northern hemisphere, the phenology and performance of macadamia cultivars originating there may exhibit similar cycles when grown in the southern hemisphere, albeit over a shorter period, given the temperature-dependence of growth cycles in macadamias. In Hawaii, vegetative flush, flowers and fruit are often present simultaneously during the cropping cycle, making it necessary to harvest numerous times (Nagao *et al.* 1994). The protracted flowering period results in a number of fruit growth stages being present at any one time, therefore increasing pest pressure over an extended period. The high cost of harvesting is economically detrimental as multiple harvests are made due to the prolonged period of mature nut-drop or year-round yields (Hardner *et al.* 2009).

In South Africa, a generalised concept of macadamia phenology is used with refinements based on whether a cultivar is believed to be early-, mid- or late-bearing under local conditions (Anon. 2007). The general overview of macadamia phenology in South Africa is presented in Figure 4.3 (Anon. 2007).

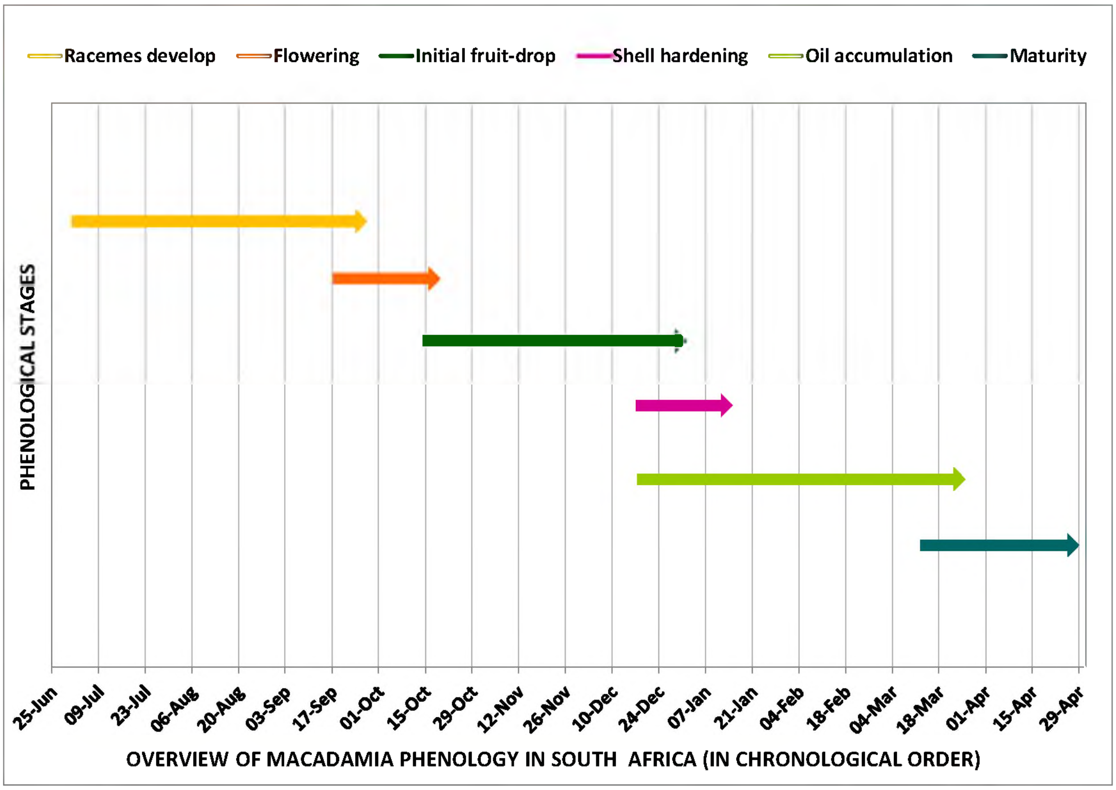


Figure 4.3 General overview of the macadamia phenological development stages shown over time in South Africa (from Anon. 2007).

A description of cultivar characteristics used in this study is presented in Table 4.1.

Table 4.1 Characteristics of cultivars used in this study (from Wiid-Hobson 2003b, Allan 2006, Andrew Sheard pers. comm.)

Cultivar / Selection	Tree Size	Growth Habit	Density	Nut-Drop Period	Flowering Pattern	Yield	Bunching Habit	Husk	Nuts
Hidden Valley A4 **Precocious bearer** **Patented in Australia 1989** **Hybrid cultivar ± 30% *M tetraphylla***	Medium	Spreading to rounded	Open canopy	Mid-season	Short, intense late-flowering Short inflorescences Some out of season flowering	Early-bearing High yield	Mainly singles	Smooth dark husk	Large to very large even-sized nuts Very high total kernel recovery
Hidden Valley A16 **Precocious bearer** **Patented in Australia 1989** **Hybrid cultivar ± 30% *M tetraphylla***	Small	Upright to rounded	Moderate to dense canopy with willowy branches	Very late maturing	Moderately intense, condensed, late-flowering Medium inflorescence length	Early-bearing High kernel yield Good kernel consistency	Tends to open bunching	Fairly smooth husk	Large nuts of uniform size Some stick-tights
816 ***M integrifolia* selection ex-Hawaii**	Medium to large	Moderately upright	Open canopy	Early to mid-season	Light intensity, late-flowering, long inflorescence length	Not early bearing High kernel yield	Mostly singles and doubles	Smooth husk	Large, round kernel of uniform size Very high total kernel recovery High percentage whole kernel recovery

Cultivar / Selection	Tree Size	Growth Habit	Density	Nut-Drop Period	Flowering Pattern	Yield	Bunching Habit	Husk	Nuts
788 'Pahala' *M integrifolia* cultivar named in Hawaii 1981	Medium	Spreading	Open canopy	Early to mid-season (depends on area)	Medium length inflorescence	Medium yields Med to high kernel recovery	Tends to open bunching	Smooth very thick husk (up to 60%)	Very good kernel quality
Nelmak 2 Hybrid cultivar ± 50% *M tetraphylla* Selected in South Africa	Medium	Spreading	Open canopy	Early	Long inflorescence length	Medium	Mostly singles and doubles	Flat round husk	Large round nuts sometimes variable in size High whole kernel recovery
Nelmak D Selected in South Africa	Medium to large	Very upright	Open canopy	Very late	Very long inflorescence length Does not set out-of-season flowers	Very poor	Tends to open bunching on very long racemes	Slightly pubes-cent, oval shape	Medium kernel recovery Only starts bearing at 6-7 years
695 Beaumont Very precocious bearer Hybrid cultivar first selected in California, USA	Large	Spreading	Dense canopy	Late Nuts do not dehisce – "stick-tights"	Medium inflorescence length Pink flowers	High yielding	Single nuts on raceme	Rough dark green husk	Medium to low percentage whole kernel recovery

4.2 Materials and Methods

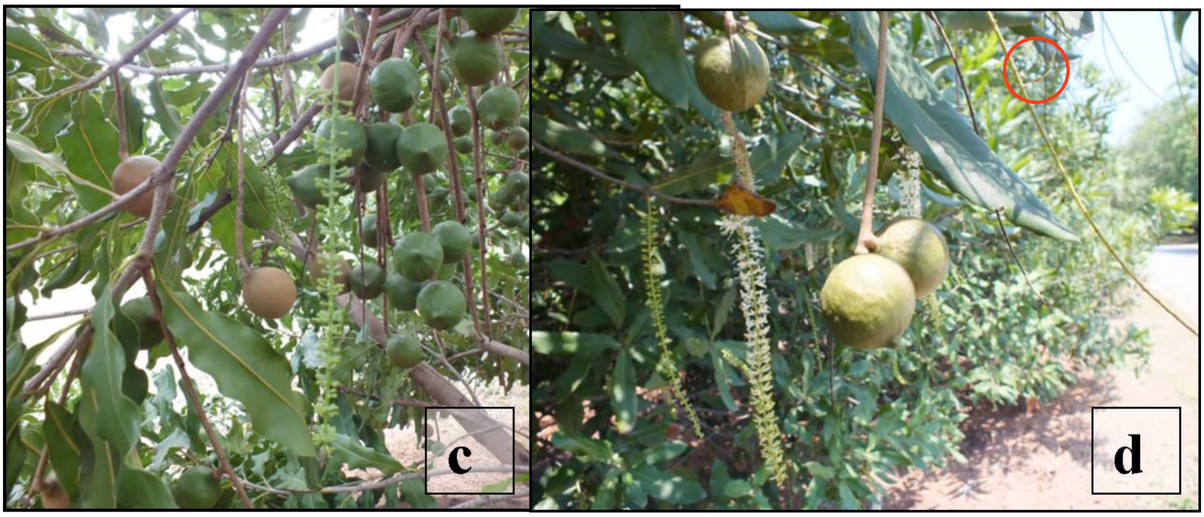
4.2.1 Study sites

A full description of the study sites and localities is given in Chapter 1 (Table 1.2).

4.2.2 Photographic recording of macadamia phenology

Numerous photographs of the data trees at each site were taken weekly to document the growth stages present. Collectively more than 7,000 photographs were taken throughout the study. Photographs were taken using a Fujifilm Finepix HS 20 EXR (16.0-megapixel) digital camera. The photographs were individually scored as to whether any of the pre-determined seven developmental stages were present. The stages were: new flush, closed buds, open flowers, nut-set, small nuts, medium nuts and large nuts (Figs. 4.4 a-d).

Assessing new flush was based on the same principle used by Stephenson *et al.* 1986; visually separating the terminals in the canopy into categories of "flush" or "mature" foliage. The shoots classified as "new flush" included growth when the leaves were fully extended, but excluded any fully-expanded, light green leaves which had hardened-off.



Figures 4.4 a-d Examples of weekly photographic records taken of data trees at each study site: **a.** open blossoms; **b.** new flush; **c.** closed buds, medium and large nuts; and **d.** closed buds, open blossoms, nut-set (circled), and large nuts.

4.2.3 Thrips occurrence

The total numbers of thrips collected weekly for each site, over both seasons, are incorporated into the phenological data set presented here to determine at which developmental stages of the plant thrips populations occurred, the increase / decrease in number, and whether reproduction was taking place. The identification and phenology of the thrips occurring in the macadamia orchards is more-fully discussed in Chapter 5; a detailed description of the method used to collect thrips is given under materials and methods.

4.3 Results

By incorporating the data collected over the two seasons a clearer representation of macadamia phenology is depicted in Figure 4.5. From 10 September to 15 October flowering and fertilization took place; abscission of initial nut-set took place between 24 September and 15 October; immature nut-drop from 18 October to 26 November; abscission of larger nuts from 17 December to 19 March; and mature nut-drop from 5 March until harvest in May / June.

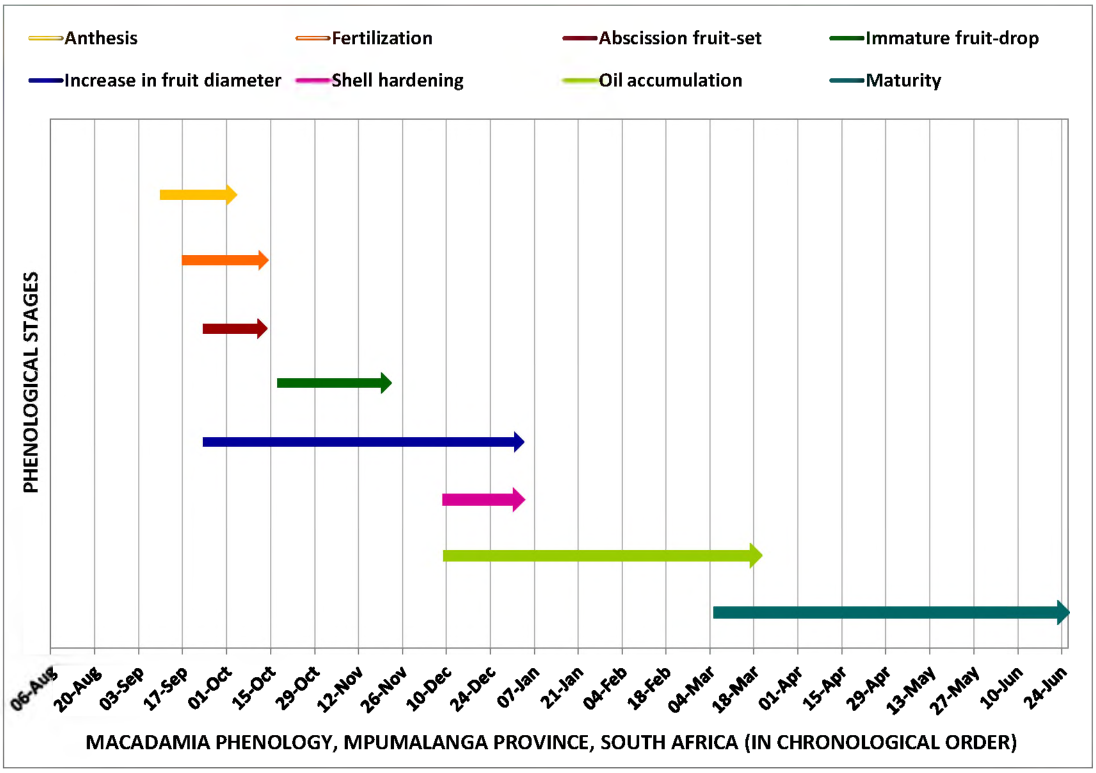


Figure 4.5 Macadamia phenological development stages in Mpumalanga Province, South Africa, over the 2011/2012 and 2012/2013 growing seasons.

4.3.1 Phenological variation within cultivars

Macadamia developmental stages for each study site, for both seasons, were combined with the thrips data and are presented in Figures 4.6-4.28. The phenological stages are shown as horizontal arrows for the duration(s) when each of the seven growth stages occurred. Vertical arrows indicate dates of anthesis, and the beginning and end of immature nut-drop. At some of the sites it was clear that a number of development stages occurred simultaneously; out-of-season flowering and nut-set was also evident.

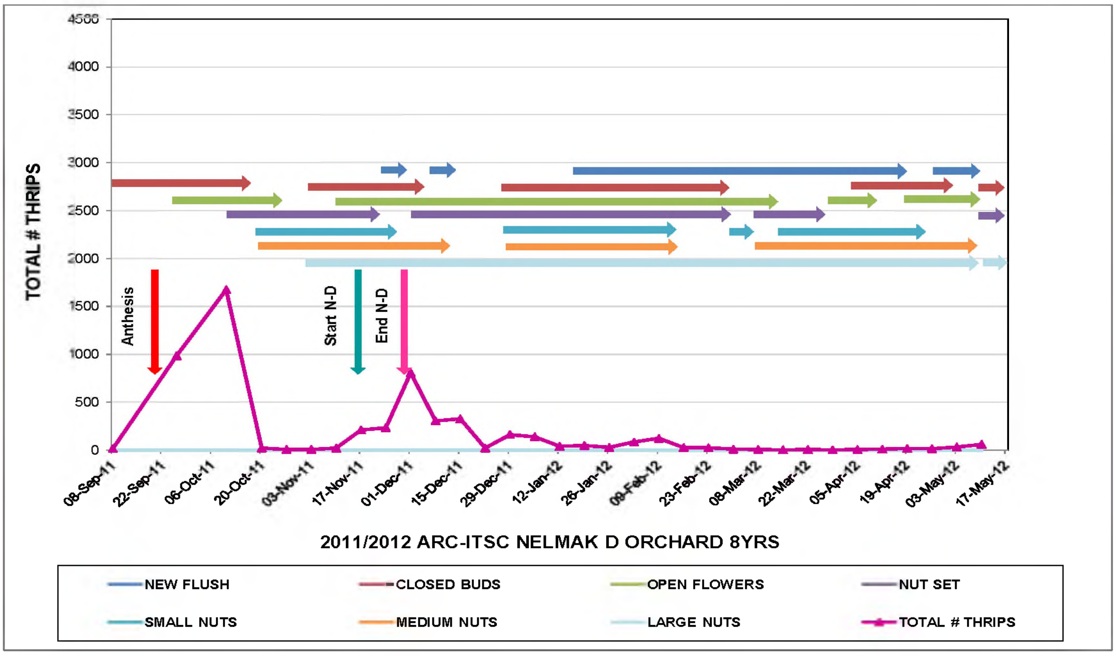


Figure 4.6 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Nelmak D (8-year-old) site.

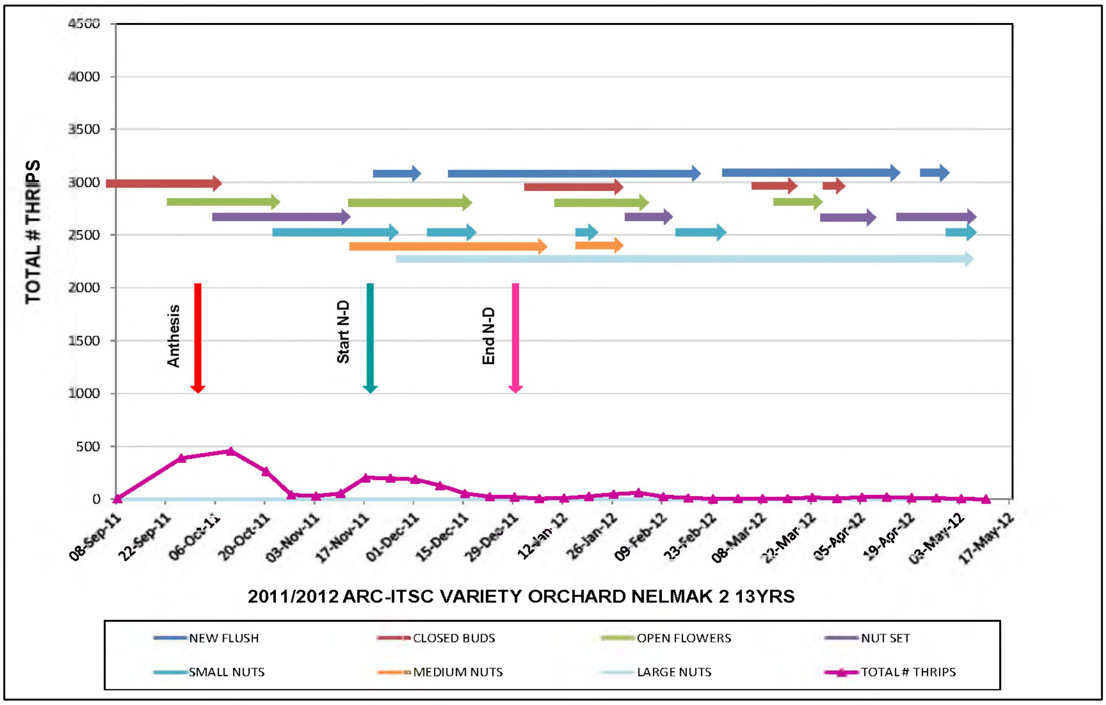


Figure 4.7 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard Nelmak 2 (13-year-old) site.

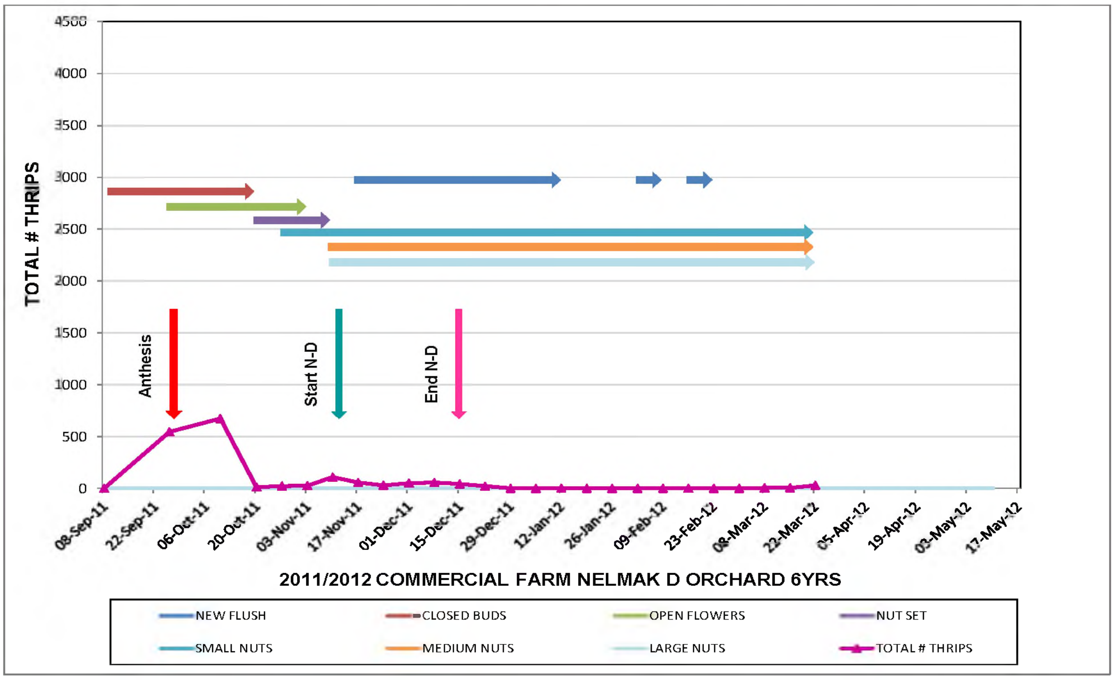


Figure 4.8 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Nelmak D Orchard (6-year-old) site.

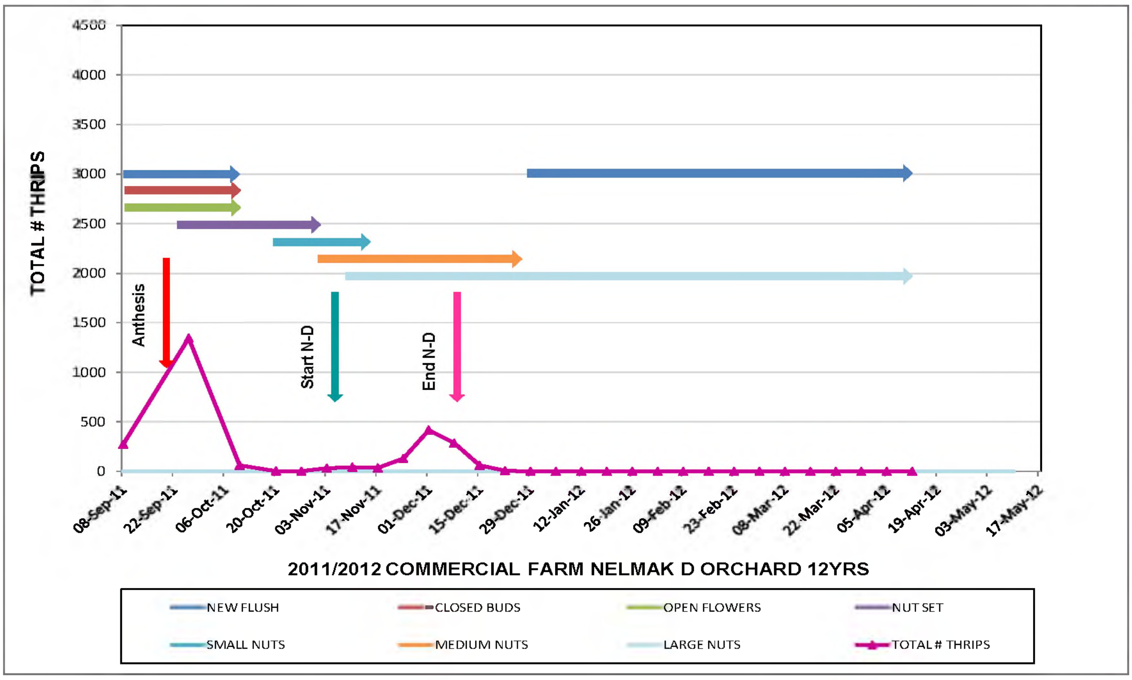


Figure 4.9 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Nelmak D Orchard (12-year-old) site.

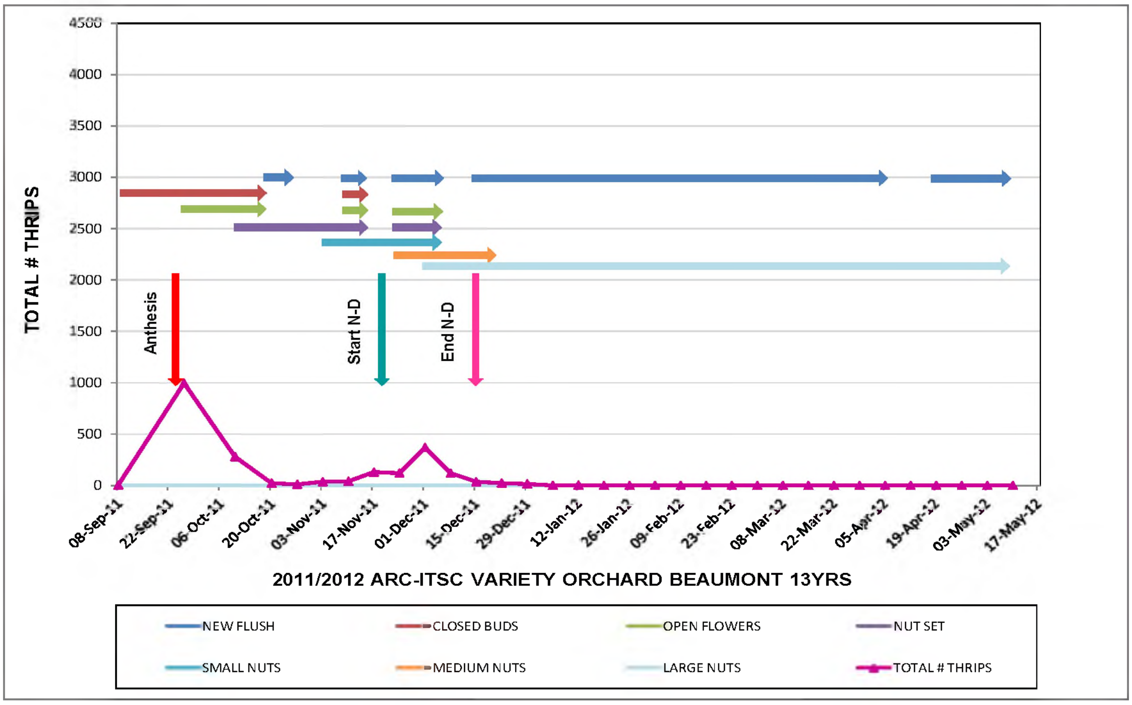


Figure 4.10 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard Beaumont (13-year-old) site.

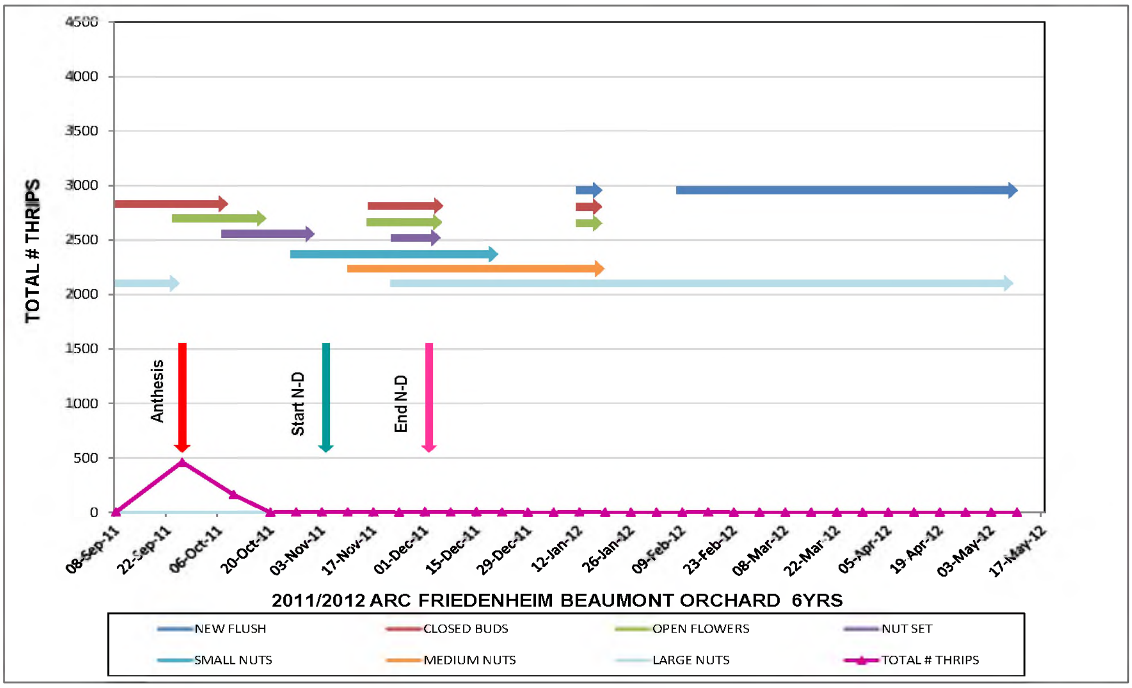


Figure 4.11 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC Friedenheim Orchard Beaumont (6-year-old) site.

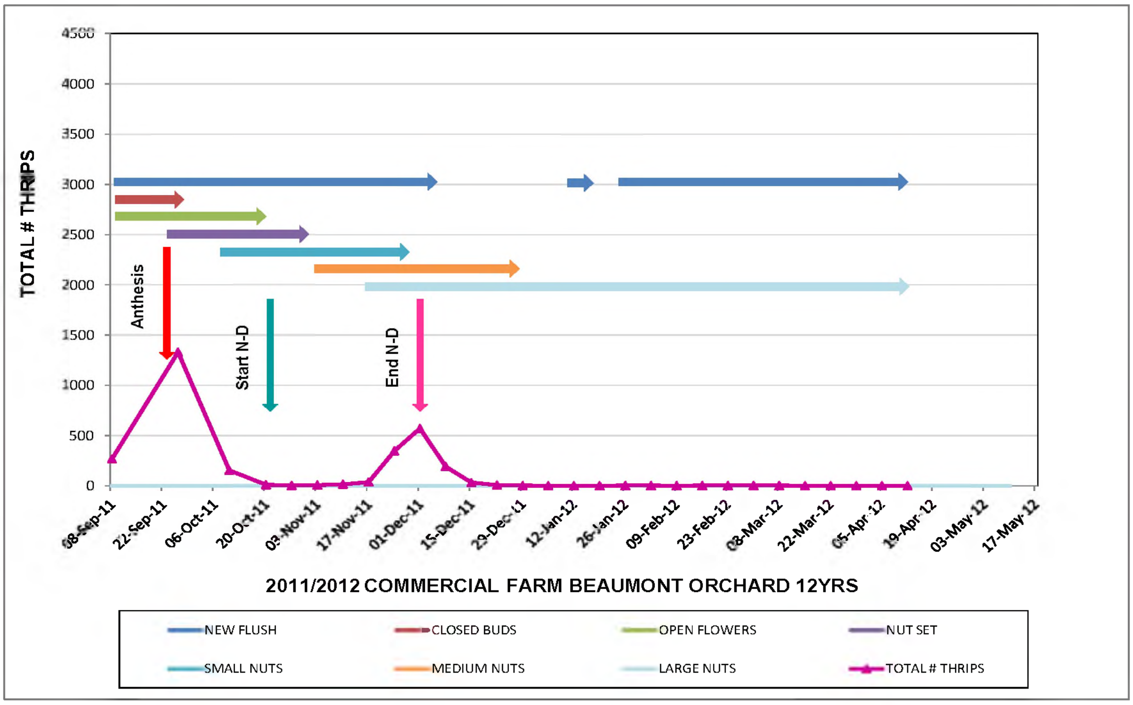


Figure 4.12 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Beaumont Orchard (12-year-old) site.

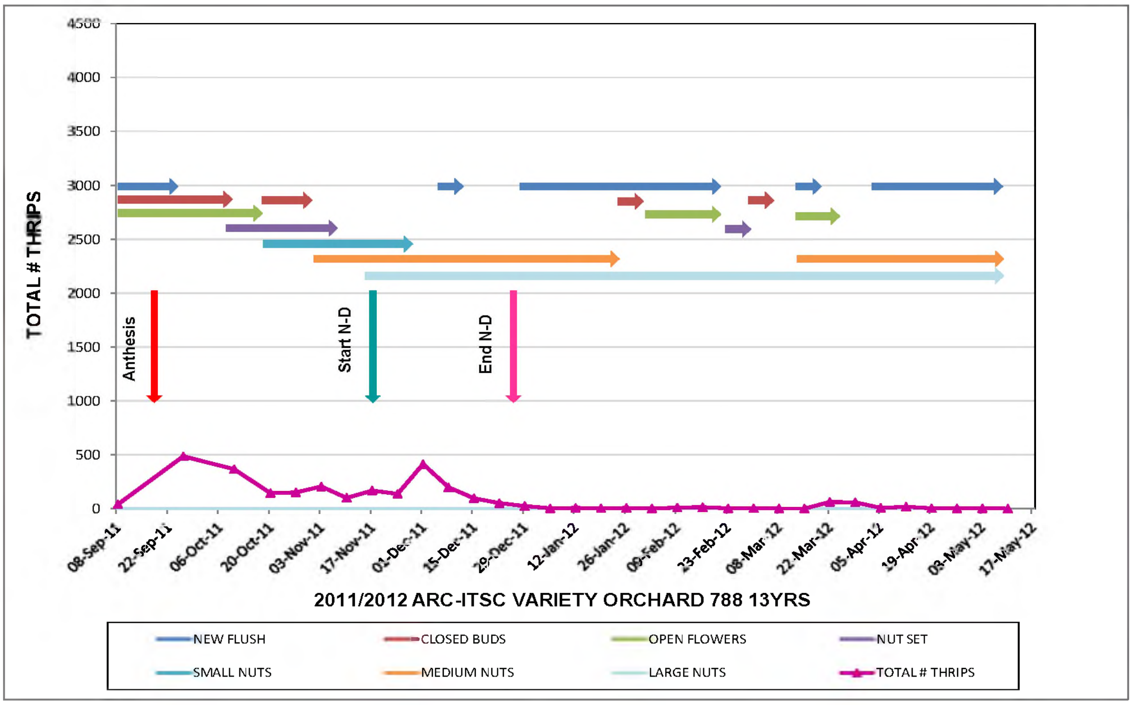


Figure 4.13 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard 788 (13-year-old) site.

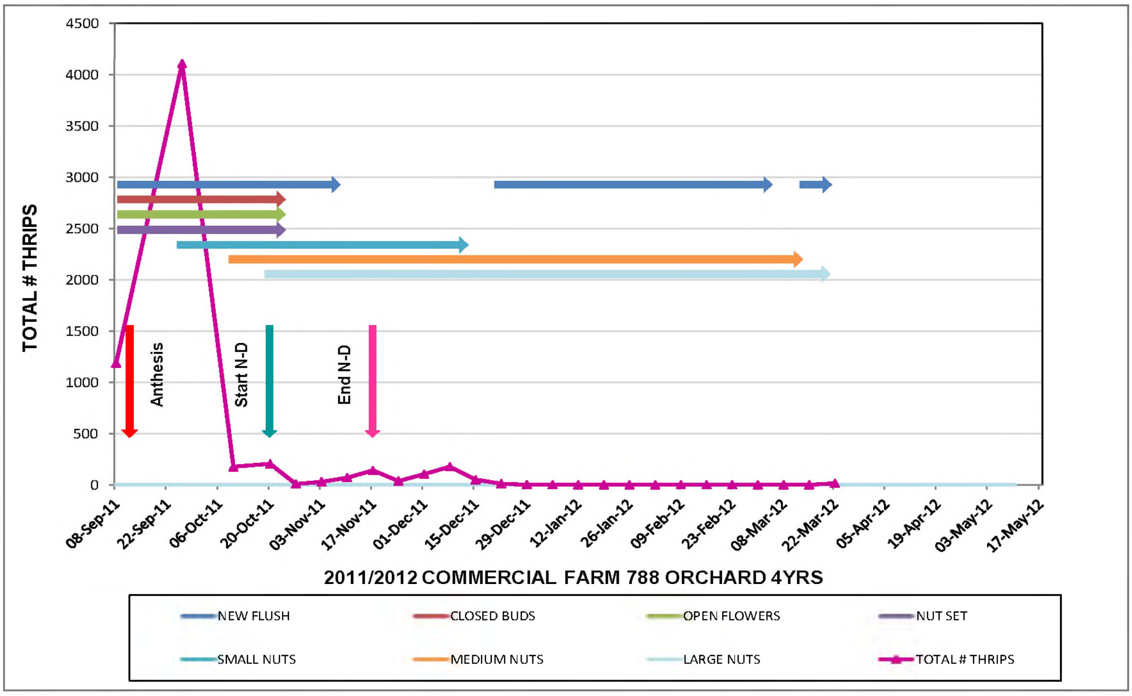


Figure 4.14 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm 788 Orchard (4-year-old) site.

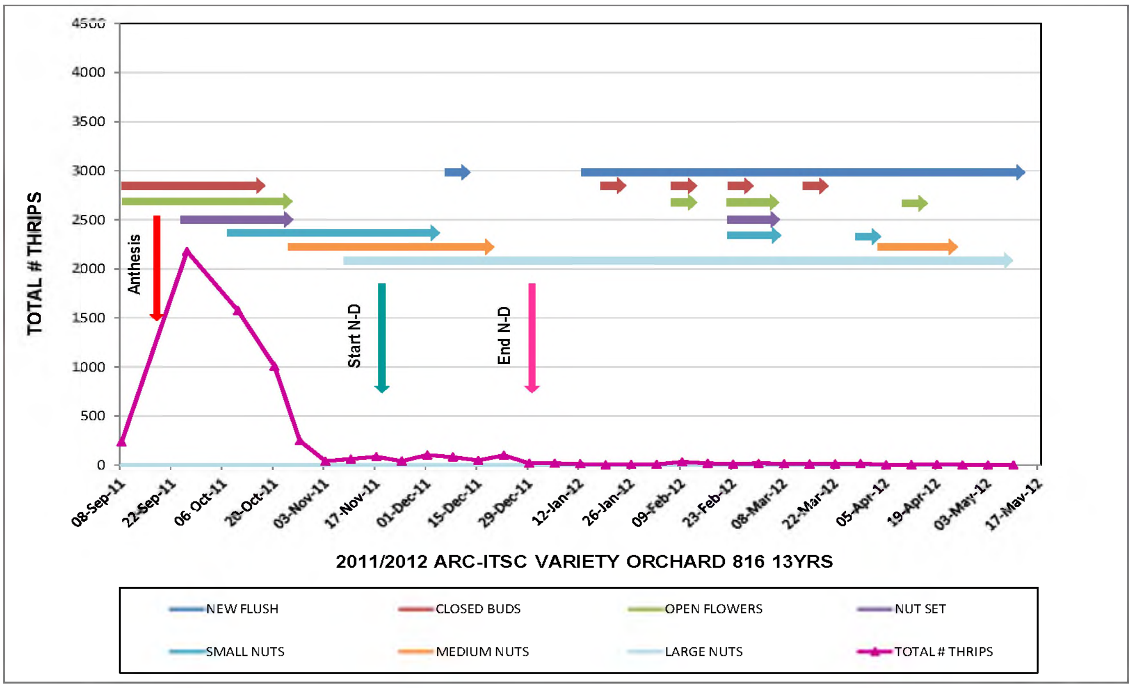


Figure 4.15 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard 816 (13-year-old) site.

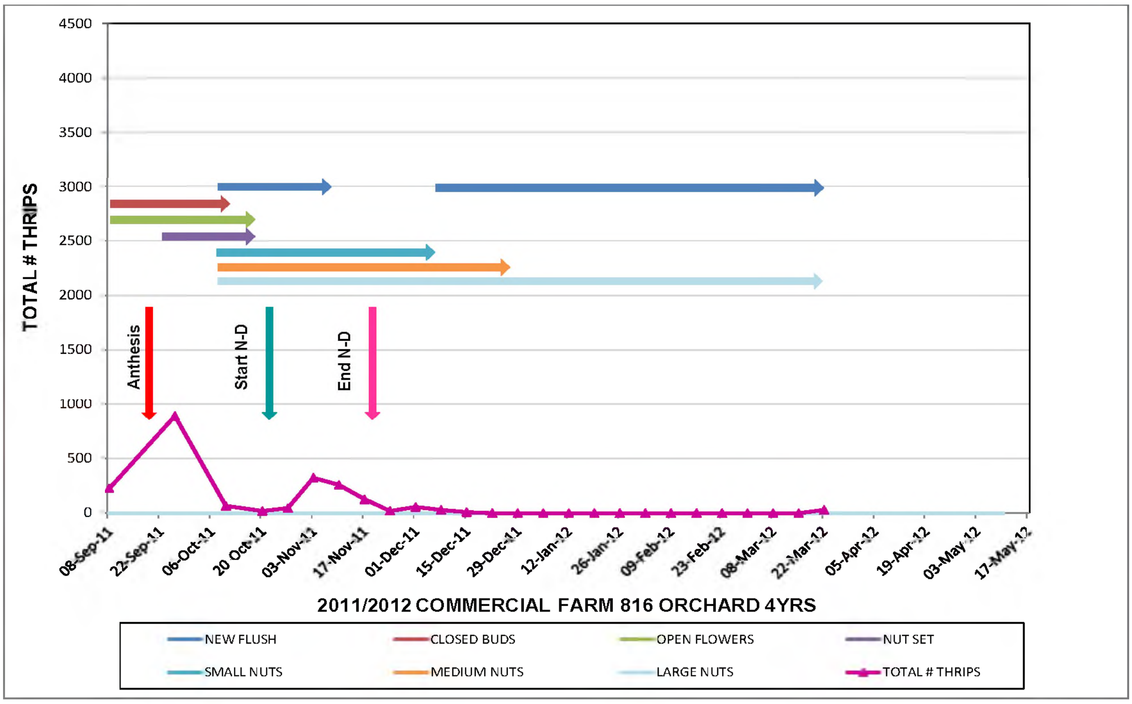


Figure 4.16 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm 816 Orchard (4-year-old) site.

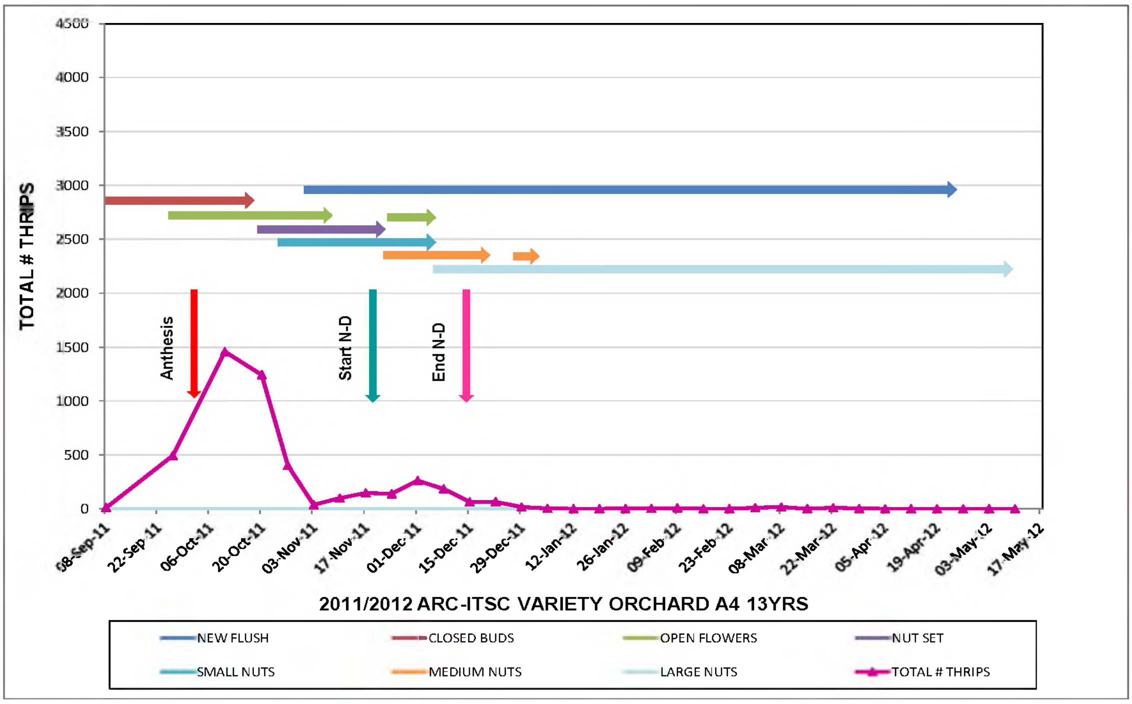


Figure 4.17 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard A4 (13-year-old) site.

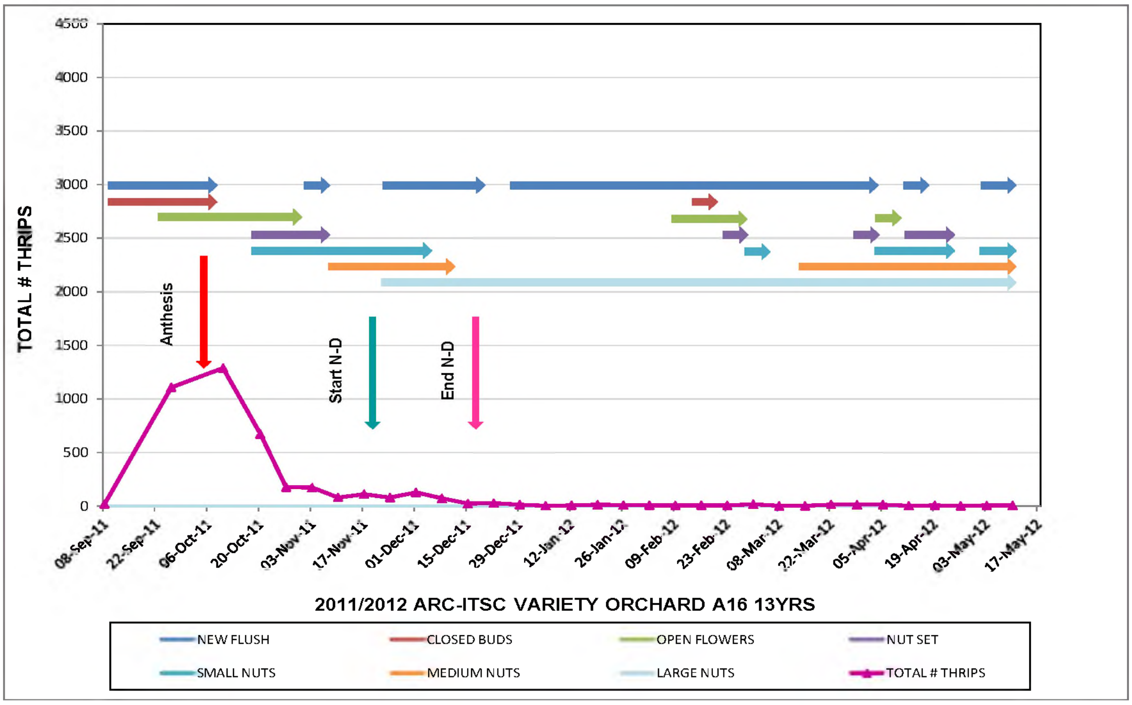


Figure 4.18 2011/2012 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard A16 (13-year-old) site.

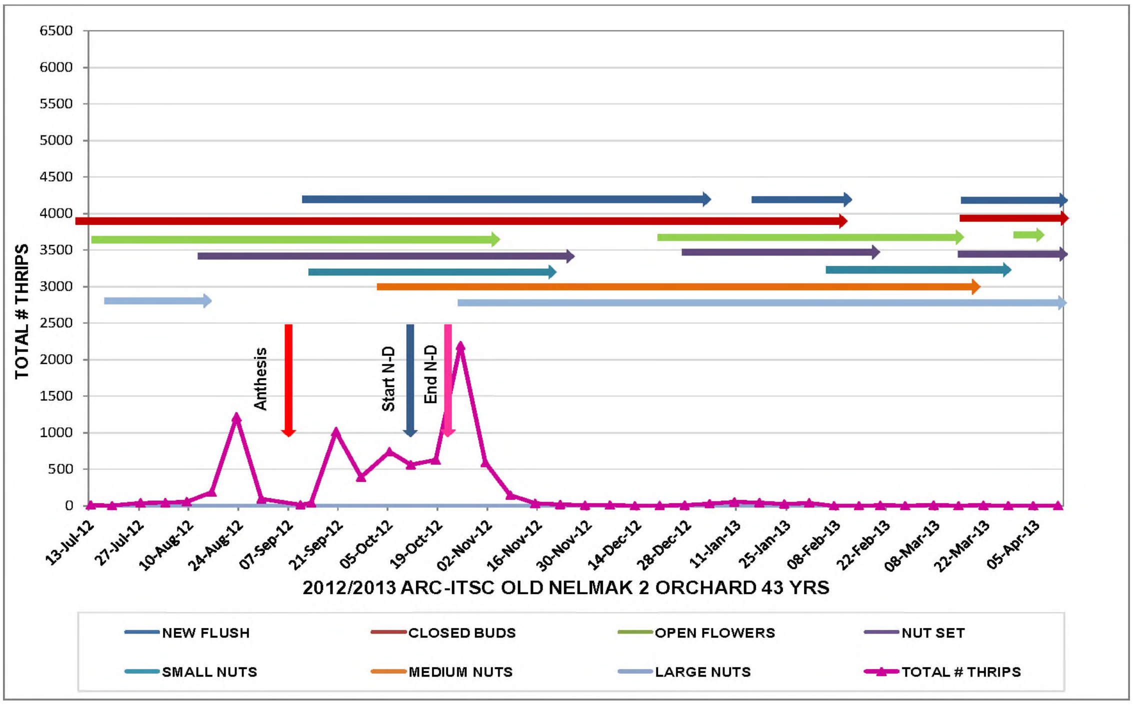


Figure 4.19 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Nelmak 2 Orchard (43-year-old) site.

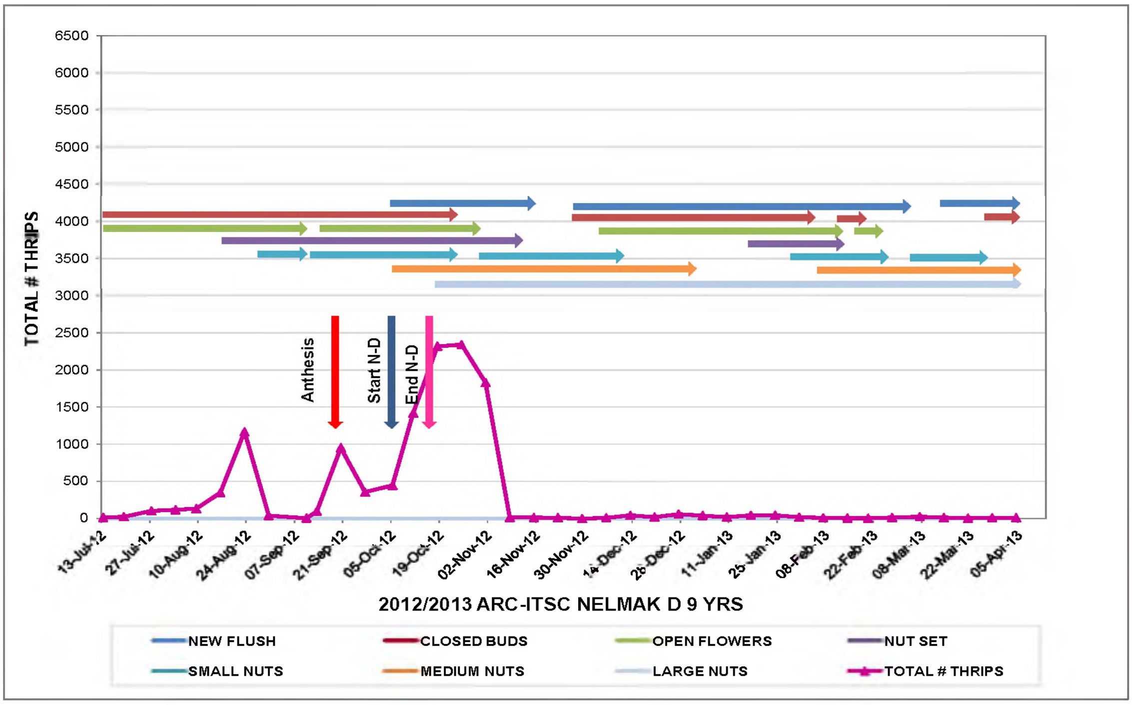


Figure 4.20 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Nelmak D (9-year-old) site.

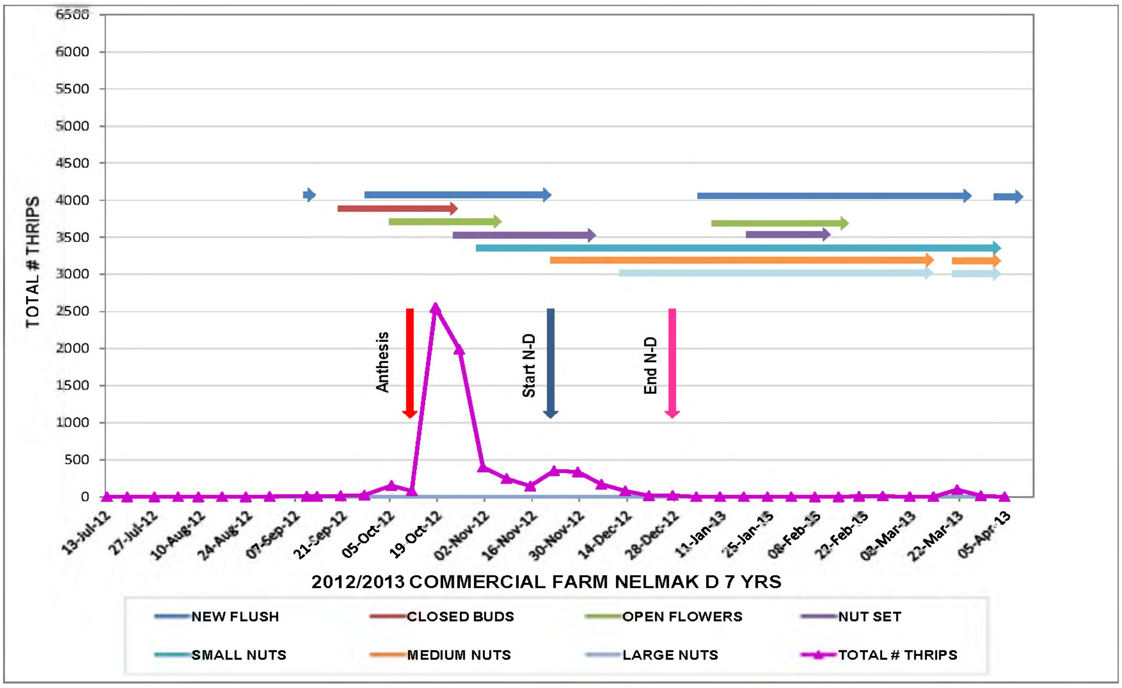


Figure 4.21 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Nelmak D (7-year-old) site.

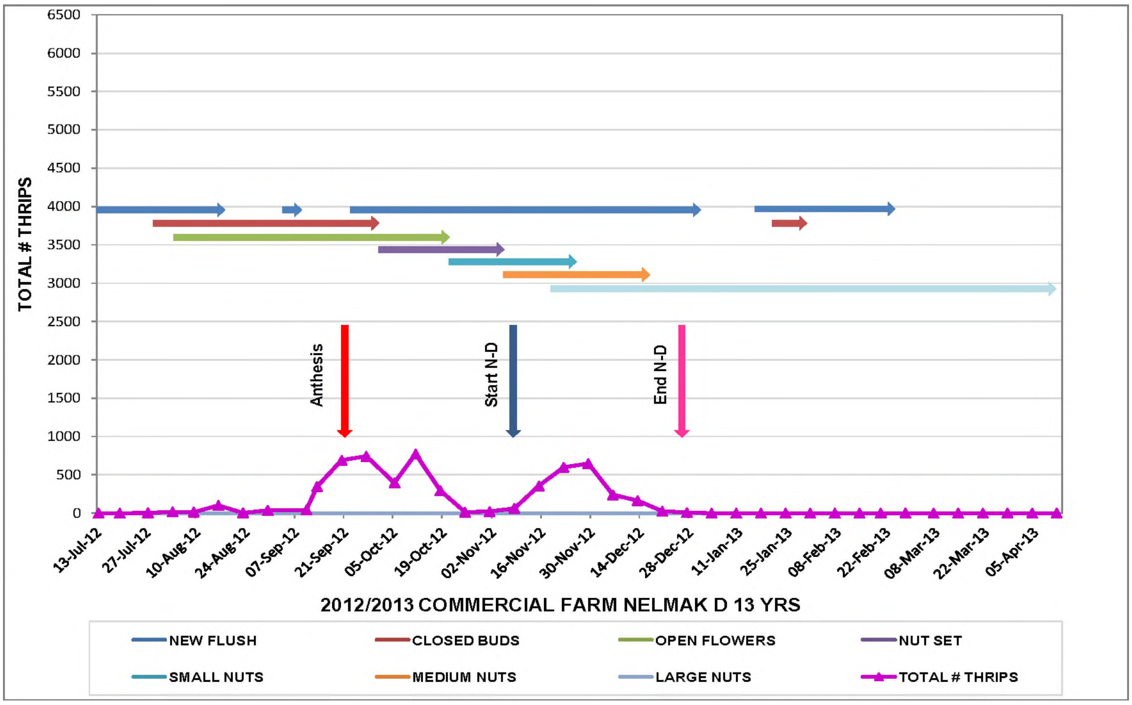


Figure 4.22 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Nelmak D (13-year-old) site.

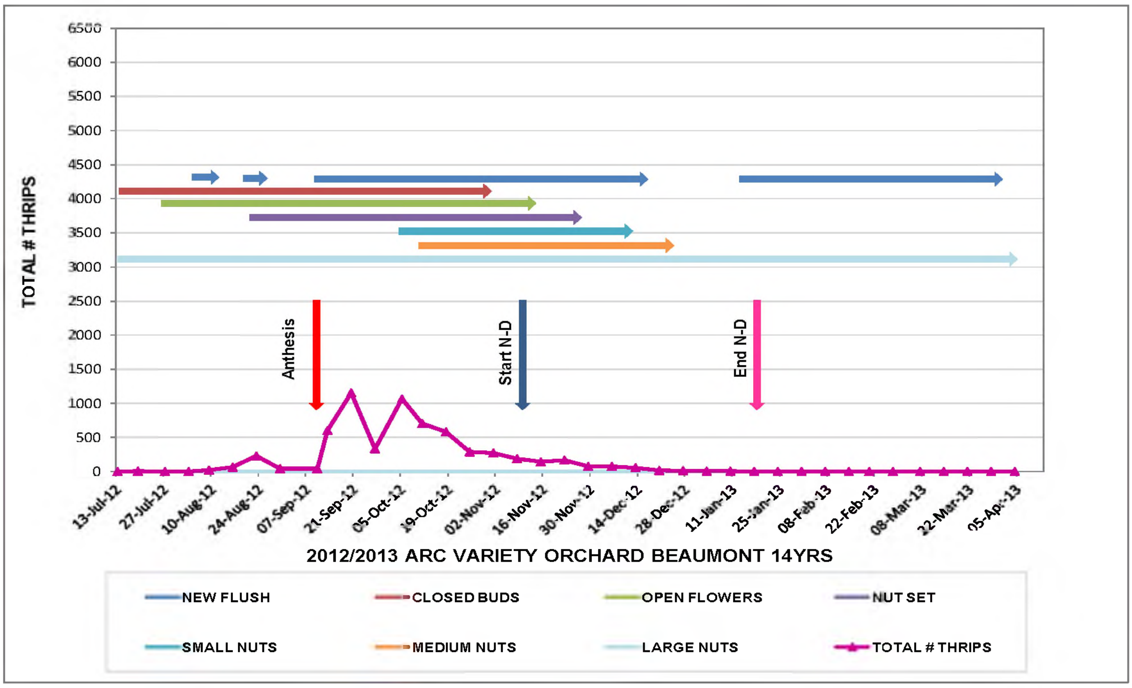


Figure 4.23 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard Beaumont (14-year-old) site.

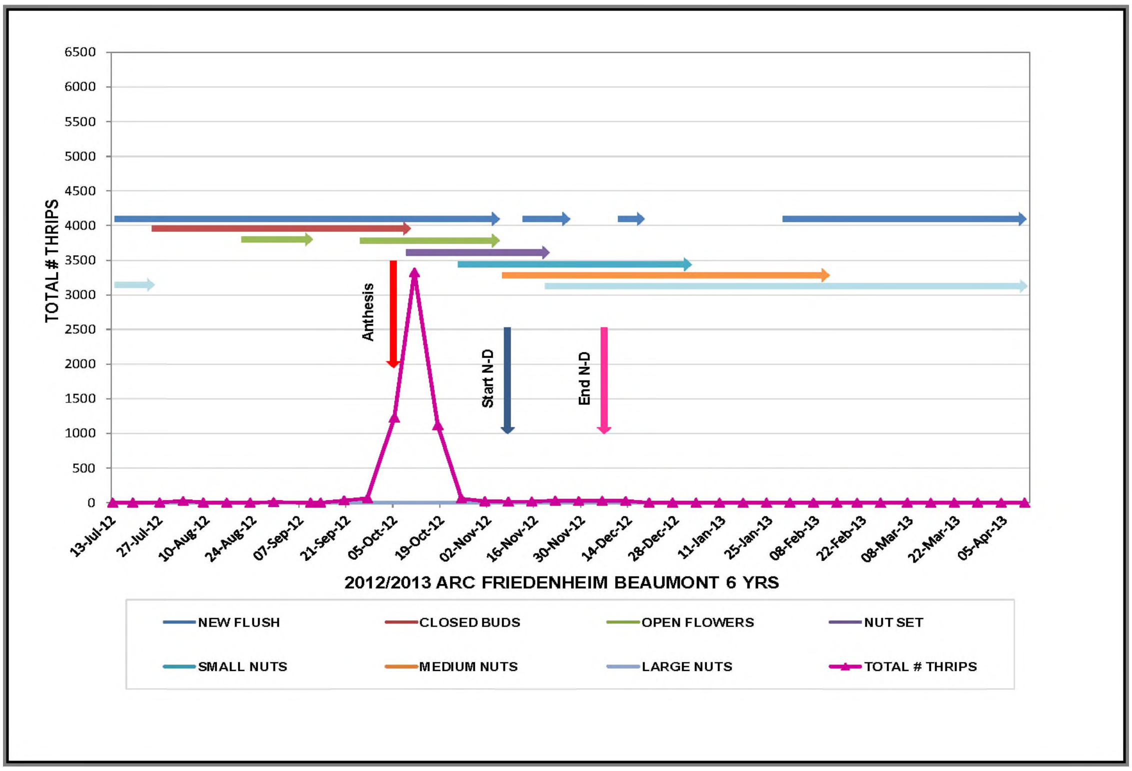


Figure 4.24 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC Friedenheim Beaumont (7-year-old) site.

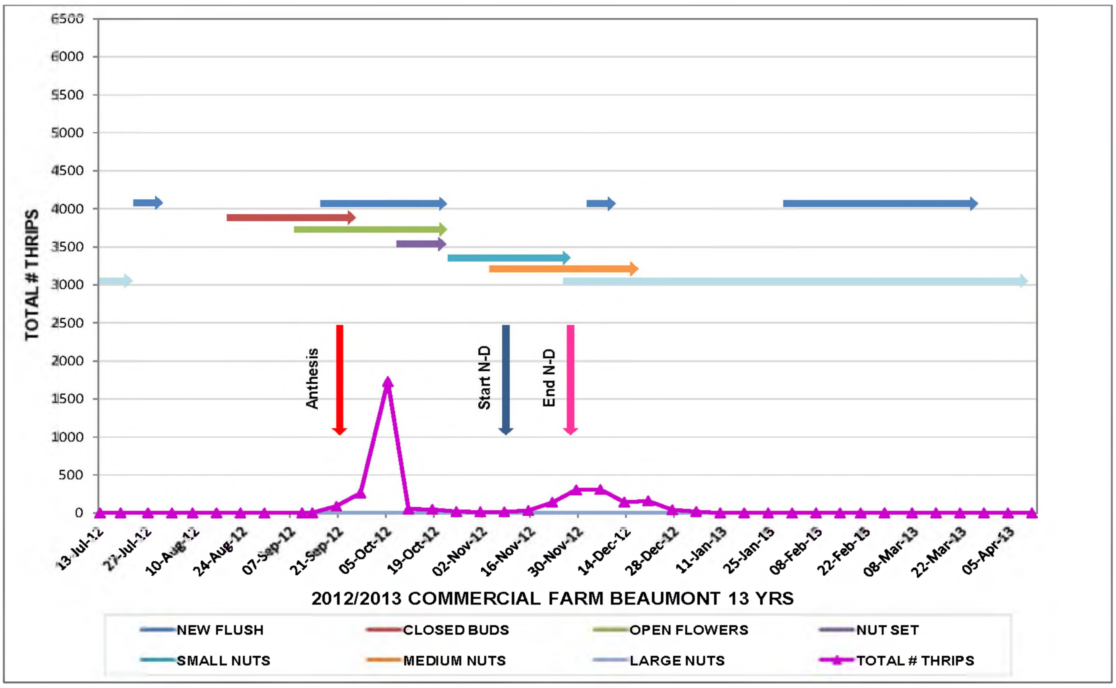


Figure 4.25 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm Beaumont (13-year-old) site.

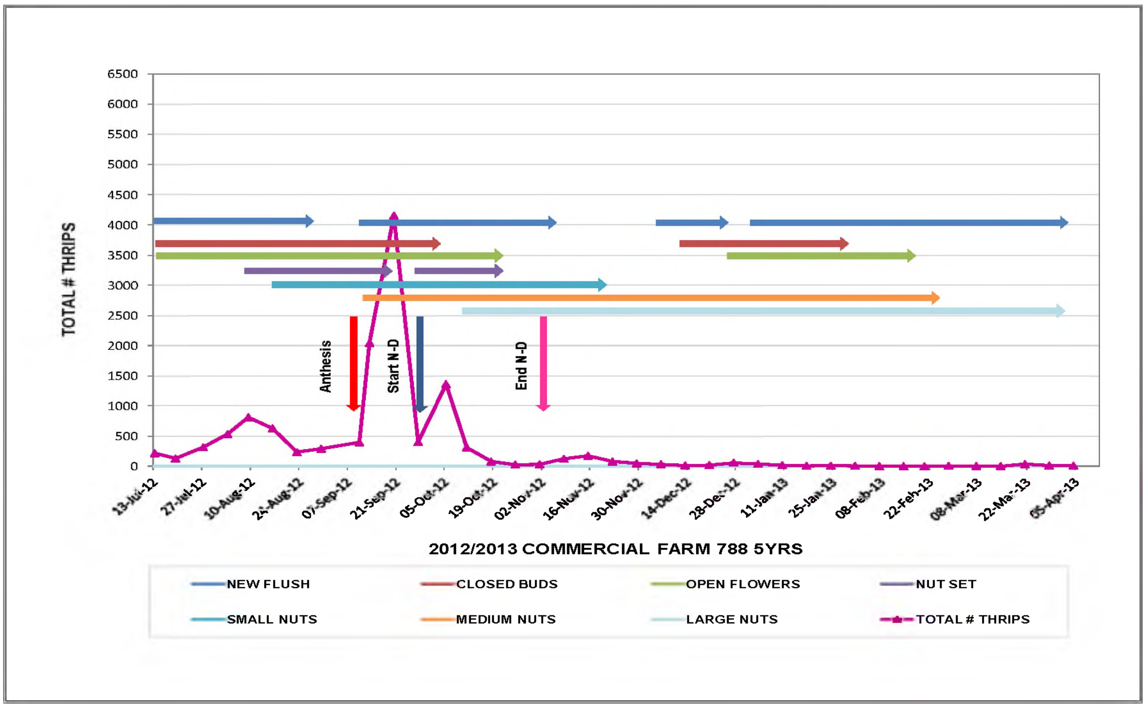


Figure 4.26 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm 788 (5-year-old) site.

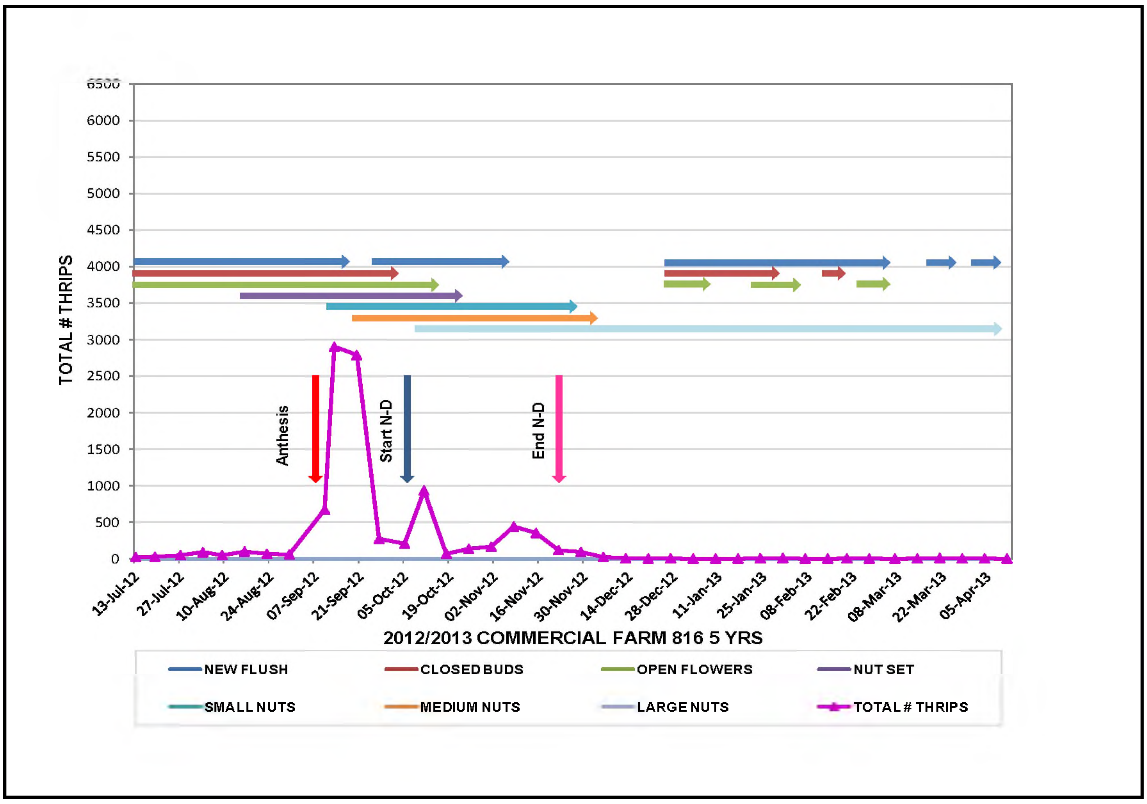


Figure 4.27 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the Commercial Farm 816 (5-year-old) site.

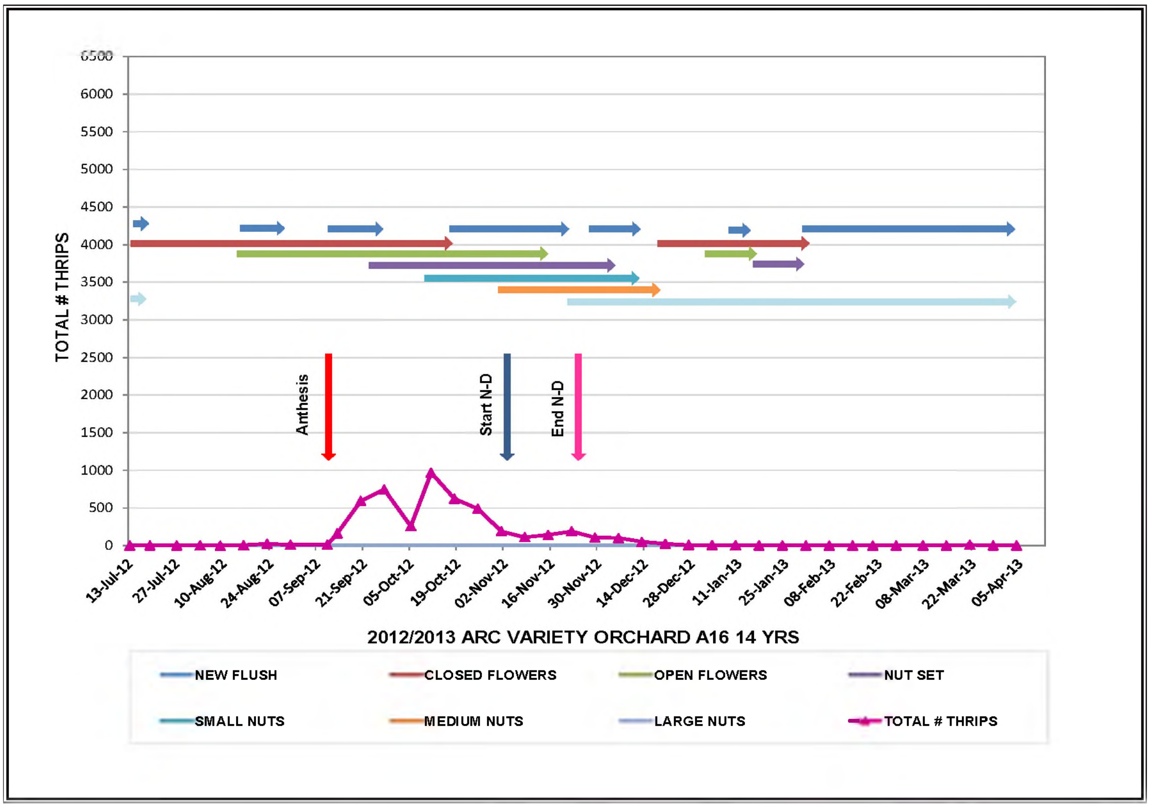


Figure 4.28 2012/2013 Macadamia phenology, time of anthesis, duration of immature nut-drop and thrips present at the ARC-ITSC Variety Orchard A16 (14-year-old) site.

4.3.2 Anthesis and immature nut-drop

The study sites collectively for both seasons (n = 23 sites) were analysed qualitatively to compare differences within and between sites (Table 4.2). Anthesis for each site was determined using the photographic data. The beginning and end of initial immature nut-drop was calculated using weekly nut abscission data (Chapter 6) and photographs of a sample of the abscised nuts from each site to establish size. During both seasons the time between anthesis and the beginning of abscission at each site averaged 5 weeks; the time between the start of abscission and the end of initial nut-drop at each site averaged 6 weeks.

Table 4.2 Macadamia study sites showing dates of anthesis, period between anthesis and the beginning of abscission, the duration and end of initial nut-drop during the 2011/2012 and 2012/2013 growing seasons.

Orchard, Age and Season	Date of Anthesis	Weeks: Anthesis to Abscission	Date Start of Abscission	Duration: Weeks	Date End Initial Nut-Drop
ARC Nel D 8/9 Yr					
2011/2012	16 Sep 2011	7	3 Nov 2011	5	1 Dec 2011
2012/2013	20 Sep 2012	2	5 Oct 2012	3	18 Oct 2012
CF Nel D 6/7 Yr					
2011/2012	27 Sep 2011	5	3 Nov 2011	6	8 Dec 2011
2012/2013	13 Oct 2012	4½	15 Nov 2012	7	27 Dec 2012
CF Nel D 12/13 Yr					
2011/2012	17 Sep 2011	6½	3 Nov 2011	5	1 Dec 2011
2012/2013	13 Sep 2012	5	18 Oct 2012	7	29 Nov 2012
ARC VO Nel 2 13 Yr					
2011/2012*	4 Oct 2011	4½	3 Nov 2011	8	22 Dec 2011
ARC Old Nel 2 43 Yrs					
2012/2013*	10 Sep 2012	4½	11 Oct 2012	3	25 Oct 2012
ARC VO B'mont 13/14 Yr					
2011/2012	26 Sep 2011	5½	3 Nov 2011	7	15 Dec 2011
2012/2013	10 Sep 2012	5½	18 Oct 2012	7	29 Nov 2012
ARC F. Heim B'Mont 6/7 Yr					
2011/2012	27 Sep 2011	5½	3 Nov 2011	5	1 Dec 2011
2012/2013	5 Oct 2012	5	8 Nov 2012	4	29 Nov 2012
CF B'mont 12/13 Yr					
2011/2012	21 Sep 2011	4	20 Oct 2011	7	1 Dec 2011
2012/2013	20 Sep 2012	4	18 Oct 2012	7	29 Nov 2012
ARC VO 788 13 Yrs					
2011/2012*	19 Sep 2011	5½	27 Oct 2011	5	24 Nov 2011
CF 788 4/5Yr					
2011/2012	10 Sep 2011	5½	20 Oct 2011	5	18 Nov 2011
2012/2013	10 Sep 2012	6½	27 Sep 2012	4	18 Oct 2012
ARC VO 816 13 Yr					
2011/2012*	19 Sep 2011	5½	27 Oct 2011	7	8 Dec 2011

Orchard, Age and Season	**Date of Anthesis**	**Weeks: Anthesis to Abscission**	**Date Start of Abscission**	**Duration: Weeks**	**Date End Initial Nut-Drop**
CF 816					
4/5 Yr					
2011/2012	17 Sep 2011	4½	20 Oct 2011	6	24 Nov 2011
2012/2013	10 Sep 2012	2½	27 Sept 2012	7	8 Nov 2012
ARC VO A4					
13 Yr					
2011/2012*	3 Oct 2011	5½	10 Nov 2011	6	15 Dec 2011
ARC VO A16					
13/14 Yr					
2011/2012	3 Oct 2011	3½	27 Oct 2011	7	8 Dec 2011
2012/2013	13 Sep 2012	7	1 Nov 2012	4	22 Nov 2012
Average Overall		**5**		**6**	

*Denotes study sites where data was only collected during one growing season.

4.3.3 Phenological variation between cultivars

One of the seven phenological stages recorded was “nut-set” which was used to determine which of the cultivars, if any, bore a secondary, late crop (Table 4.3). It was determined that nut-set is a more accurate indication as to whether the cultivar set a secondary crop or not, as periodic flowering sometimes occurred with no subsequent nut-set or further maturing stages. Two examples of this happened during the 2012/2013 season at both the 788 and 816 sites at the Commercial Farm; open flowers were present on 27 December 2012, but no subsequent developmental stages or nut-set occurred (Figs. 4.26 and 4.27).

Over both study periods, without exception, no secondary nut-set was present at any of the Beaumont cultivar sites, whether the sites were managed or not (Table 4.3 and Figs. 4.10-4.12, 4.23-4.25).

Table 4.3 2011/2012 and 2012/2013 secondary, late out-of-season macadamia crop at study sites (grouped by cultivar).

Study Site and Growing Season	**Unmanaged / Managed**	**2nd Late Crop**	**Phenological Stage**	**Date**
ARC-ITSC Old Nel 2 43 Yrs				
2012/2013	Unmanaged	Yes	Nut-set	27/12/12
ARC-ITSC Nel D 8/9 Yrs				
2011/2012	Unmanaged	Yes	Nut-set	10/05/13
2012/2013	Unmanaged	Yes	Nut-set	17/01/13

Study Site and Growing Season	Unmanaged / Managed	2nd Late Crop	Phenological Stage	Date
ARC-ITSC VO Nel 2 13 Yrs				
2011/2012	Unmanaged	Yes	Nut-set	29/03/12
Comm Farm Nel D 6/7 Yrs				
2011/2012	Managed	No	-	-
2012/2013	Managed	Yes	Nut-set	17/01/13
Comm Farm Nel D 12/13 Yrs				
2011/2012	Managed	No	-	-
2012/2013	Managed	No	-	-
ARC-ITSC VO B'mont 13/14 Yrs				
2011/2012	Unmanaged	No	-	-
2012/2013	Unmanaged	No	-	-
ARC F. Heim B'mont 6/7 Yrs				
2011/2012	Unmanaged	No	-	-
2012/2013	Unmanaged	No	-	-
Comm Farm B'mont 12/13 Yrs				
2011/2012	Managed	No	-	-
2012/2013	Managed	No	-	-
ARC-ITSC VO 788 13 Yrs				
2011/2012	Unmanaged	Yes	Nut-set	23/02/12
Comm Farm 788 4/5 Yrs				
2011/2012	Managed	No	-	-
2012/2013	Managed	Yes	Open flowers	27/12/12
ARC-ITSC VO 816 13 Yrs				
2011/2012	Unmanaged	Yes	Nut-set	23/02/12
Comm Farm 816 4/5 Yrs				
2011/2012	Managed	No	-	-
2012/2013	Managed	Yes	Open flowers	27/12/12
ARC-ITSC VO A4 13 Yrs				
2011/2012	Unmanaged	No	-	-
ARC-ITSC VO A16 13/14 Yrs				
2011/2012	Unmanaged	Yes	Nut-set	23/02/12
2012/2013	Unmanaged	Yes	Nut-set	17/01/13

Even though it is said that Nelmak do not set nuts out-of-season (Wiid-Hobson 2003), this proved correct only for the two Nelmak D sites at the Commercial Farm; during 2011/2012 at both the Nelmak D 6- (Fig. 4.8) and 12-year-old (Fig. 4.9) orchards; and in

2012/2013 at the Nelmak D 13-year-old site (Fig. 4.22). During 2012/2013 the Commercial Farm Nelmak D 7-year-old orchard bore out-of-season flowers and subsequently nut-set (Fig. 4.21), as did every one of the ARC Nelmak cultivar stands over both the 2011/2012 and 2012/2013 study periods (Table 4.3 and Figs. 4.6, 4.7, 4.19, 4.20).

Looking at the unmanaged orchards over the two-year period (excluding the Beaumont sites), a secondary, off-season crop was set at all sites apart from the ARC-ITSC Variety Orchard A4 site in 2011/2012 (Fig. 4.17).

4.3.4 Occurrence of thrips population peaks

Prior to anthesis

During the 2011/2012 study, no thrips population peaks occurred prior to anthesis. However, during the 2012/2013 season, population peaks, not the major peak, occurred at 4 sites before anthesis: ARC Old Nelmak 2 43-year-old (2 weeks prior) (Fig. 4.19); ARC Nelmak D 9-year-old (4 weeks prior) (Fig. 4.20); ARC Variety Orchard Beaumont 14-year-old (2 weeks prior) (Fig. 4.23); and Commercial Farm 788 5-year-old (4 weeks prior) (Fig. 4.26) and Chapter 5). Of these sites, three situated at the ARC were unmanaged, which may have partially contributed towards the occurrence of thrips before anthesis, but the author is unable to account for why the other unmanaged sites at the ARC did not also experience this pre-anthesis thrips peak. This anomaly occurred only during the 2012/2013 season.

Post-anthesis and end of immature nut-drop

Looking at all the sites collectively (n = 23) for both seasons, the major thrips population peaks occurred after anthesis (Table 4.4). Thrips population major peaks occurred: at two of the sites during the same week as anthesis, at six sites 1 week after anthesis, 6 sites - 2 weeks after anthesis; four sites - 3 weeks after anthesis; and five sites - 4 weeks after anthesis.

Before the initiation of abscission, the major thrips peaks had occurred at 21 of the 23 sites. The major peaks at the remaining two sites (ARC Nelmak 2 43-year-old and ARC Nelmak D 9-year-old sites) took place after the initial period of abscission had begun. All major thrips peak events had taken place by the end of the initial nut-drop.

During the 2011/2012 season, late thrips population peaks, again not the major peak (Chapter 5), occurred at four sites after the end of initial abscission: ARC Nelmak D 8-year-old (5 weeks after) (Fig. 4.6); ARC Variety Orchard Nelmak 2 13-year-old (4 weeks after)

(Fig. 4.7); ARC Variety Orchard 788 13-year-old (12 weeks after) (Fig. 4.13); and Commercial Farm 788 4-year-old (3 weeks after) (Fig. 4.14).

Scirtothrips aurantii Fauré, the South African citrus thrips, occurred at 17 of the 23 sites; at the remaining six, no *S. aurantii* populations occurred (Table 4.4 and Chapter 5). *Scirtothrips aurantii* populations only peaked later in the growing seasons; at eight sites *S. aurantii* populations were present before or at the commencement of immature nut-drop.

Table 4.4 2011/2012 and 2012/2013 Macadamia study sites, dates of anthesis, major thrips population peaks, beginning and end of nut-drop events, dates when *Scirtothrips aurantii* were present.

Study Site	**± Date of Anthesis**	**Major Thrips Peak**	**Start Abscission**	**End Initial Nut-Drop**	***Scirtothrips aurantii* Present**
ARC Nel 2 43 Yr 2012/2013	10/09/12	26/10/12	11/10/12	1/11/12	None
ARC Nel D 8 Yr 2011/2012	16/09/11	10/10/11	3/11/11	1/12/11	None
ARC Nel D 9 Yr 2012/2013	20/09/12	19/10/12	5/10/12	25/10/12	None
ARC VO Nel 2 13 Yr 2011/2012	4/10/11	10/10/11	3/11/11	22/12/11	None
CF Nel D 6 Yr 2011/2012	27/09/11	10/10/11	3/11/11	8/12/11	10/11/11
CF Nel D 7 Yr 2012/2013	13/10/12	19/10/12	15/11/12	27/12/12	22/11/12
CF Nel D 12 Yr 2011/2012	17/09/11	26/09/11	3/11/11	1/12/11	1/12/11
CF Nel D 13 Yr 2012/2013	13/09/12	12/10/12	18/10/12	29/11/12	20/10/13
ARC VO B'mont 13 Yr 2011/2012	26/09/11	26/09/11	3/11/11	15/12/11	1/12/11
ARC VO B'Mot 14 Yr 2012/2013	10/09/12	5/10/12	18/10/12	29/11/12	23/11/13
ARC F.Heim B'mont 6 Yr 2011/2012	27/09/11	27/09/11	3/11/11	1/12/11	None
ARC F.Heim B'mont 7 Yr 2012/2013	5/10/12	11/10/12	8/11/12	29/11/12	None
CF B'mont 12 Yr 2011/2012	21/09/11	26/09/11	20/10/11	1/12/11	1/12/11
CF B'mont 13 Yr 2012/2013	20/09/12	5/10/12	18/10/12	29/11/12	30/11/13
ARC VO 788 13 Yr 2011/2012	19/09/11	26/09/11	27/10/11	24/11/11	26/09 & 1/12/11

Study Site	**± Date of Anthesis**	**Major Thrips Peak**	**Start Abscission**	**End Initial Nut-Drop**	***Scirtothrips aurantii* Present**
CF 788 4 Yr 2011/2012	10/09/11	26/09/11	20/10/11	18/11/11	18/11/11
CF 788 5 Yr 2012/2013	10/09/12	21/09/12	27/09/12	18/10/12	16/11/12
ARC VO 816 13 Yr 2011/2012	19/09/11	10/10/11	27/10/11	8/12/11	10/10, 1/12 & 22/12/11
CF 816 4 Yr 2011/2012	17/09/11	26/09/11	20/10/11	24/11/11	26/09, 3/11 & 1/12/11
CF 816 5 Yr 2012/2013	10/09/12	15/09/12	27/09/12	8/11/12	15/09 & 10/11/12
ARC VO A4 13 Yr 2011/2012	3/10/11	10/10/11	10/11/11	15/12/11	10/10 & 1/12/11
ARC VO A16 13 Yr 2011/2012	3/10/11	10/10/11	27/10/11	8/12/11	10/10 & 1/12/11
ARC VO A16 14 Yr 2012/2013	13/09/12	11/10/12	1/11/12	22/11/12	11/10 & 23/11/12

4.4 Discussion

4.4.1 Variation within and between cultivars

There was pseudoreplication within the study sites, only Nelmak D (n >3) approaches true replication. This was caused by various unavoidable limitations (i.e. finding multiple cultivar sites close together for replicates, and time and labour constraints). Variation within and between cultivars could not be quantitatively analysed because there were insufficient replicates (Chapter 1, Table 1.2). However, the data were qualitatively assessed and the data gathered over the two seasons gives an indication of the variation within and between cultivars (Figs. 4.6-4.28).

Future studies of the most productive and profitable cultivars should be undertaken over a period of at least five years, to gather quantitative data to assess performance within and between cultivars.

4.4.2 Effects of orchard management

Comparison cultivar sites were selected where a) no management practices were undertaken; and b) at commercial (managed) sites, to see what effects these had on the macadamia phenology, particularly abscission of nuts, and the occurrence of thrips populations.

The inclusion of the unmanaged ARC-ITSC Old Nelmak 2 43-year-old site proved problematic as the sheer size, canopy area, nut-set and abscission far exceeded any other site. Macadamia trees are not removed from the orchard at any specific age; as long as the return on yield is still economically viable; trees continue producing a crop when they are well over 30-years-old. However, pruning, skirting and topping have to be undertaken to maintain an open canopy, which facilitates light penetration, good coverage of spray applications and makes harvesting easier. The likelihood that Nelmak cultivars set out-of-season nuts, when no management practices are applied, further compounded matters in that different phenological stages were present, over an extended period, over the season.

It is therefore proposed that should Nelmak cultivar orchards be maintained under proper management practices, out-of-season flowering and nut-set would probably not occur, thereby saving the trees' reserves and limiting the duration of insect pest activity. Some of the other cultivars also bore a secondary crop towards the end of the growing season, namely three sites at the ARC Variety Orchard 788, 816 and A16 (2011/2012 season), and the 788 5-year-old site at the Commercial Farm (2012/2013 season). The setting of this secondary crop could present logistical problems when implementing Integrated Pest Management (IPM) programmes as the density of insect pest populations may very well remain at a higher level for longer, thereby increasing economic damage to the crop.

No small, secondary crop was set at any of the Beaumont cultivar sites which may well be another positive trait of this cultivar; it is a very precocious bearer, tolerant of cooler temperatures and bears very high yields (Wiid-Hobson 2003).

4.4.3 Thrips populations pre- and post-anthesis

As sampling only began in September in the 2011/2012 season, it is uncertain when the immigration/increase in numbers in the orchards occurred. During the 2012/2013 season thrips numbers began to gradually increase at the beginning of July, with a minor peak around 23 August, whilst closed-budded racemes were present. Combining the data for both study periods, anthesis occurred around the first week of September, and the numbers of thrips began to escalate, continuing to increase until the highest peaks were attained around 20 September (Chapter 6, Fig. 6.22). By the end of October, the number of thrips numbers had drastically decreased. Minor *S. aurantii* peaks occurred towards the end of November and lasted approximately four weeks.

Over both seasons the highest numbers of thrips were recorded throughout anthesis, and on open blossoms. These high counts prevailed during the time at which the drop of nut-set was initiated, and only began declining towards the end of the abscission of nut-set. This suggests that most of the thrips species present were feeding on the soft tissue of flowers and/or were pollen-feeders. It was not possible to tell whether the abscised nut-set had any thrips feeding damage as the nuts are densly pubescent at this stage.

All major thrips peaks occurred after anthesis. At 21 of the 23 sites collectively these peaks took place before the initiation of immature nut-drop, and at the two remaining sites, after immature nut-drop had begun. In fact, at the time when immature nut-drop began, thrips numbers were already in decline, and all major thrips peak events had taken place by the end of initial nut-drop.

Although a nominal number of *S. aurantii* were present at other times during the seasons, their numbers only peaked at the end of November, coinciding with the presence of new flush in the orchards and only once the numbers of the other thrips species had declined.

The data show that the highest counts were recorded just prior to and during flowering, after which the numbers decreased rapidly, indicating that the presence of blossoms was the primary attraction rather than the nuts themselves.

5 Identification and Phenology of Thrips (Thysanoptera) Species in *Macadamia* Orchards, Southern Mpumalanga

5.1 Introduction

Many thrips species are polyphagous, moving between host plants so that often there are more than one species present in a commercial crop. Not all species cause damage; some are predacious; others can be polyphagous, predacious and even cannibalistic at times; and then there are the pollen and fungi feeding species. A number of factors also significantly contribute to the overall impact thrips infestations have on cultivated crops; the size of thrips populations, growth stage of the host plant, vulnerability to direct feeding and oviposition damage or to virus infection, the duration of the infestation and the temperature and climatic conditions conducive to thrips population growth (Lewis 1997a). Bearing these interactions in mind, this research was conducted to ascertain the thrips species communities and link their phenology with that of the macadamia crop.

During the 2011/2012 and 2012/2013 macadamia growing seasons a number of thrips species were collected from the study sites (Chapter 1, Table 1.2). It was imperative that correct identifications of the thrips species were made and reference specimens prepared and recorded. The challenge was to get to know the species from their appearance, both in preservative and from slide-mounted specimens. *Scirtothrips aurantii* Fauré, the South African citrus thrips, is a species of economic agricultural importance in South Africa; as Nelspruit is in a major citrus and subtropical fruit producing region, it could be assumed that this would be the dominant species in macadamia orchards.

A study of the phenology of the cultivars was undertaken to reveal if there was any relationship between the developmental phases of the host plant and the time at which thrips species occurred over the growing season. It was important to get a precise "snap shot" of the thrips species present each week and to plot these data against the phenology of the cultivars. Weekly samples of thrips were collected from five data trees at each site, to determine if:

a) thrips populations were present;

b) and/or when thrips occurred in the orchards;

c) the number of thrips increased or decreased when specific developmental stages were present (5.2 below);

d) there were phenological differences in the growth stages within and between cultivars (early- and late-season) and how this relates to the presence of thrips over these periods; and

e) there were any significant differences between the number of thrips and abscised nuts at managed and unmanaged study sites of the same cultivar.

5.2 Materials and methods

The growth points sampled included seven stages of macadamia development: new flush, closed buds, open flowers, nut-set, small, medium and large nuts. Not all stages were present at the same time; there were usually 3 or 4 developmental stages on the data trees. Samples were collected from a total of 20 growth points per tree; when various developmental stages occurred simultaneously, a mixed sample incorporating the different stages were collected.

Weekly samples from the five data trees at each study site were collected using a direct sampling technique devised by the author. The growth tip to be sampled (e.g. new flush, flower, fruit), was carefully held in the centre of a cylindrical container (8 cm wide by 17 cm high), containing 5 ml of 90% ethyl alcohol, and firmly shaken to dislodge any thrips. This technique was developed to ensure the specimens would be rendered immobile immediately, thereby removing the threat of them escaping whilst sampling the 20 growth points from each data tree.

After sampling a total of 20 growth tips, a fine paintbrush was used to transfer the contents, including plant debris, from the cylinder into a pre-marked plastic vial containing a collection label. The same sampling and processing protocols were used throughout both seasons to allow comparative analyses (Hepburn and Stiller, 2013).

The weekly samples were examined using a dissection microscope. For the first 8 weeks or so, excessive amounts of plant debris consisting of blossoms, dried florets and tiny nuts from initial nut-set, were collected when shaking the growth points over the collecting container of alcohol. Each vial was individually processed; the contents were emptied into a tea strainer positioned over a Petri dish. A pipette filled with 90% alcohol was used to repeatedly rinse the sample with alcohol to separate the thrips from the plant debris; this was continued until there were no thrips left on the debris. The remaining plant debris in the strainer was checked under the microscope for any remaining individuals, after which the insect by-catch was removed and the debris discarded. The excess alcohol was siphoned from the Petri dish using a pipette; the thrips were counted and stored in microreaction vessels containing 90% alcohol. These were sent for identification to Mr. M. Stiller of the National Collection of Insects, Biosystematics Division, Agricultural Research Council, Plant Protection Research (ARC-PPR, formerly PPRI), Pretoria, South Africa.

Photographs were taken of whole specimens, especially those which appeared visually different from the individuals in the rest of the sample, using a Zeiss Stemi 2000-C microscope (zoom range 6.5x - 50x) with an Axiocam ERc 5s camera attached. This served to assist with the identification of specimens collected throughout the study period.

For identification purposes, to facilitate distinction between the various species, specimens from the weekly samples were sorted within the Petri dish into groups by colour or if they were predatory, before counting with the aid of a dissection microscope. The colouration groups included yellow, brown, grey/brown and black, with two additional groups, the leaf-feeding Panchaetothripinae and predatory *Scolothrips* species.

Preparing slide-mounted specimens for identification involved placing specimens in 10% sodium hydroxide (NaOH) to remove soft tissues from within the exoskeleton (clearing the specimen). The abdomen of the specimen was punctured and gently massaged to expel most of the body contents. Once cleared, the thrips were rinsed, dehydrated in alcohol, transferred to clove oil and then mounted on a microscope slide in Canada Balsam centred on the slide, with legs, antennae and wings positioned appropriately and covered with a cover-slip. For this study, maceration was very time-consuming, lasting hours or even days as the specimens took longer to clear as they were preserved in 90% alcohol. This strong alcohol denatured the gut contents and viscera to such an extent that maceration was less effective. The high ethanol concentration was however necessary to preserve specimens for future genetic analyses.

It was noted that the reaction of the specimen or species to treatment with NaOH during slide preparation could be an indication of the wide and varied feeding sources (M. Stiller pers. comm.). For instance, *Scirtothrips aurantii* Fauré was more difficult to clear in NaOH than other species sorted into the yellow or brown colouration groups (see 5.3 below). The abdomen of *S. aurantii* often contained circular globules that were less readily dissolved than gut contents of the other species. This has been observed in all *S. aurantii* specimens processed for identification, irrespective of the associated feeding plant (M. Stiller pers. comm.), and may suggest that *S. aurantii* feeds on proteins or fatty substances which could be derived from certain parts of the plant (leaves, flowers or fruit). In contrast, a number of the other species in the yellow colouration group cleared readily in NaOH, as did species in the brown group (M. Stiller pers. comm.).

All voucher specimens are deposited in the National Collection of Insects, Biosystematics Division, ARC-PPR, Pretoria, under accession numbers THYS04992–THYS05017, THYS05041, THYS05042 in the Thysanoptera collection and database.

5.3 Results

Identification of the thrips communities

Weekly sampling of the data trees at the thirteen (2011/2012) and ten (2012/2013) study sites, resulted in the total number of growth points sampled as 42,900 and 40,000 respectively (Hepburn *et al.* 2014). The number of thrips collected during the first season was ≈ 44,000, and ≈ 98,000 for the second season; a total of ≈ 142,000 individuals.

The identification of thrips species collected on macadamias in Mpumalanga Province is shown in Table 5.1.

Table 5.1 Thrips communities collected in macadamia orchards, Mpumalanga Province, South Africa, during the 2011/2012 and 2012/2013 growing seasons.

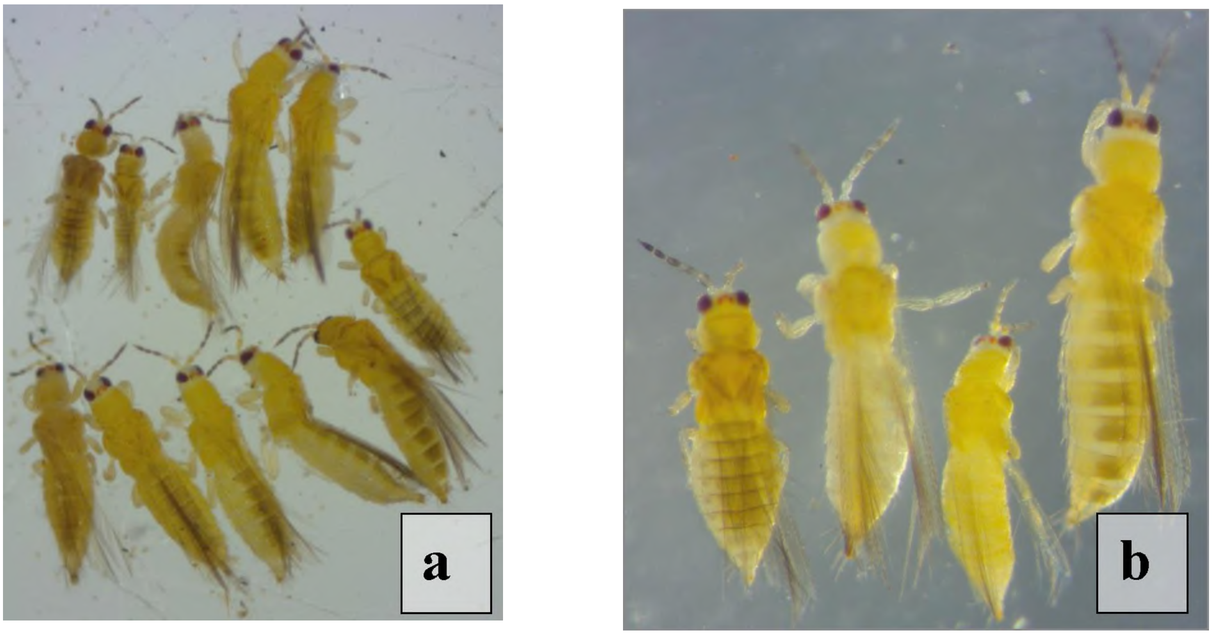
Family	Sub-family	Genus or species	Colouration Group
Suborder Terebrantia			
Thripidae	Thripinae	*Frankliniella occidentalis*	Grey/Brown
		Scirtothrips aurantii	Yellow
		Scolothrips spp.	Yellow
		Thrips acaciae	Yellow
		Thrips gowdeyi	Brown
		Thrips pusillus	Yellow
		Thrips simplex	Dark Brown
		Thrips speratus	Dark Brown
		Thrips tenellus	Yellow
		Thrips microchaetus	Yellow
		Thrips pretiosus	Dark Brown
		Thrips priesneri	Light Brown
		Thrips solari	Medium Brown
		Thrips subnudula	Yellow

Family	Sub-family	Genus or species	Colouration Group
		Megalurothrips sjostedti	Dark Brown/Black
Suborder Tubulifera			
Phlaeothripidae	Phlaeothripinae	*Haplothrips gowdeyi*	Black
		Haplothrips sp.	Black

5.3.1 Yellow group

The highest number of thrips belonged to the yellow group (Fig. 5.1a). Features included were an overall yellow colour, the abdomen either banded with narrow or wide brown markings or uniformly yellow; antennae are either embrowned, uniformly yellow or distinctly brown in segments IV-VII.

The most abundant species of the yellow group, consisted of males and females of *Thrips tenellus* Trybom and *S. aurantii* Fauré (South African citrus thrips), with the latter being the only species recognised as of agricultural importance (M. Stiller, pers. comm.). Two diagnostic characteristics of *S. aurantii* males were the presence of a comb of dark setae on the ventral side of the hind femur and two dark hook-like appendages, drepanae, at the end of the abdomen on either side. The other species collected were *Thrips subnudula* (Karny) (Fig. 5.1b), *Thrips pusillus* Bagnall, *Thrips microchaetus* Karny and *Thrips acaciae* Trybom. The relatively short length of setae on the pronotum was used to recognize *T. subnudula* (Karny). *Thrips pusillus*, *Thrips microchaetus* and *Thrips acaciae* could not be distinguished from each other by any prominent colour or obvious physical features under a dissection microscope. The only way to separate these three species was to make slide-mounts of individual specimens, as reported in Hepburn *et al.* (2014). A key to species is provided by Mound and Stiller, 2011.



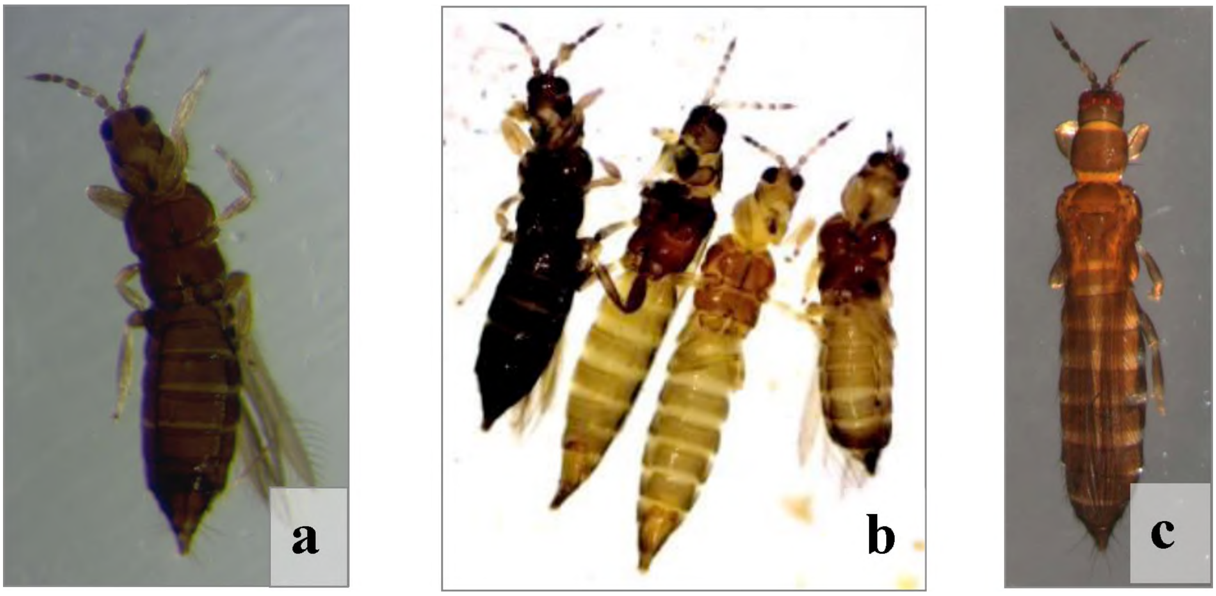
Figures 5.1 a. Specimens of the yellow group depicting colour, shape and size differences. **b.** Left-right: *Scirtothrips aurantii*, *Thrips* sp. (pale abdomen), *Thrips subnudula* and *Thrips tenellus*.

5.3.2 Brown group

Thrips of the brown group were the second-most abundant, comprising *Thrips gowdeyi* (Bagnall), *Thrips speratus* Zur Strassen, *Thrips pretiosus* (Priesner), *Thrips preisneri* Hood, *Thrips solari* (Mound), *Thrips simplex* (Morison) and *Megalurothrips sjostedti* Trybom. The brown group was uniformly brown in specimens that had contracted in the alcohol; in distended specimens, the abdomen appeared lighter in colour than the head, pronotum and thorax.

The brown group (Figs. 5.2 a-b) was dominated by one species, *T. gowdeyi*. In revising the African *Thrips* species, Mound (2010) reported that *T. gowdeyi* was a widely-distributed flower-living species; *T. seperatus* occurred in the northern parts of the Afrotropical region, *T. pretiosus* was known from Zaire, and *T. priesneri* and *T. solari* were described from the Cameroons and Nigeria respectively. These species all had brown bodies and light brown wings and are of similar length and width. Two species in the brown group, namely *M. sjostedti* and *T. simplex* (Fig. 5.2 c), were distinctly larger than the other species in this group; features included their size and longer, more distinct setae on the body and wings. Both these species occurred only rarely in the collection samples from macadamias (Hepburn *et al*. 2014).

An odd member in the brown group was *Frankliniella occidentalis* (Pergande), recognized as grey-brown, with the abdomen brown, and the folded wings and thorax appearing grey. More reliable was the presence of long, paired setae on the anterior margin of the pronotum, readily visible in lateral view. This species occurred in very low numbers.



Figures 5.2 a. and **b.** Specimens showing variation amongst the brown group. **c.** *Thrips simplex*, one of the larger species in the brown group.

5.3.3 Black group

The black group consisted of large specimens, with black, dark brown or sometimes reddish bodies, translucent wings and the apex of the abdomen is tubular, typical of the Tubulifera, Phlaeothripidae. *Haplothrips gowdeyi* (Franklin) was identified from the samples sent for identification, whilst other species of *Haplothrips* could well be present in the remainder of the samples. According to Mound (2013a) this species has a world-wide distribution, and is associated with grasses in the Poaceae. Some records in the South African National Collection (SANC) Thysanoptera database reflect an association with grasses, but include numerous records of flowers of a wide range of plants. The African members of this genus require revision (M. Stiller pers. comm.). The black group occurred at low numbers but were more conspicuous due to their larger body size (Fig. 5.3 a-b); the tubular apex of the abdomen is longer than any of the other groups. Separation to species level can only be achieved by slide-mounting specimens (Hepburn *et al*. 2014).

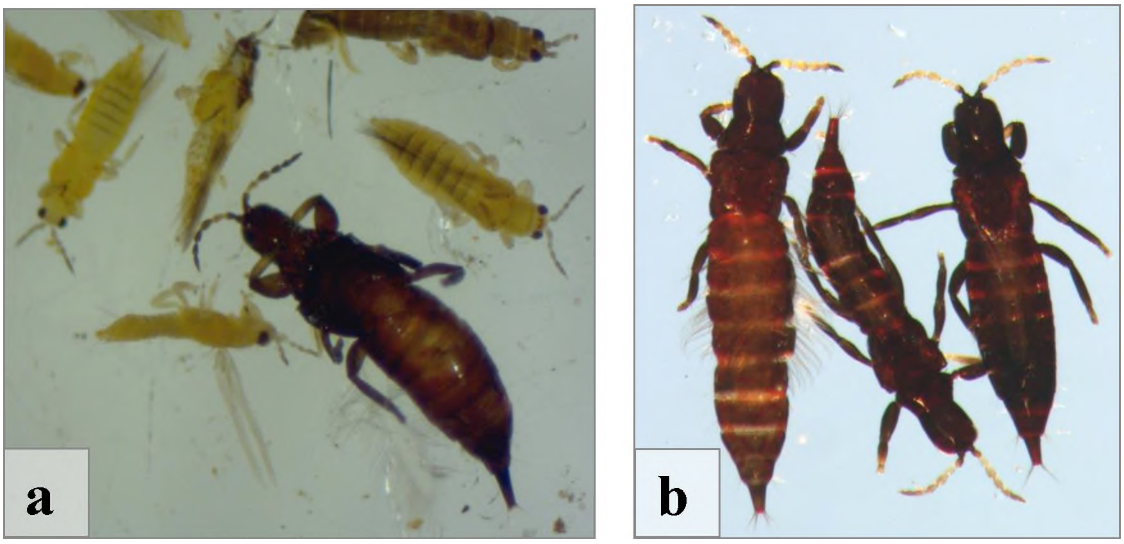
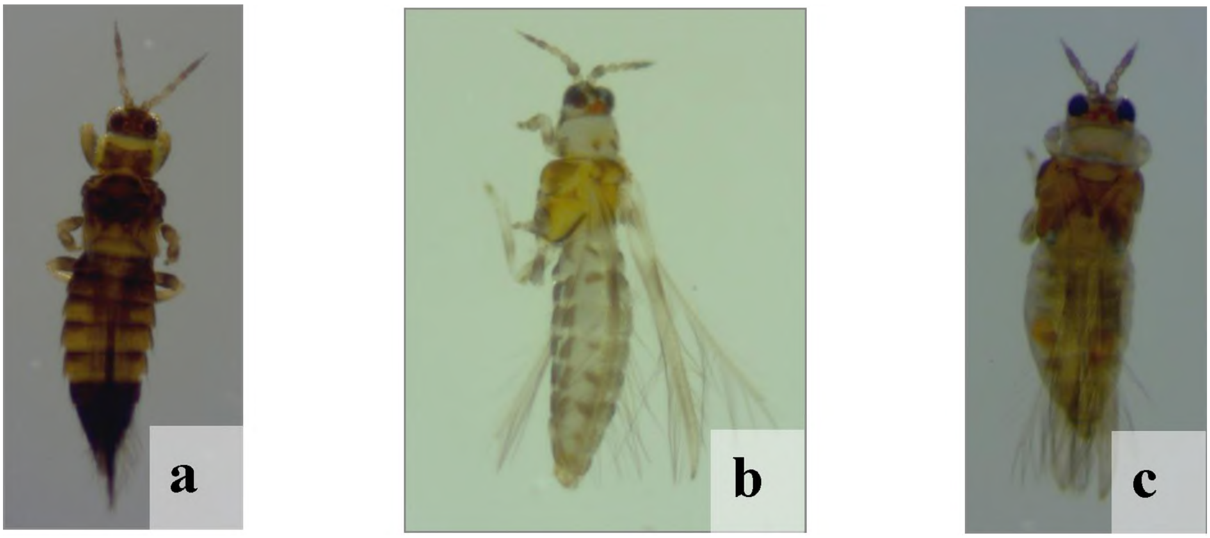


Figure 5.3 a. *Haplothrips* (the large brown individual) amongst yellow thrips species and one Panchaetothripinae specimen (fourth from the top left; yellow with brown markings). **b.** Specimens of the black group showing the distinguishing tubular apex of the abdomen, all *Haplothrips* species.

5.3.4 Leaf-feeding group

Various species of the sub-family Panchaetothripinae, the leaf-feeding group, were collected at very low numbers. The adults were mostly multi-coloured and could be readily recognized by shape of the antennae (specifically the apex), and sometimes, as in the paler specimens, the "collar" on the posterior margin of the head (Figs. 5.4 a-c).



Figures 5.4 a - c Specimens of the leaf-feeding group (Thripidae: Panchaetothripinae), which only rarely occurred in the thrips samples collected from macadamia.

5.3.5 Predatory thrips

Specimens of a predatory thrips, *Scolothrips*, occurred very rarely in the macadamia orchards throughout the two seasons (Hepburn *et al.* 2014). *Scolothrips* species were distinguished by the very long setae on the pronotum which were longer than in any of the species found in this study.

5.3.6 Statistical analysis

A Type III Generalized Linear Model (GLM) was used to estimate the effect of season and management practice on individual species of thrips. Cultivar was not included in the model because not all cultivars were present in both seasons and both management practices. Examination of the data showed that the dispersion parameter was not 1, so a Poisson distribution (which assumes that the dispersion parameter equals 1) would not be appropriate, and instead the quasipoisson family of distributions was chosen and the dispersion parameter estimated in the analysis. The link function was logistic, and the model included an interaction term.

Thrips community dynamics

Scirtothrips aurantii was one of the most abundant species in the orchards. It is a recognised pest of economic importance in South Africa and is easily identifiable within the "yellow group" of thrips; because of these factors precise data were recorded for *S. aurantii*. Two extreme outlying observations (out of 601) were excluded from the data to better meet the assumptions of the model and to minimise biasing the data by including points with excessive leverage, and the resulting GLM had an estimated dispersion parameter of 82.63, justifying the choice to not use a Poisson distribution. Only the interaction of farming management practice (managed = farming practices employed; unmanaged = no farming practices undertaken) and season were statistically significant; the season only slightly exceeding the 0.05 level (Table 5.2). The effect of the interaction was about twice as large as that of farming management practices and over an order of magnitude larger than that of season.

Table 5.2 Effect sizes of Season and Management on numbers of *S. aurantii*, estimated using a Type III Generalized Linear Model with a quasipoisson distribution and a logistic link function.

Source	Estimate	Std. Error	t-value	$P_{(>\|t\|)}$	Deviance
(Intercept)	2.9635	0.1784	16.608	0.0000	
Management	0.1303	0.2145	0.607	0.5438	713.53
Season	0.4116	0.2149	1.915	0.0558	117.41
Management*Season	-1.2964	0.3263	-3.974	0.0001	1427.41

A more detailed model incorporating cultivar or tree age was not feasible due to incomplete replication of cultivars across seasons and management practices, and confounded effects of age and season. For this reason, comparisons of cultivars were made qualitatively.

5.3.7 2011/2012 Season

Over the 33-week collecting period, a total number of 44 066 individual thrips were collected. The data show that thrips populations were already present in all study sites when collections began on 8 September 2011 (Fig. 5.5). This meant that future sampling had to begin earlier in the second season to determine when populations built up, or the time during which immigrating populations moved into the orchards. The combined distribution data show two higher periods of thrips concentration; the first of which was already beginning to increase on 8 September and only declined from around 6 - 13 October 2011.

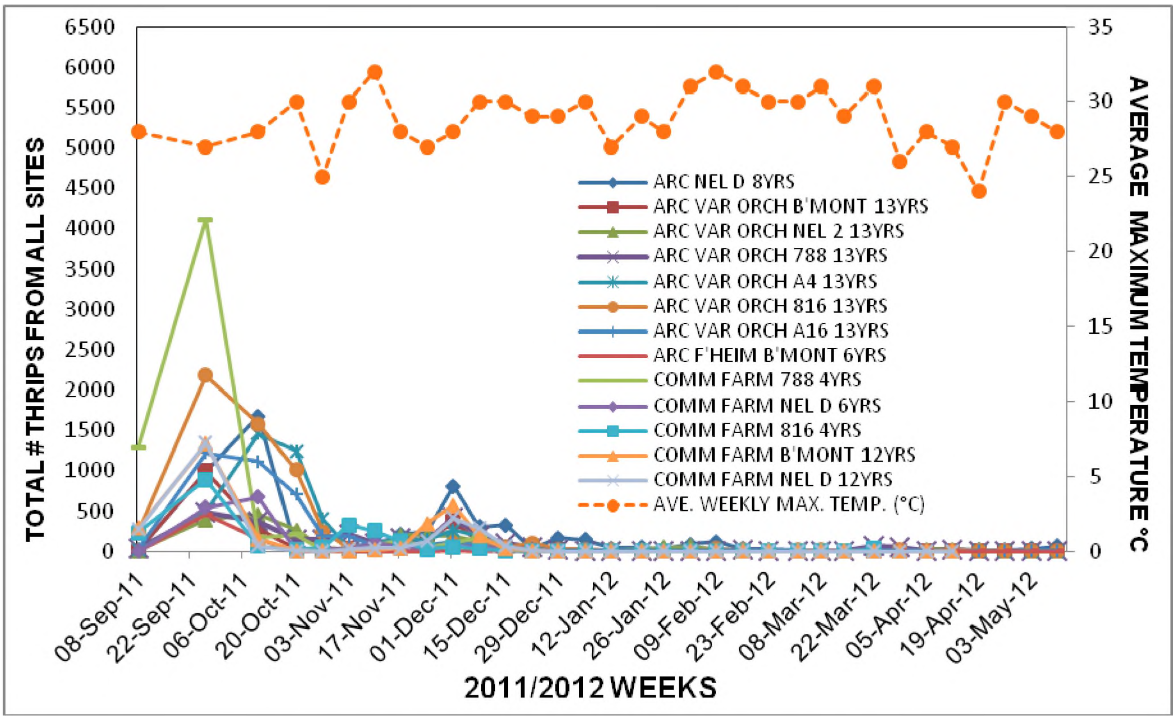


Figure 5.5 Total number of thrips collected during the 2011/2012 season from each of the 13 study sites.

The second, lower concentration is evident over a four-week period, beginning 17 November until 8 December 2011. The major thrips population peaks at all 13 cultivar sites occurred within a two-week period; either on 26 September or 10 October 2011. The total numbers of thrips recorded for all cultivar sites are shown in Table 5.3, and a chronological record of the main thrips population peaks, by cultivar group, are presented in Table 5.4.

Table 5.3 2011/2012 Total number of thrips collected from the five data trees, by study site, in descending order.

STUDY SITE	TREE AGE	MANAGED	THRIPS NOS.
Commercial Farm 788	4	Yes	6,128
ARC Variety Orchard 816	13	No	5,727
ARC-ITSC Nelmak D	8	No	5,350
ARC Variety Orchard A4	13	No	4,658
ARC Variety Orchard A16	13	No	4,084
Commercial Farm Beaumont	12	Yes	3,060
Commercial Farm Nelmak D	12	Yes	2,765
ARC Variety Orchard 788	13	No	2,626
ARC Variety Orchard Nelmak 2	13	No	2,491
Commercial Farm 816	4	Yes	2,323
ARC Variety Orchard Beaumont	13	No	2,258
Commercial Farm Nelmak D	6	Yes	1,989
ARC Friedenheim Beaumont	6	Yes	607
TOTAL:			**44,066**

Table 5.4 2011/2012 Date at which the highest thrips population peaks occurred by cultivar group for all 13 study sites.

SITE SITE	DATE OF MAIN THRIPS PEAK
ARC Variety Orchard Beaumont 13 Yrs	26 September 2011
ARC Friedenheim Beaumont 6 Yrs	26 September 2011
Commercial Farm Beaumont 12 Yrs	26 September 2011
ARC Variety Orchard 788 13 Yrs	26 September 2011
Commercial Farm 788 4 Yrs	26 September 2011
Commercial Farm 816 4 Yrs	26 September 2011
ARC Variety Orchard 816 13 Yrs	10 October 2011
Commercial Farm Nelmak D 12 Yrs	26 September 2011
ARC-ITSC Nelmak D 8 Yrs	10 October 2011
ARC Variety Orchard Nelmak 2 13 Yrs	10 October 2011
Commercial Farm Nelmak D 6 Yrs	10 October 2011
ARC Variety Orchard A4 12 Yrs	10 October 2011
ARC Variety Orchard A16 12 Yrs	10 October 2011

5.3.7.1 Comparison of the Nelmak sites

The composition of species among the four Nelmak sites is shown in Table 5.5 and the distribution of thrips populations and comparisons are presented in Fig. 5.6. The number of population peaks at the Nelmak sites during the season ranged between two and four. At the ARC Nelmak D 8-year-old orchard (Fig. 5.7) the initial (main) peak occurred on 10 October, the second peak on 1 December, the third peak on 29 December 2011, and the final peak on 9 February 2012. In the ARC Variety Orchard Nelmak 2 site (Fig. 5.8) the main peak was also on 10 October, followed by a secondary peak on 17 November 2011, and a third much lower peak on 2 February 2012. Data collected at the Nelmak D 6-year-old orchard at the Commercial Farm (Fig. 5.9) also showed an initial (main) peak on 10 October followed by a second peak on 10 November 2011. Thrips populations in the Nelmak D 12-year-old orchard (Fig 5.10) reached their main peak on 26 September, with a secondary peak occurring on 1 December 2011.

Table 5.5 2011/2012 Comparison of thrips population peaks and composition of species at the Nelmak cultivar sites.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
ARC Nel D 8 Yrs	**10 Oct 2011***	1 Dec 2011	29 Dec 2011	9 Feb 2012
1st (main) peak – low number of larvae, 'yellow other' adult ♀ and ♂; 2nd peak – larvae,				

‘yellow other’ adult ♀ and low number ♂; 3rd peak – larvae, low number ‘yellow other’ adult ♀ and ♂; 4th peak – very low number of larvae, ‘yellow other’ adult ♀.				
ARC Var Orch Nel 2 13Yrs	**10 Oct 2011***	17 Nov 2011	2 Feb 2012	--
1st (main) peak – mainly larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – larvae, ‘yellow other’ adult ♀ and ♂; 3rd peak – very low number of larvae, ‘yellow other’ adult ♀.				
Comm Farm Nel D 6Yrs	**10 Oct 2011***	10 Nov 2011	--	--
1st (main) peak – larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – very low number of larvae, *S. aurantii* adult ♀.				
Comm Farm Nel D 12Yrs	**26 Sept 2011***	1 Dec 2011	--	--
1st (main) peak – larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – low number of larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the ‘main’ peak event.

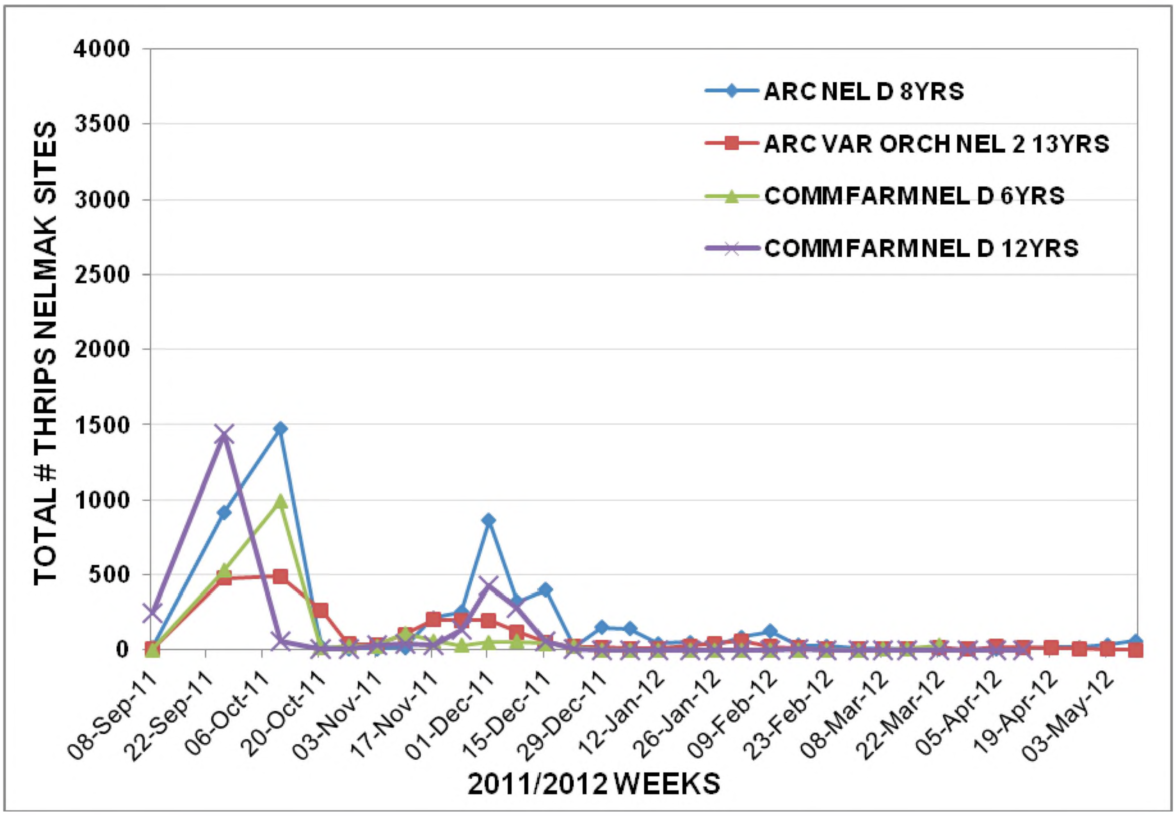


Figure 5.6 2011/2012 Total number of thrips collected from all four Nelmak sites.

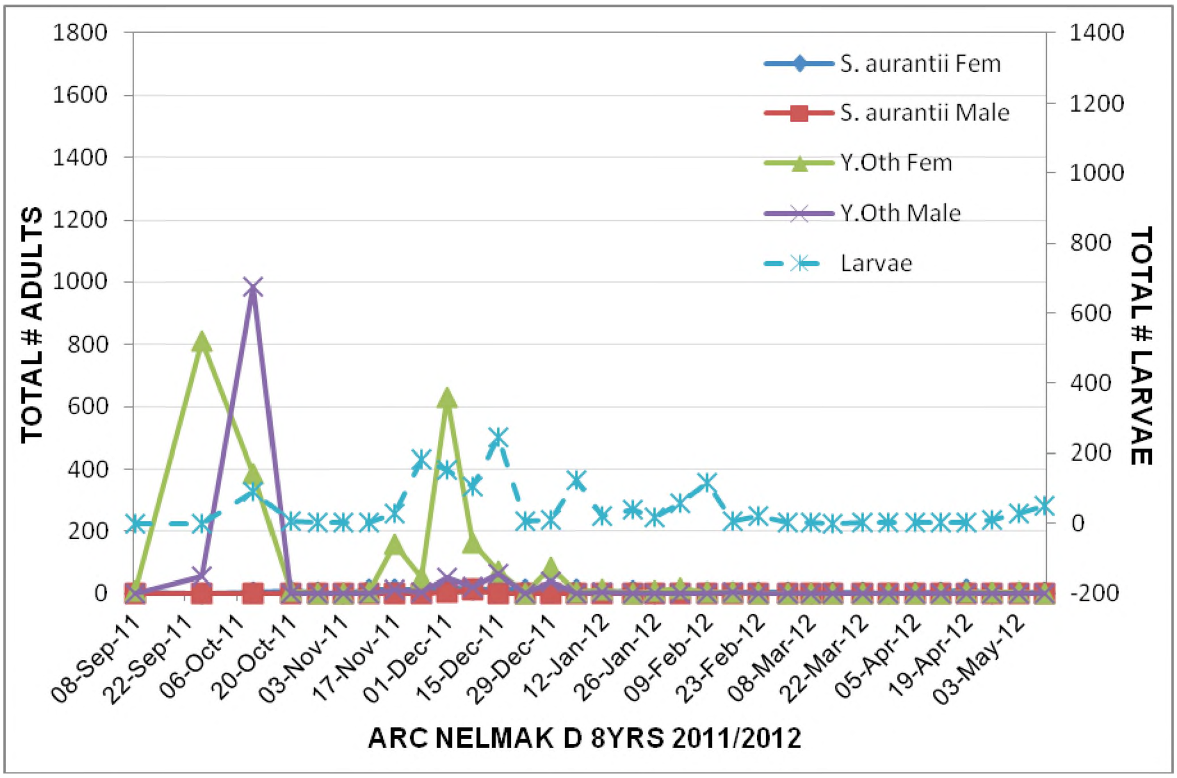


Figure 5.7 2011/2012 Thrips species phenology in the ARC Nelmak D (8-year-old) orchard.

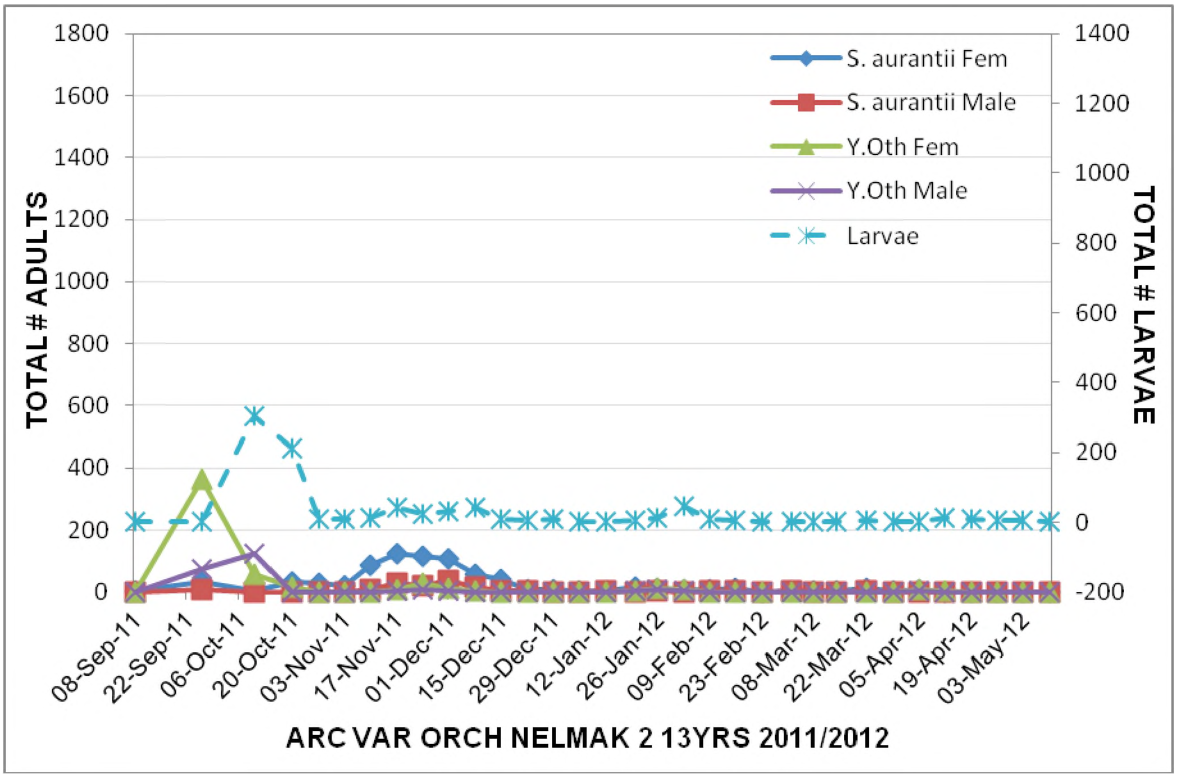


Figure 5.8 2011/2012 Thrips species phenology in the ARC Variety Orchard Nelmak 2 (13-year-old) site.

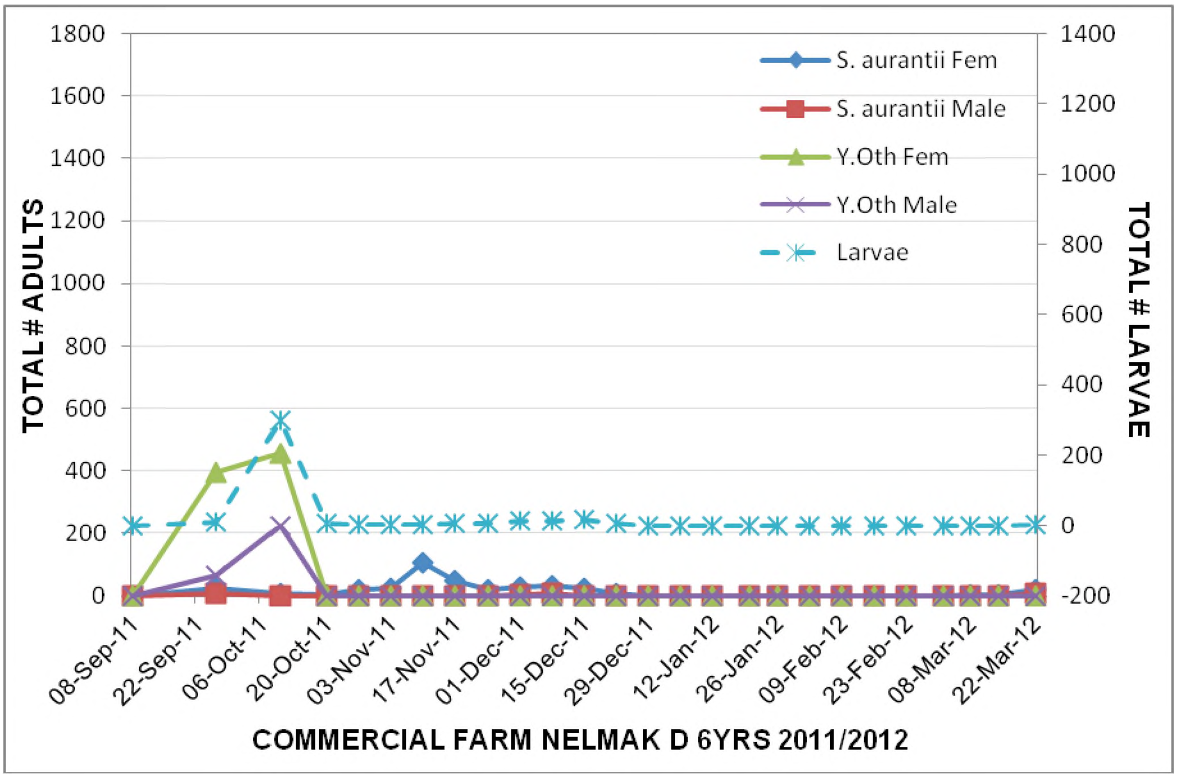


Figure 5.9 2011/2012 Thrips species phenology in the Commercial Farm Nelmak D (6-year-old) orchard.

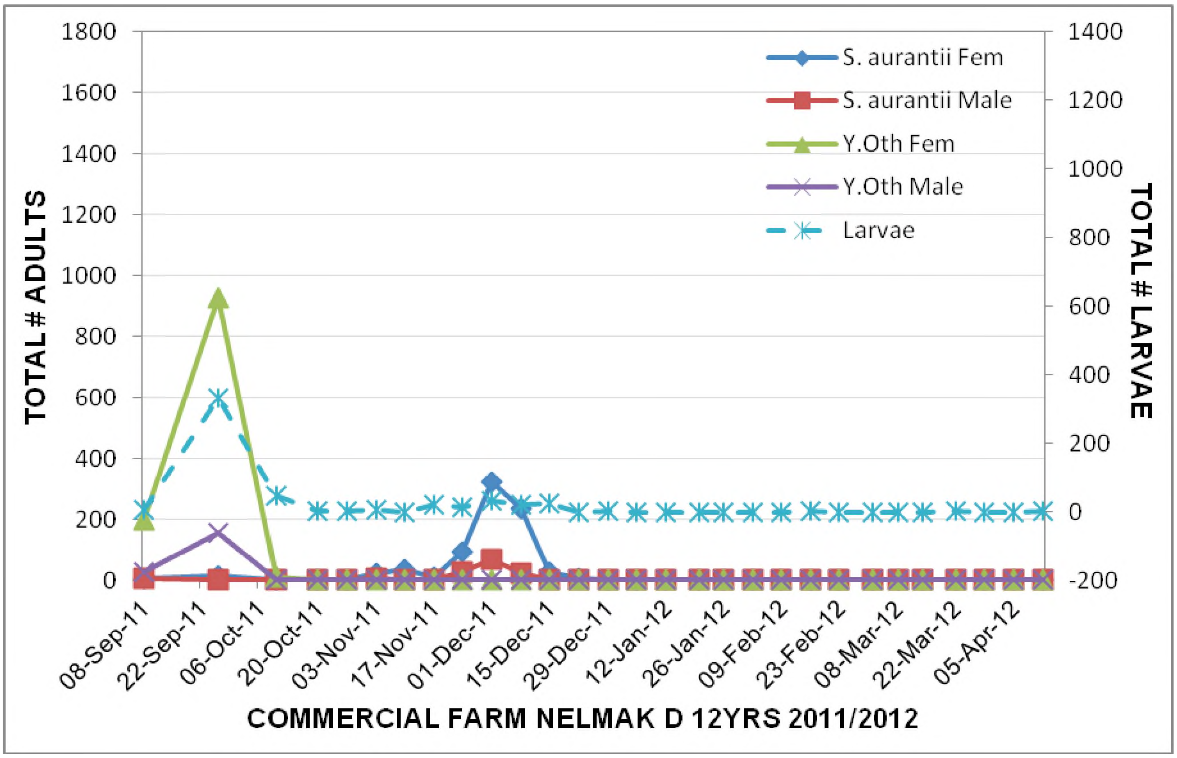


Figure 5.10 2011/2012 Thrips species phenology in the Commercial Farm Nelmak D (12-year-old) orchard.

5.3.7.2 Comparison of the Beaumont sites

Thrips population distributions for the three Beaumont sites are presented in Table 5.6 and Fig. 5.11. The initial (main) peaks at all sites occurred on 26 September, followed by the second and final peak on 1 December at both the ARC Variety Orchard Beaumont 13-year-old (Fig. 5.12) and Commercial Farm Beaumont 12-year-old (Fig. 5.14) orchards. The thrips populations at the ARC Friedenheim Beaumont study site (Fig. 5.13) differed from all other sites in this study in that a second peak of abundance did not occur. This could be attributed to the fact that a synthetic pyrethroid insecticide was applied for Heteroptera control on 17 November and 19 December 2011, and 19 January and 20 February 2012, therefore suppressing a second population peak (see 5.3.8 and Fig. 5.23).

Throughout the first season the number of thrips collected at this site was extremely low apart from the period 26 September to 10 October 2011 when the count for 1 of the 5 data trees reached 199, the next highest count was of 77 individuals. Aside from these two weeks, the counts per data tree were < 7 individuals per week.

Table 5.6 2011/2012 Comparison of thrips population peaks and composition of species at the Beaumont cultivar sites.

Site	**1st Peak**	**2nd Peak**	**3rd Peak**	**4th Peak**
ARC Var Orch Beaumont 13 Yrs	**26 Sept 2011***	1 Dec 2011		
1st (main) peak – low number of larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – low number of larvae, ‘yellow other’ adult ♀ and ♂; *S. aurantii* adult ♀ and ♂.				
ARC Friedenheim Beaumont 6Yrs	**26 Sept 2011***	--	--	--
1st (main) peak – low number of larvae, ‘yellow other’ adult ♀ and ♂.				
Comm Farm Beaumont 12 Yrs	**26 Sept 2011***	1 Dec 2011	--	--
1st (main) peak – larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – low number of larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the ‘main’ peak event.

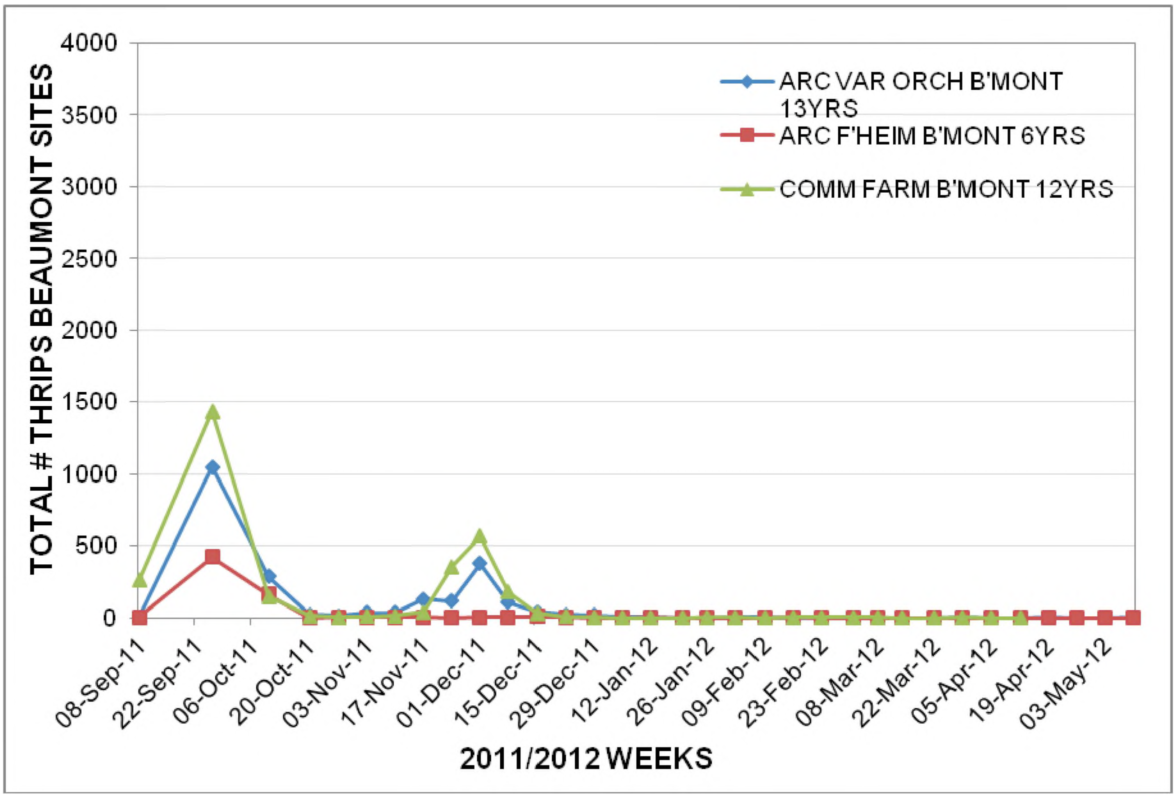


Figure 5.11 2011/2012 Total number of thrips collected from all three Beaumont sites.

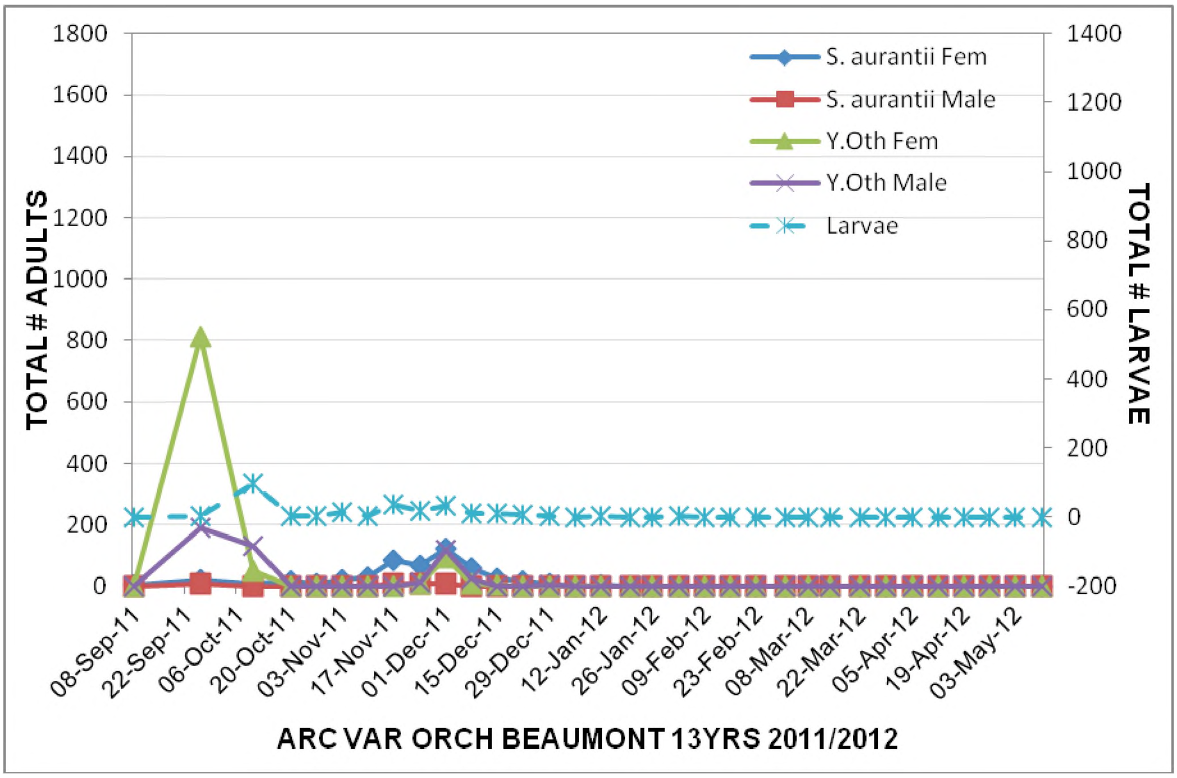


Figure 5.12 2011/2012 Thrips species phenology in the ARC Variety Orchard Beaumont (13-year-old) site.

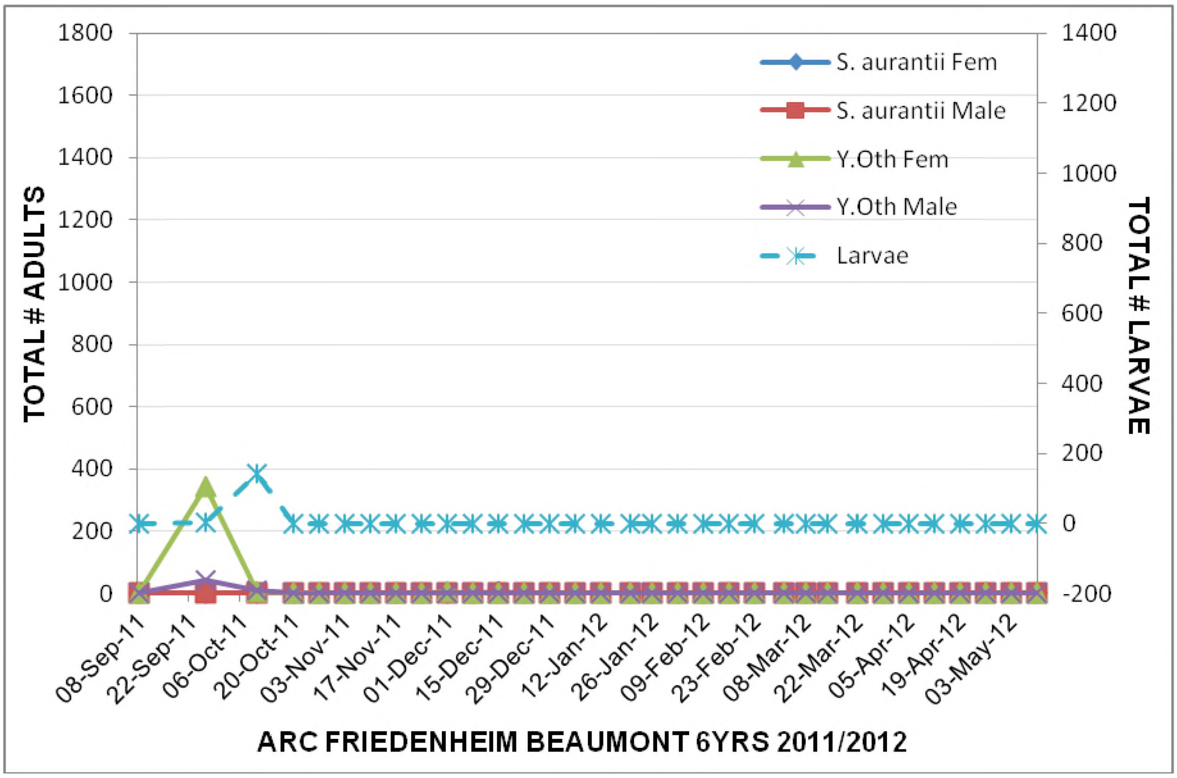


Figure 5.13 2011/2012 Thrips species phenology in the ARC Friedenheim Beaumont (6-year-old) orchard.

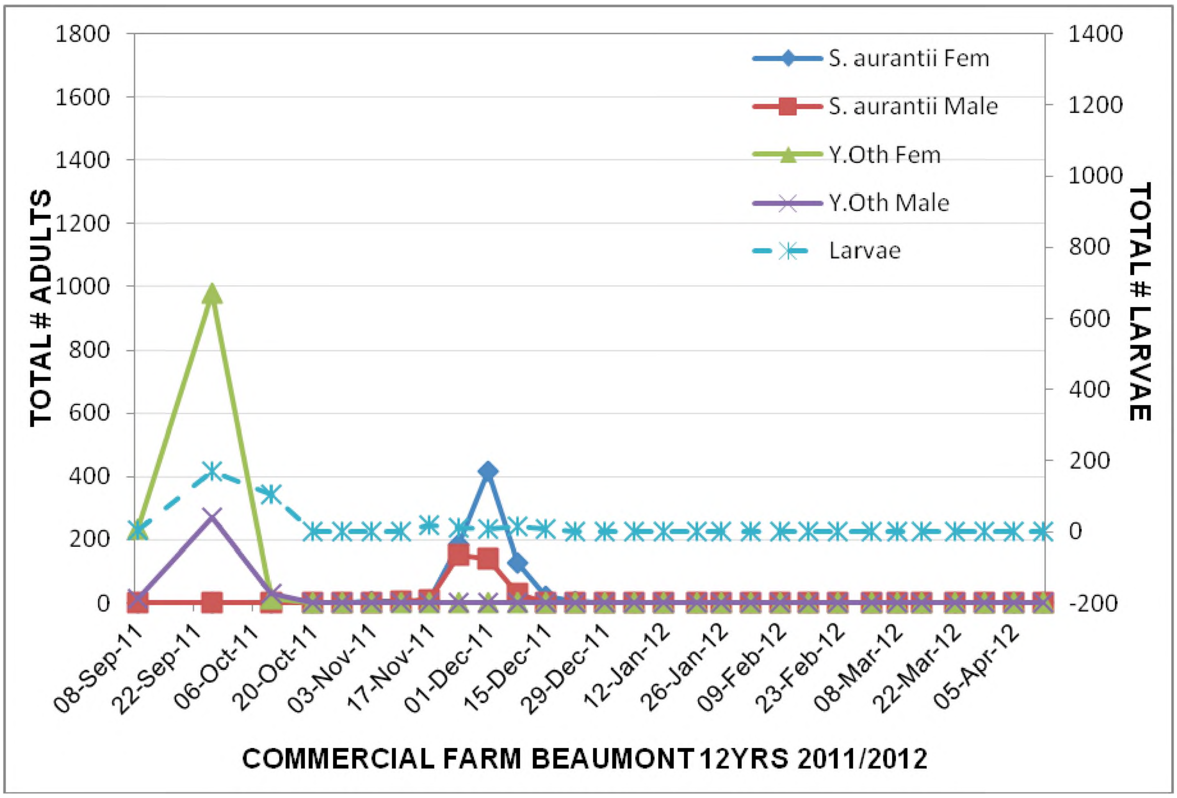


Figure 5.14 2011/2012 Thrips species phenology in the Commercial Farm Beaumont (12-year-old) orchard.

5.3.7.3 Comparison of the 788 sites

Thrips populations at the ARC Variety Orchard 788 13-year-old and Commercial Farm 788 4-year old orchards are presented in Table 5.7 and Fig. 5.15. At the ARC Variety Orchard 788 orchard (Fig. 5.16) the first (main) peak occurred on 26 September, followed by a second peak on 3 November, a third peak on 1 December 2011, and a fourth late peak on 22 March 2012. Virtually all the thrips specimens collected at the ARC Variety Orchard 788 site during fourth peak, 22 March 2012, were larvae. The first (main) peak at the Commercial Farm 788 4-year-old orchard (Fig. 5.17) also occurred on 26 September, followed by a second peak on 17 November, and a third peak on 8 December 2011.

Table 5.7 2011/2012 Comparison of thrips population peaks and composition of species at the 788 cultivar sites.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
ARC Var Orch 788 13 Yrs	**26 Sept 2011***	3 Nov 2011	1 Dec 2011	22 Mar 2012
1st (main) peak – low number of larvae, 'yellow other' adult ♀ and ♂, *S. aurantii* adult ♀ and ♂; 2nd peak – low number of larvae, 'yellow other' adult ♀ and ♂; 3rd peak – low number of larvae, *S. aurantii* adult ♀ and ♂; 4th peak - larvae.				
Comm Farm 788 4 Yrs	**26 Sept 2011***	17 Nov 2011	8 Dec 2011	--
1st (main) peak – larvae, 'yellow other' adult ♀ and ♂; 2nd peak – larvae, *S. aurantii* adult ♀ and ♂; 3rd peak – low number of larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the 'main' peak event.

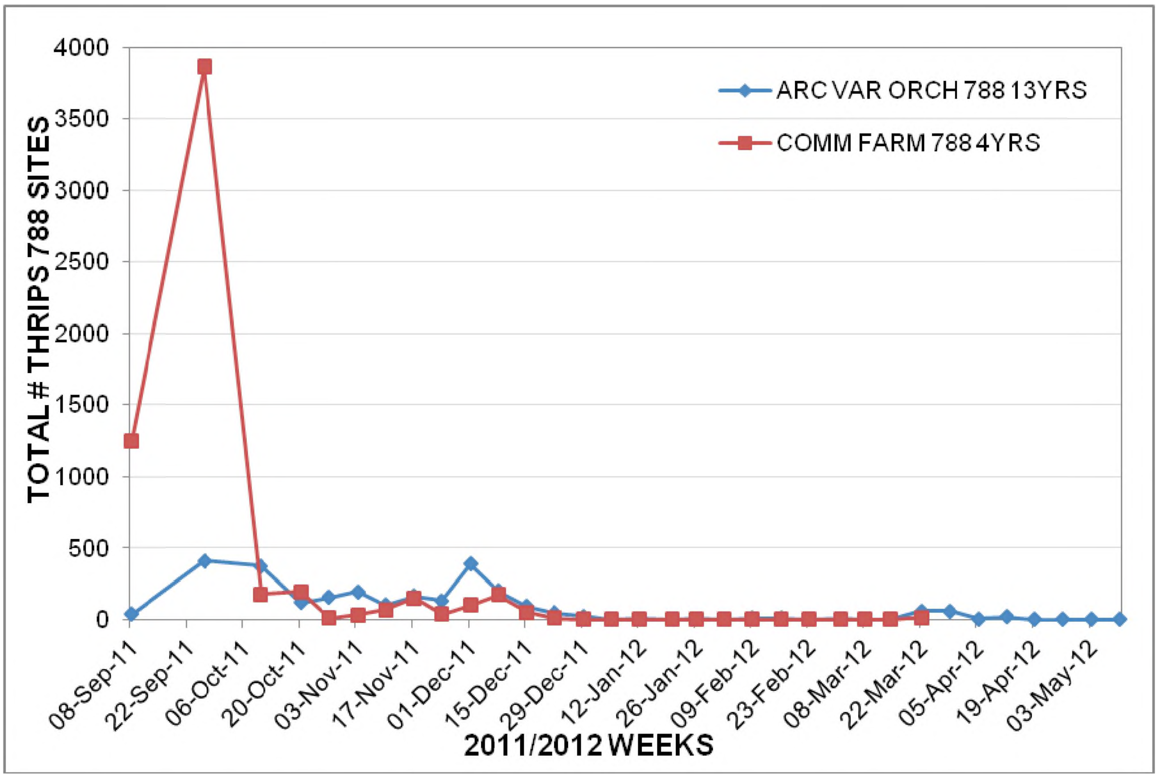


Figure 5.15 2011/2012 Total number of thrips collected from both 788 sites.

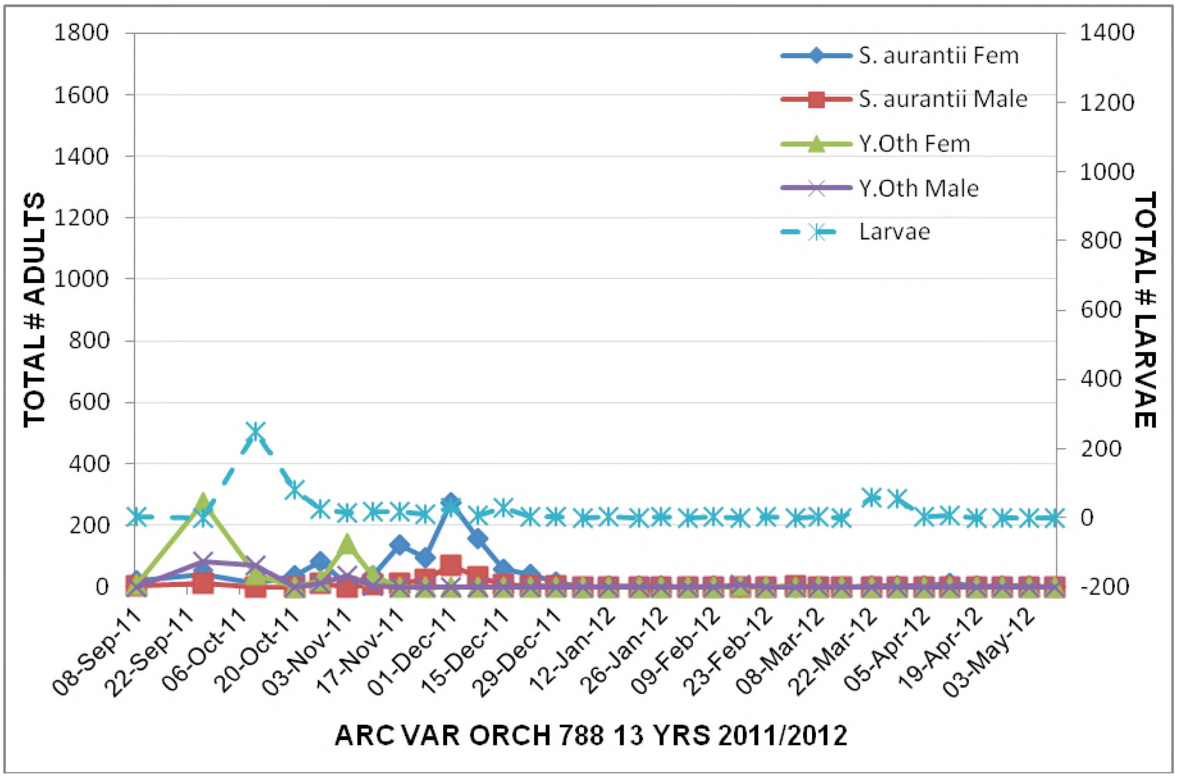


Figure 5.16 2011/2012 Thrips species phenology in the ARC Variety Orchard 788 (13-year-old) site.

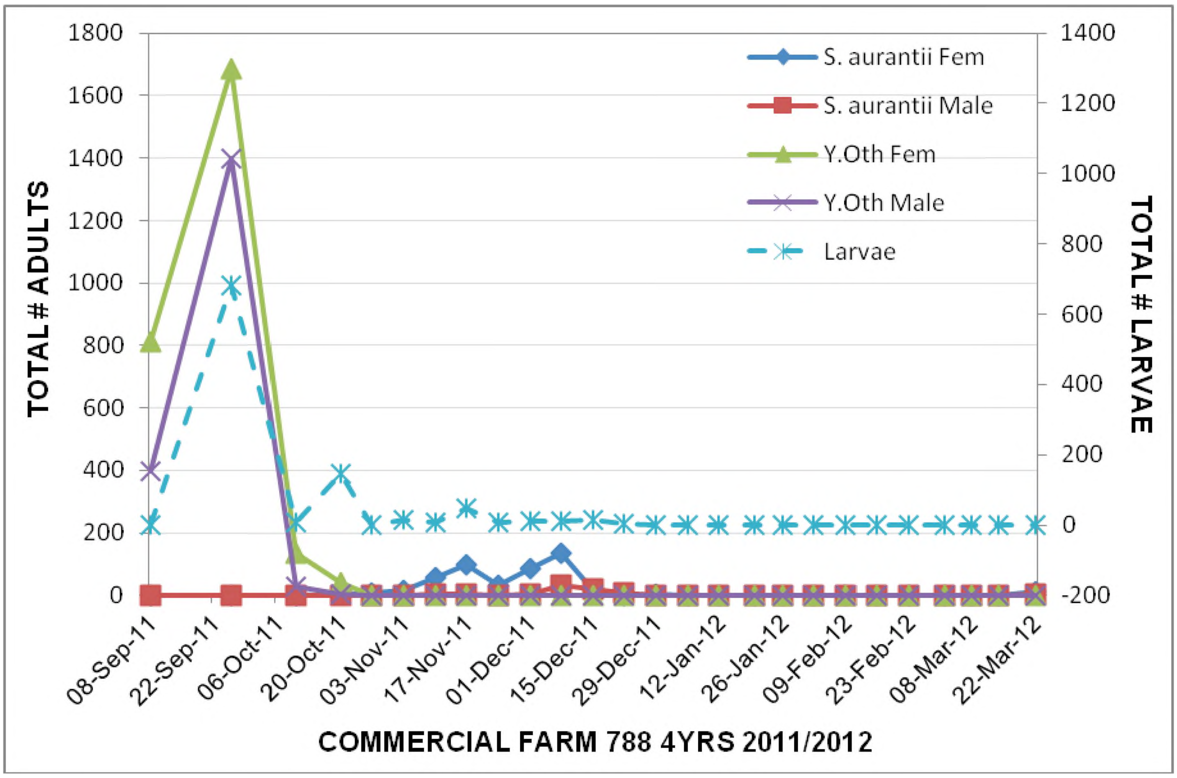


Figure 5.17 2011/2012 Thrips species phenology in the Commercial Farm 788 (4-year-old) orchard.

5.3.7.4 Comparison of the 816 sites

Comparisons between the two 816 cultivar sites are presented in Table 5.8 and Fig. 5.18. The thrips populations at the ARC Variety Orchard 816 13-year-old site (Fig. 5.19) reached an initial (main) peak on 10 October, followed by a low second peak on 1 December, and a third small peak on 22 December 2011. Populations at the Commercial Farm 816 4-year-old site (Fig. 5.20) reached the first (main) peak on 26 September, followed by a second peak on 3 November, and a third small, final peak on 1 December 2011.

Table 5.8 2011/2012 Comparison of thrips population peaks and composition of species at the 816 cultivar sites.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
ARC Var Orch 816 13 Yrs	**10 Oct 2011***	1 Dec 2011	22 Dec 2011	--
1st (main) peak - larvae, ‘yellow other’ adult ♀ and ♂, low number of *S. aurantii* adult ♀ and ♂; 2nd peak – low number of larvae, low number of *S. aurantii* adult ♀; 3rd peak – low number of larvae, *S. aurantii* adult ♀ and ♂.				

Comm Farm 816 **4 Yrs**	**26 Sept 2011***	3 Nov 2011	1 Dec 2011	--
1st (main) peak - larvae, 'yellow other' adult ♀ and ♂, very low number of *S. aurantii* adult ♀; 2nd peak – low number of larvae, low number of *S. aurantii* adult ♀ and ♂; 3rd peak – only 2 larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the 'main' peak event.

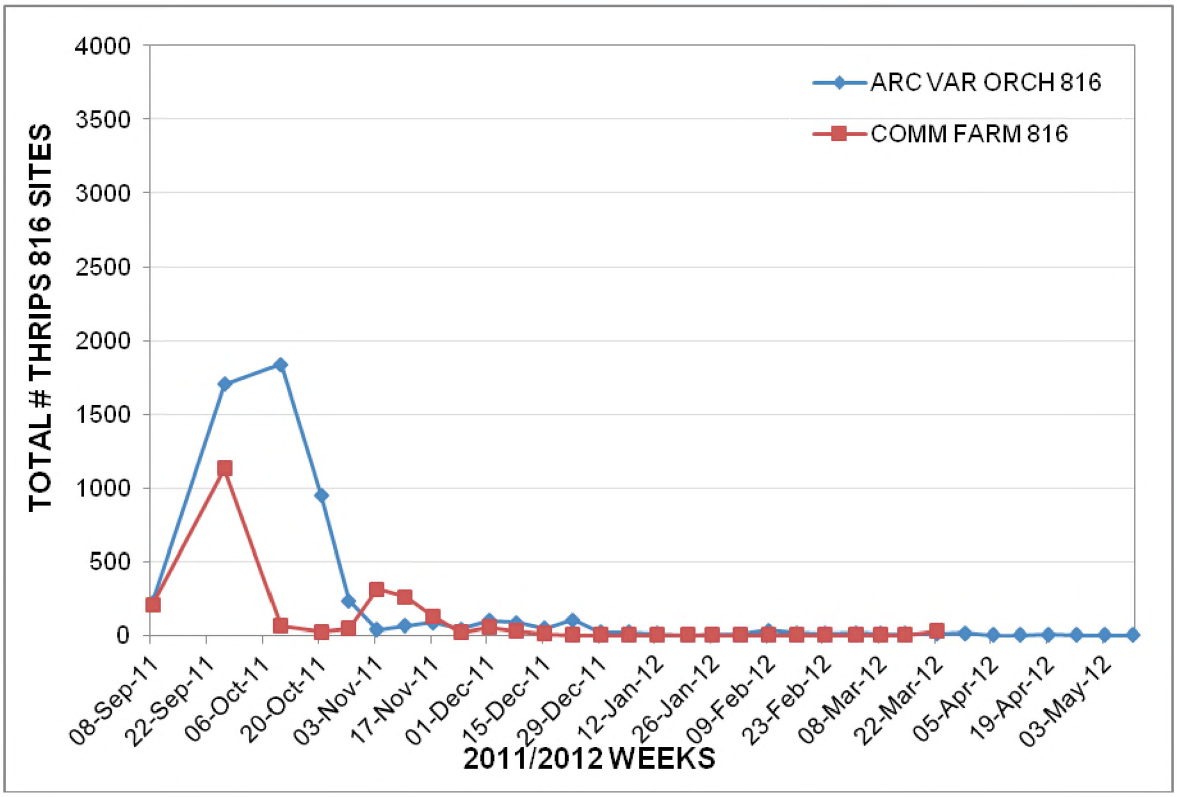


Figure 5.18 2011/2012 Total number of thrips collected from both 816 sites.

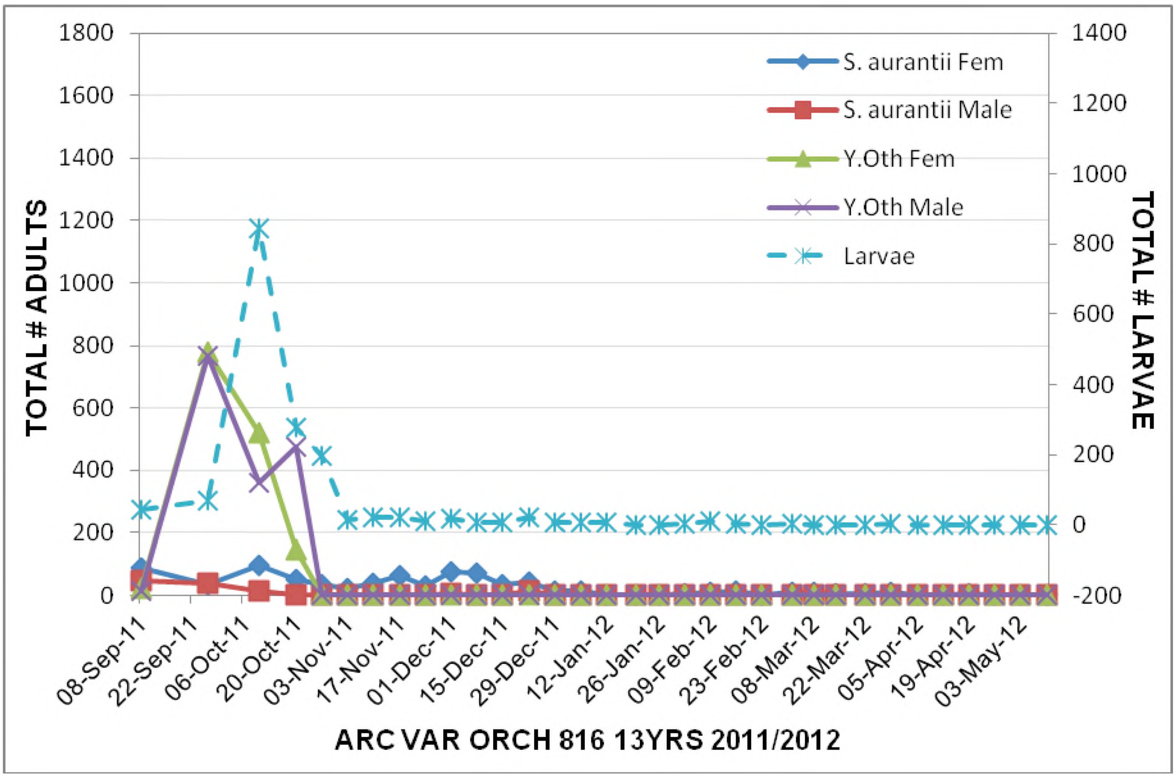


Figure 5.19 2011/2012 Thrips species phenology in the ARC Variety Orchard 816 (13-year-old) site.

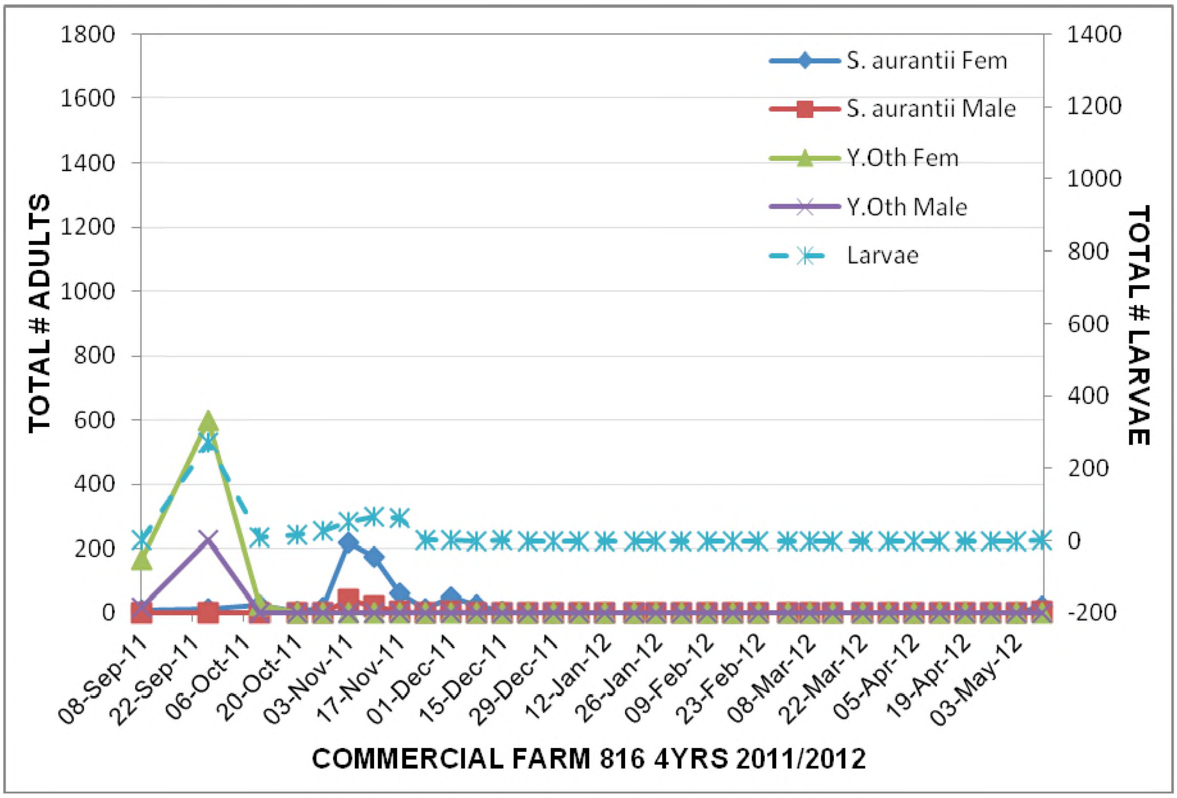


Figure 5.20 2011/2012 Thrips species phenology in the Commercial Farm 816 (4-year-old) orchard.

5.3.7.5 ARC Variety Orchard A4 site

No additional sites of the A4 cultivar were available for comparison during both study periods. Because A4 is one of the early-bearing cultivars grown in South Africa, it was included in the study. The A4 cultivar is renowned for its high yield of large, evenly sized nuts and good quality kernel recovery rates. Composition of the thrips species present are shown in Table 5.9 and Fig. 5.21. The initial (main) peak was on 10 October, with a second, lower peak, on 1 December 2011.

Table 5.9 2011/2012 Thrips population peaks and composition of species at the ARC Variety Orchard A4 cultivar site.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
ARC Var Orch A4 13 Yrs	**10 Oct 2011***	1 Dec 2011		--

1st (main) peak – mainly larvae, 'yellow other' adult ♀ and ♂, *S. aurantii* adult ♀ and ♂; 2nd peak – low number of larvae, very low number 'yellow other' adult ♀ and ♂, *S. aurantii* adult ♀ and ♂.

*Dates in bold reflect the 'main' peak event.

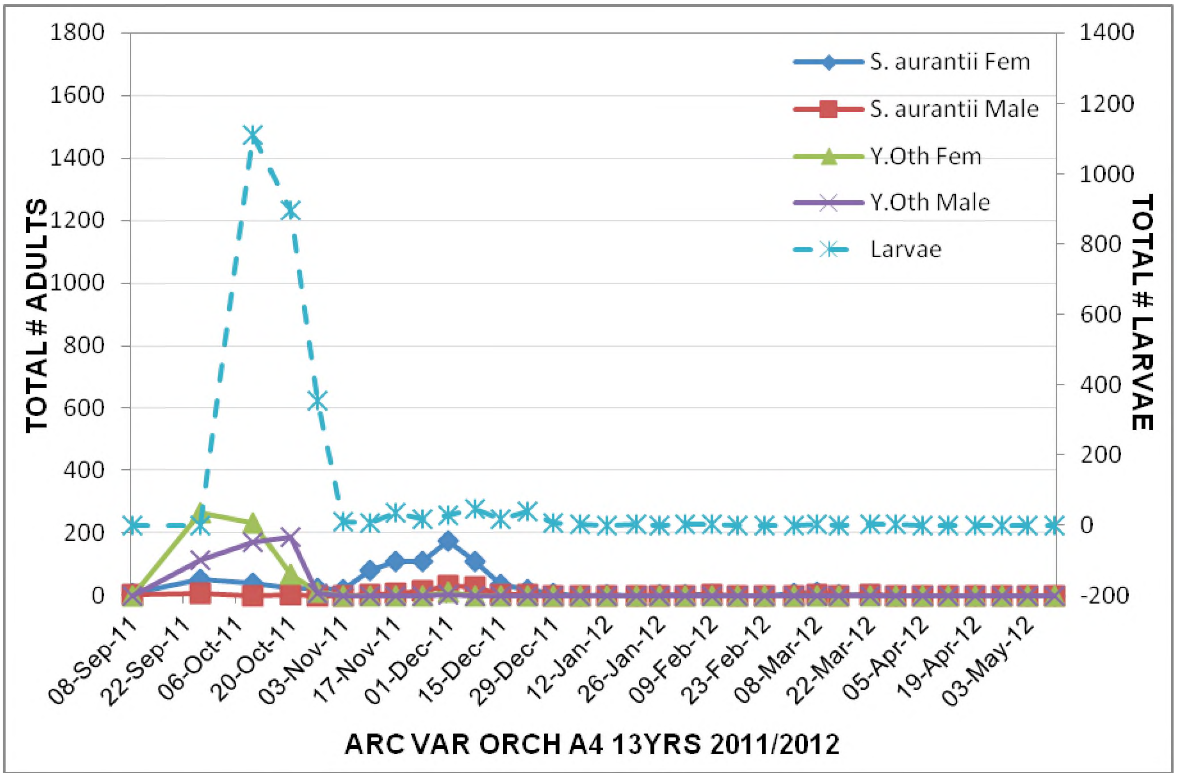


Figure 5.21 2011/2012 Thrips species phenology in the ARC Variety Orchard A4 (13-year-old) site.

5.3.7.6 ARC Variety Orchard A16 site

As with the A4 cultivar above, no comparison A16 cultivar sites were available. However, the A16 cultivar was included in this study because it is one of the early-bearing cultivars; comparisons of the presence of thrips populations could then be made against the mid- and late-bearing cultivars. The A16 cultivar tends to yield large, quality nuts and has a high kernel recovery rate. The first (main) thrips population peak was on 10 October, and a second lower peak on 1 December 2011, similar to the A4 cultivar site. The distribution and composition of the thrips populations are shown in Table 5.10 and Fig. 5.22.

Table 5.10 2011/2012 Thrips population peaks and composition of species at the ARC Variety Orchard A16 cultivar site.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
ARC Var Orch A16 13 Yrs	**10 Oct 2011***	1 Dec 2011		--
1st (main) peak – larvae, 'yellow other' adult ♀ and ♂, low number of *S. aurantii* adult ♀ and ♂; 2nd peak – very low number of larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the 'main' peak event.

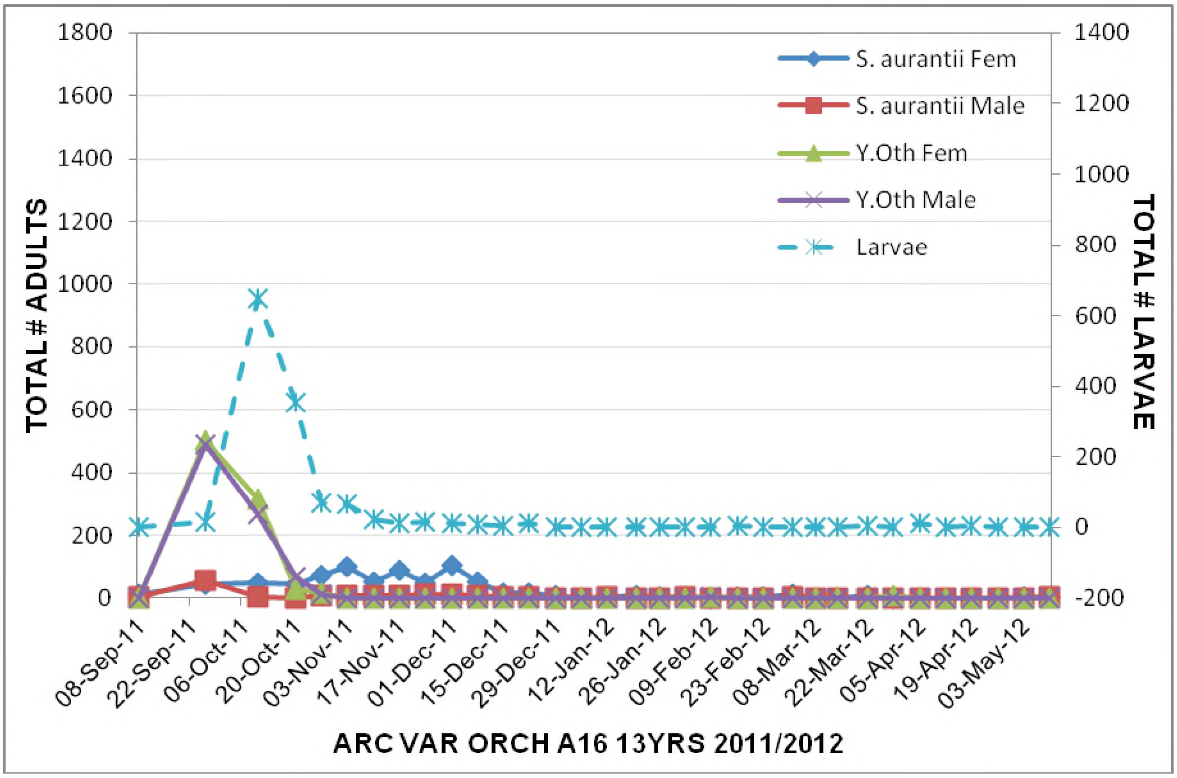


Figure 5.22 2011/2012 Thrips species phenology in the ARC Variety Orchard A16 (13-year-old) site.

5.3.8 Chemical spray applications (2011/2012)

At the ARC Friedenheim Beaumont study site four spray applications of a synthetic pyrethroid insecticide, the active ingredient being Lambda-cyhalothrin, were applied on 17 November, 19 December 2011, 19 January and 20 February 2012, which indicates a calendar/rote spray programme (Fig. 5.23). Insecticide applications are primarily used to control Heteropteran pests, notably *Bathycoelia distincta* (Hemiptera: Heteroptera: Pentatomidae), the two-spotted stink bug, the most injurious pest to macadamia in South Africa. Most of the 'late-stink bug' damage is caused by *B. distincta*, which are able to feed on the kernel through the hardened shell.

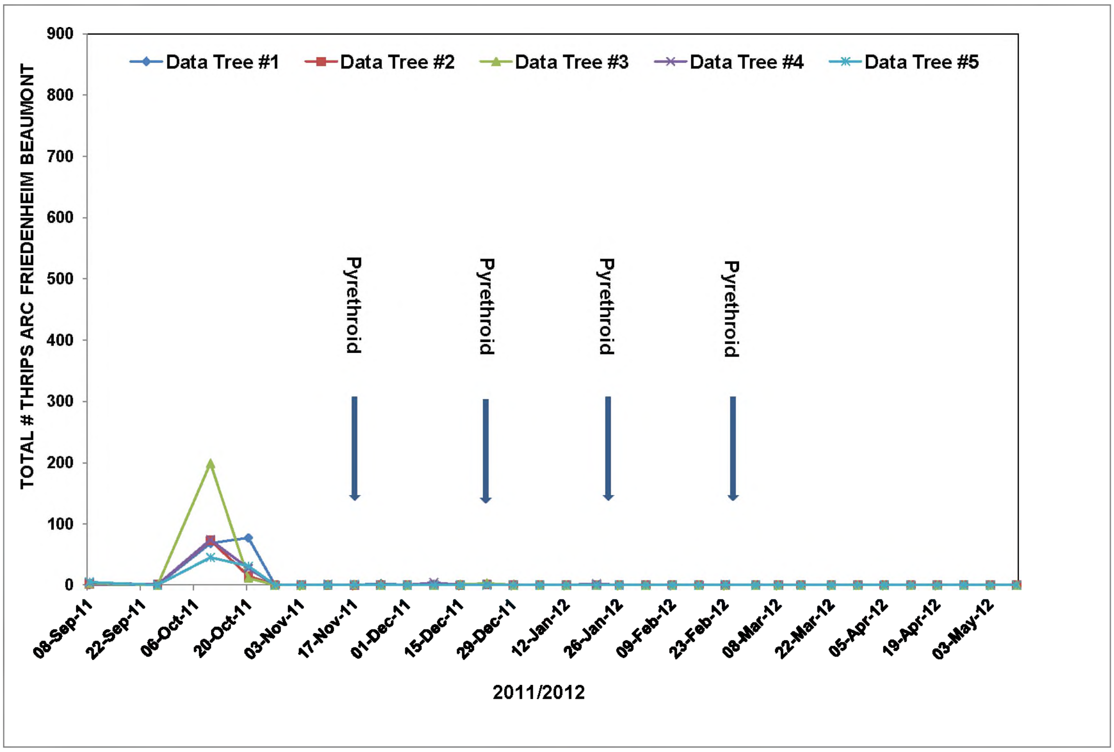


Figure 5.23 2011/2012 ARC Friedenheim Beaumont cultivar site spray application dates.

The chemical spray programme at the Commercial Farm sites differed according to the age of the trees. Cultivars 788 4-year-old, Nelmak D 6-year-old, and 816 4-year-old orchards, were sprayed with endosulfan on 18 October, 19 December 2011, 19 January and 20 February 2012 (Fig. 5.24). On the 12 December 2011, a False Codling Moth, *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) granulovirus was also applied. The Commercial Farm conducts weekly scouting programmes for *B. distincta* populations, thus spray applications were based on these weekly scouting data. However, these chemical applications do not seem to have made any impact on the subsequent thrips populations at the end of October through November and December. The thrips numbers had already declined substantially by the time the first spray was applied. Timing of these sprays are however primarily for the control of *B. distincta* populations, which occur later in the season than thrips.

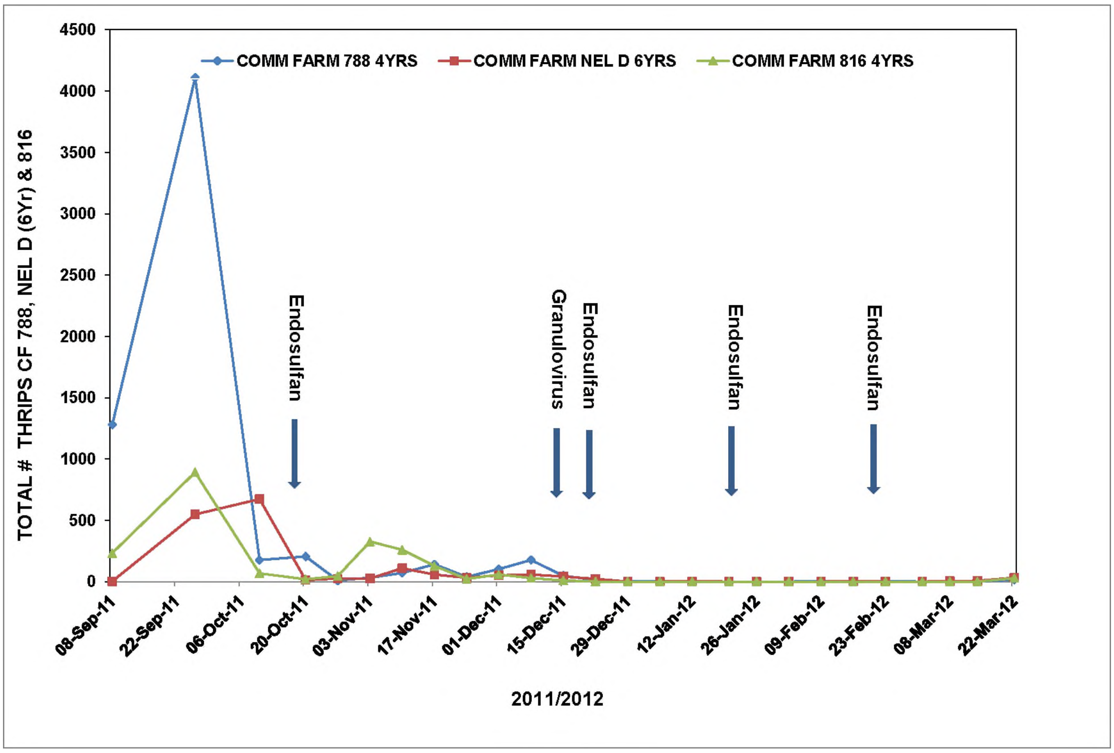


Figure 5.24 2011/2012 Commercial farm spray application dates at the 788, Nelmak D, and 816 sites.

The two sites on the Commercial Farm with older orchards of Beaumont (12-year-old) and Nelmak D (12-year-old) cultivars were sprayed with an organophosphate insecticide on 15 October and a synthetic pyrethroid insecticide on 15 November 2011, 7 January, 30 January and 10 March 2012 (Fig. 5.25). The histogram show two thrips population peaks, and even though the second application was applied just prior to the second thrips peak, there does not seem to be any effect on the subsequent increase in thrips numbers.

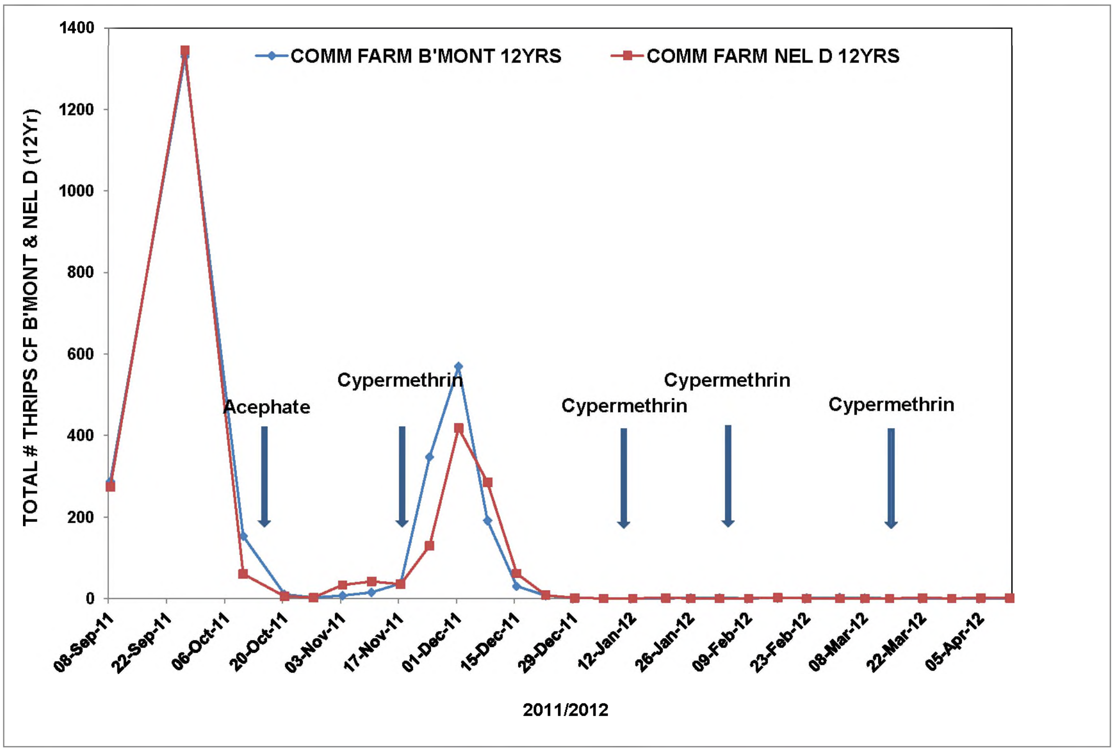


Figure 5.25 2011/2012 Commercial farm spray application dates at the Beaumont (12-year-old) and Nelmak D (12-year-old) sites.

When comparisons were made between the sites which had been treated with chemical spray applications (Fig. 5.26), and those which received no chemical treatment (Fig. 5.27), it is evident that the peaks of abundance during the season were naturally occurring trends, regardless of whether the orchards were managed or not.

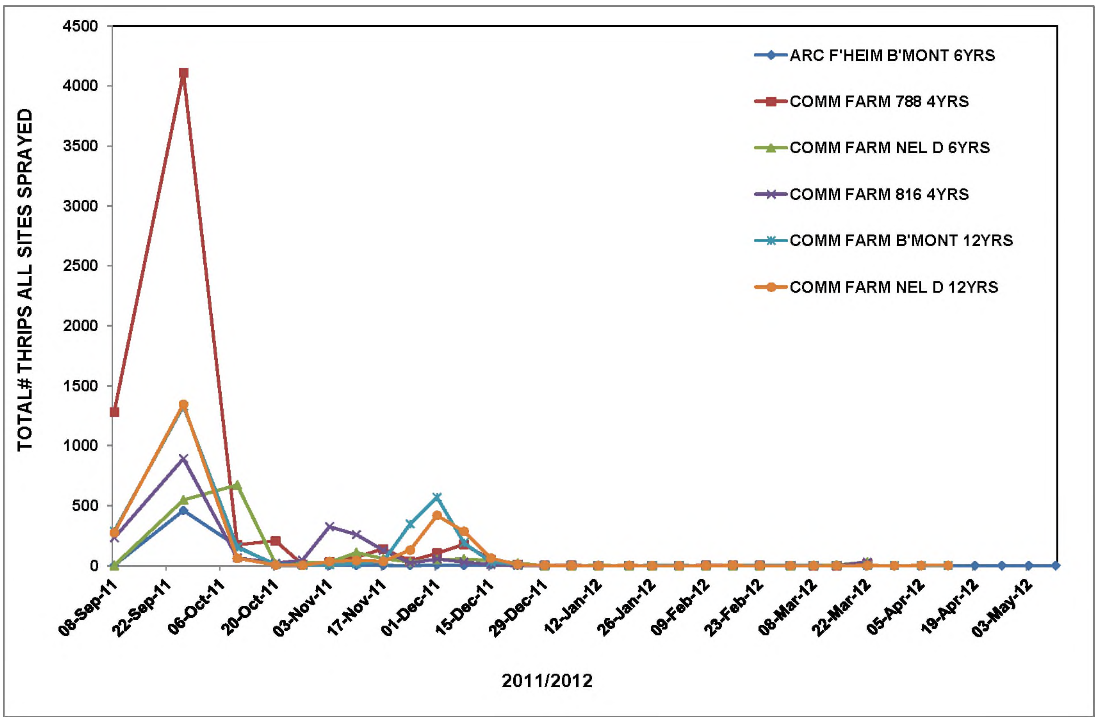


Figure 5.26 2011/2012 Total number of thrips collected from the ARC Friedenheim Beaumont and Commercial Farm orchards which were sprayed.

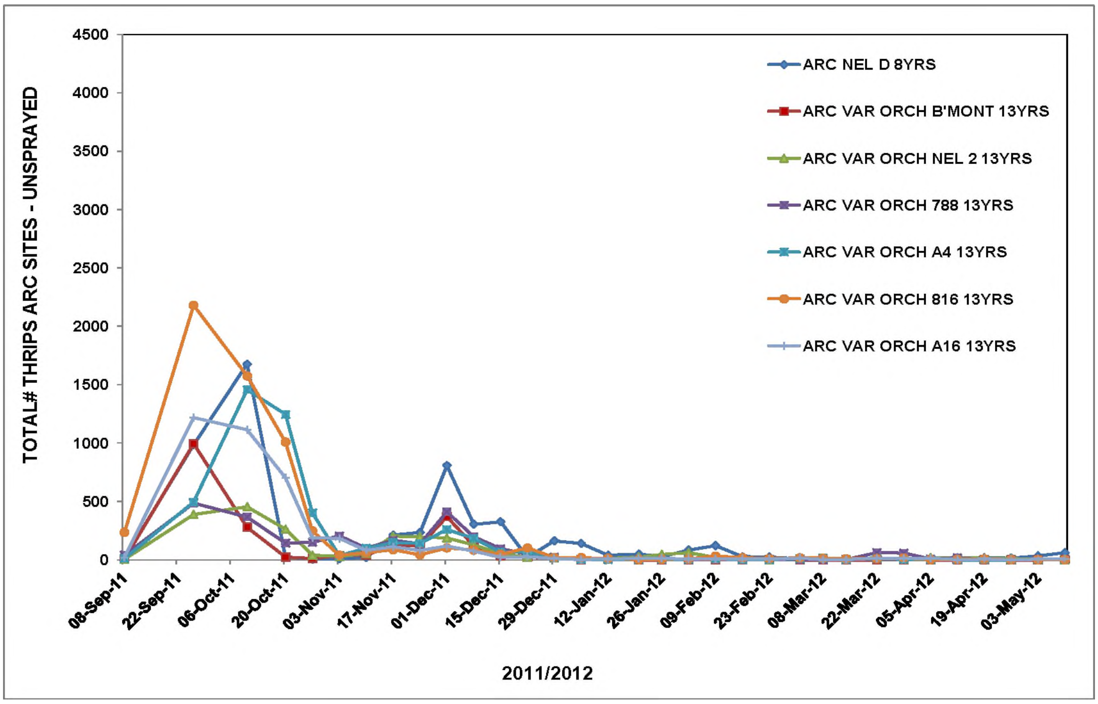


Figure 5.27 2011/2012 Total number of thrips collected at the ARC-ITSC orchards which were not sprayed.

5.3.9 2012/2013 Season

A total of 75,565 individual thrips were collected during the 2012/2013 season over a period of 40 weeks. The phenology of the thrips populations is shown in Fig. 5.28. During the first season, thrips populations at all 13 sites reached their main peak within a two-week period, either on 26 September or 10 October 2011. During the 2012/2013 season four periods occurred when thrips numbers increased; the first and last of which were lower than the two middle periods which were of higher density. The distribution of thrips numbers over the different cultivar sites during the second season was more widely dispersed. The total numbers of thrips for all 10 sites during the 2012/2013 season are presented in descending order in Table 5.11.

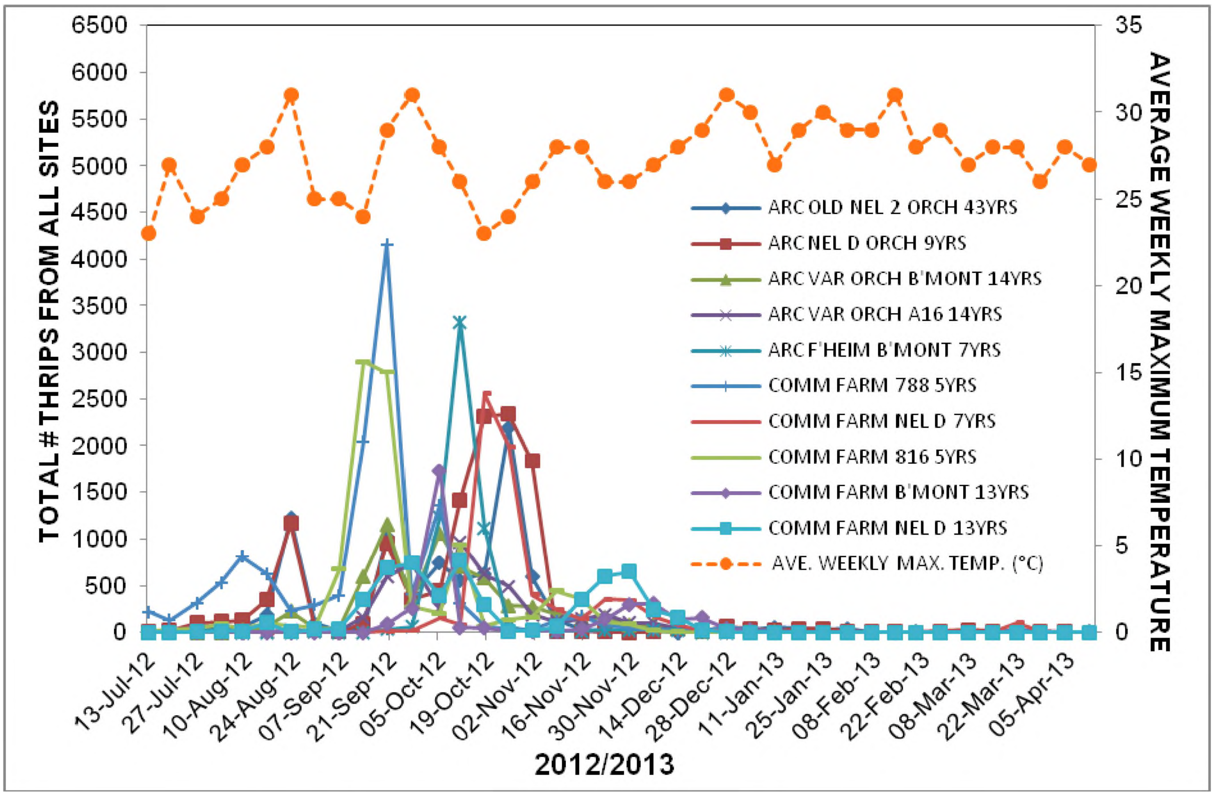


Figure 5.28 Total number of thrips collected during the 2012/2013 season from each of the 10 study sites.

Table 5.11 2012/2013 Total number of thrips collected from the five data trees, by study site, in descending order.

STUDY SITE	TREE AGE	MANAGED	THRIPS NOS.
Commercial Farm 788	5	Yes	12,423

STUDY SITE	TREE AGE	MANAGED	THRIPS NOS.
ARC-ITSC Nelmak D	9	No	12,192
Commercial Farm 816	5	Yes	8,748
ARC-ITSC Old Nelmak 2	43	No	8,356
Commercial Farm Nelmak D	7	Yes	7,705
ARC Variety Orchard Beaumont	14	No	6,259
ARC Friedenheim Beaumont	7	No	6,121
Commercial Farm Nelmak D	13	Yes	5,555
ARC Variety Orchard A16	14	No	4,855
Commercial Farm Beaumont	13	Yes	3,351
TOTAL			**75,565**

The grouping pattern between the different cultivars proved interesting; the data show that a build-up of thrips populations occurred in a somewhat chronological pattern, all within a couple of weeks of each other in same-cultivar sites. This grouping of cultivars was irrespective as to whether these sites were unmanaged orchards or orchards where proper commercial management of macadamias was undertaken. The date of the main thrips population peak at each study site is shown in chronological order in Table 5.12.

Table 5.12 2012/2013 Date at which the highest thrips population peaks occurred by cultivar group for all 10 study sites.

STUDY SITE	DATE OF MAIN THRIPS PEAK
Commercial Farm 816 5 Yrs	13 September 2012
Commercial Farm 788 5 Yrs	20 September 2012
ARC Variety Orchard Beaumont 14 Yrs	5 October 2012
Commercial Farm Beaumont 13 Yrs	5 October 2012
ARC Friedenheim Beaumont 7 Yrs	11 October 2012
ARC Variety Orchard A16 14 Yrs	11 October 2012
Commercial Farm Nelmak D 13 Yrs	11 October 2012
Commercial Farm Nelmak D 7 Yrs	18 October 2012
ARC-ITSC Nelmak D 9 Yrs	18 October 2012
ARC-ITSC Nelmak 2 43 Yrs	25 October 2012

5.3.9.1 Comparison of the Nelmak sites

Comparisons among the four Nelmak cultivar sites and the distribution of thrips are shown in Table 5.13 and Fig. 5.29; between two and four peaks occurred throughout the season in the Nelmak sites. In the ARC-ITSC Old Nelmak 2 43-year-old (Fig. 5.30) the initial peak took place on 24 August, followed by a second peak on 21September, a third peak on 5 October, and the main peak on 26 October 2012. The ARC Nelmak D 9-year-old orchards (Fig. 5.31) had three peaks: the initial peak on 24 August, the second on 21 September, and the third main peak on 19 October 2012.

Table 5.13 2012/2013 Comparison of thrips population peaks and composition of species at the Nelmak cultivar sites.

Site	**1st Peak**	**2nd Peak**	**3rd Peak**	**4th Peak**
ARC Nel 2 43 Yrs	24 Aug 2012	21 Sept 2012	5 Oct 2012	**26 Oct 2012***
1st peak – larvae; 2nd peak – larvae, ‘yellow other’ adult ♀; 3rd peak – larvae, ‘yellow other’ adult ♀ and ♂; 4th (main) peak - larvae, ‘yellow other’ adult ♀ and ♂.				
ARC Nel D 9Yrs	24 Aug 2012	21 Sept 2012	**19 Oct 2012***	--
1st peak – larvae; 2nd peak – larvae, ‘yellow other’ adult ♀; 3rd (main) peak – larvae, ‘yellow other’ adult ♀ and ♂.				
Comm Farm Nel D 7Yrs	**19 Oct 2012***	23Nov 2012	--	--
1st (main) peak – larvae, ‘yellow other’ adult ♀ and ♂; 2nd peak – larvae, *S. aurantii* adult ♀ and ♂.				
Comm Farm Nel D 13Yrs	21 Sept 2012	**12 Oct 2012***	30 Nov 2012	--
1st peak – larvae, ‘yellow other’ adult ♀; 2nd (main) peak – larvae, ‘yellow other’ adult ♀ and ♂; 3rd peak – larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the ‘main’ peak event.

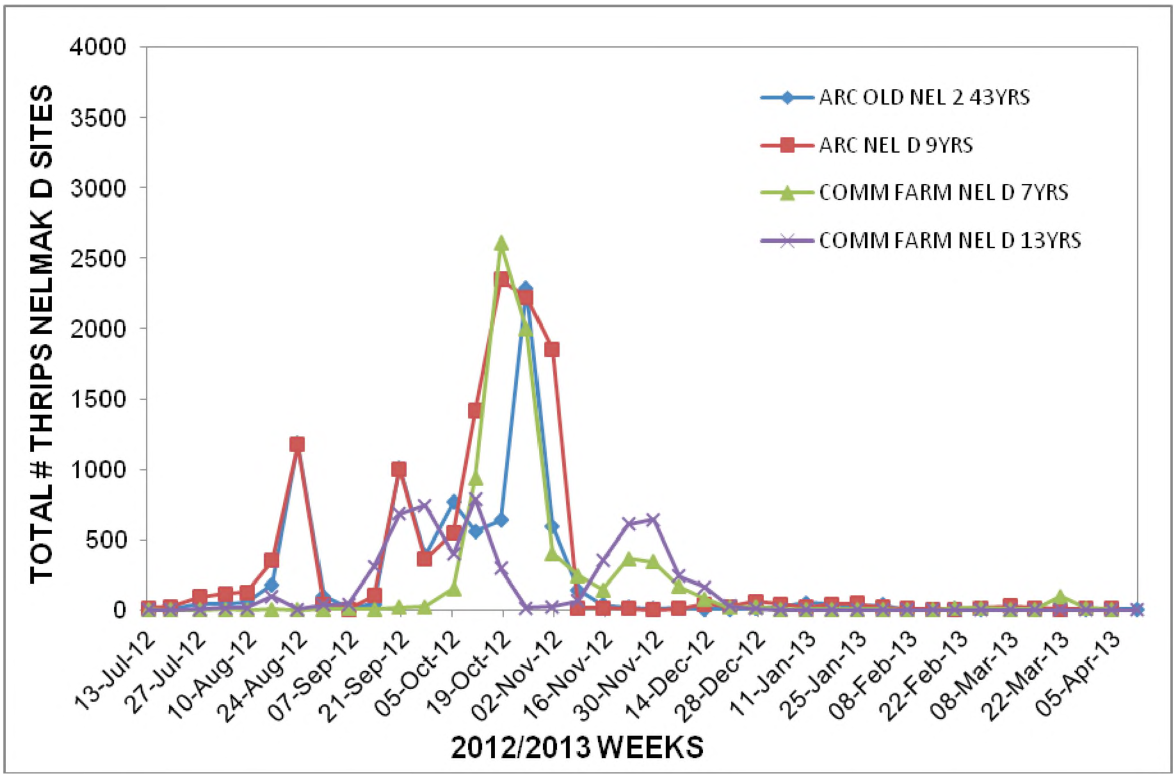


Figure 5.29 2012/2013 Total number of thrips collected from all four Nelmak sites.

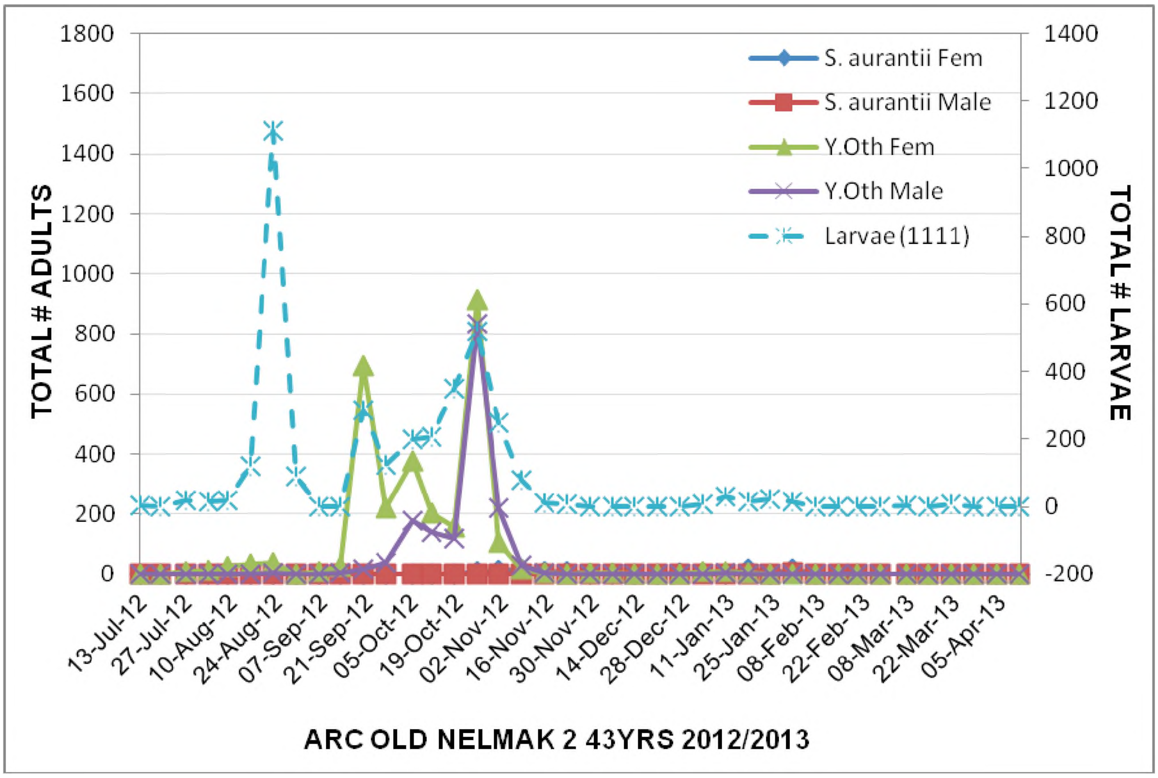


Figure 5.30 2012/2013 Thrips species phenology in the ARC Old Nelmak 2 (43-year-old) orchard.

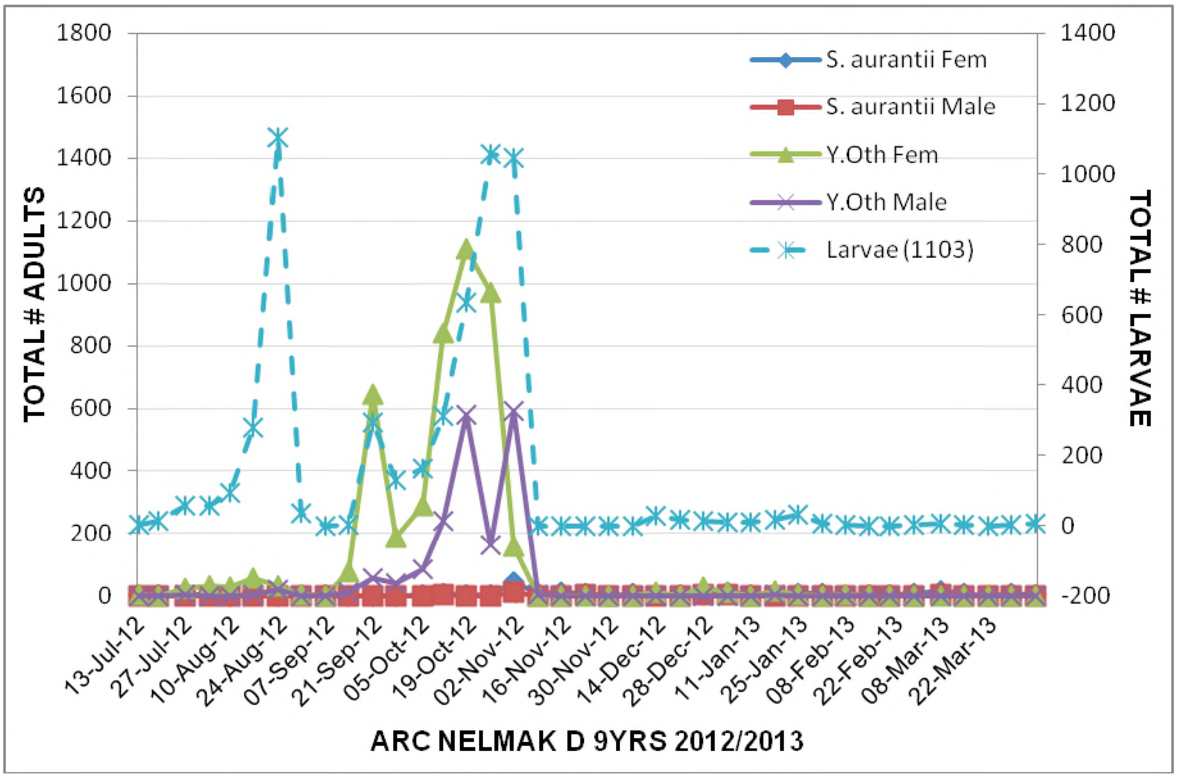


Figure 5.31 2012/2013 Thrips species phenology in the ARC Nelmak D (9-year-old) orchard.

At the Commercial Farm the thrips populations in the Nelmak D 7-year-old orchard peaked on 19 October, followed by a smaller secondary peak on 23 November 2012 (Fig. 5.32). Three population peaks occurred in the Nelmak D 13-year-old orchard (Fig. 5.33); an initial peak on 21 September, followed by a second (main) peak on 12 October, and a third peak on 30 November 2012.

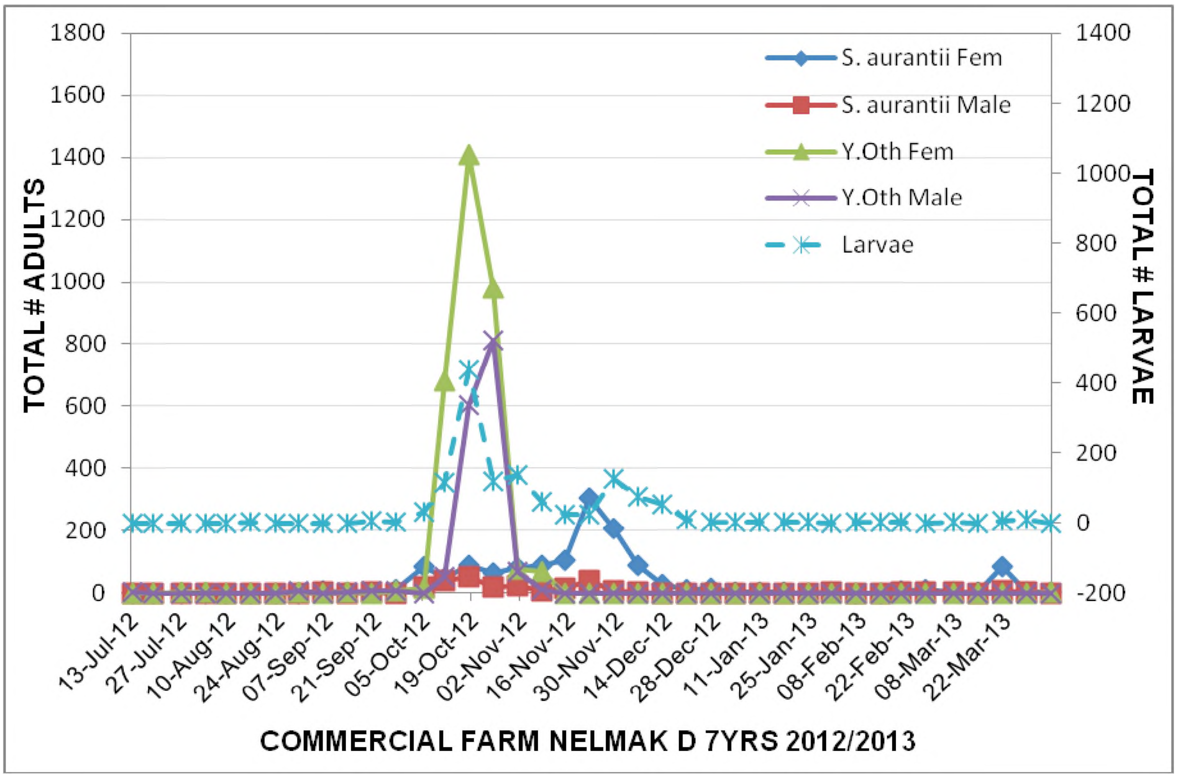


Figure 5.32 2012/2013 Thrips species phenology in the Commercial Farm Nelmak D (7-year-old) orchard.

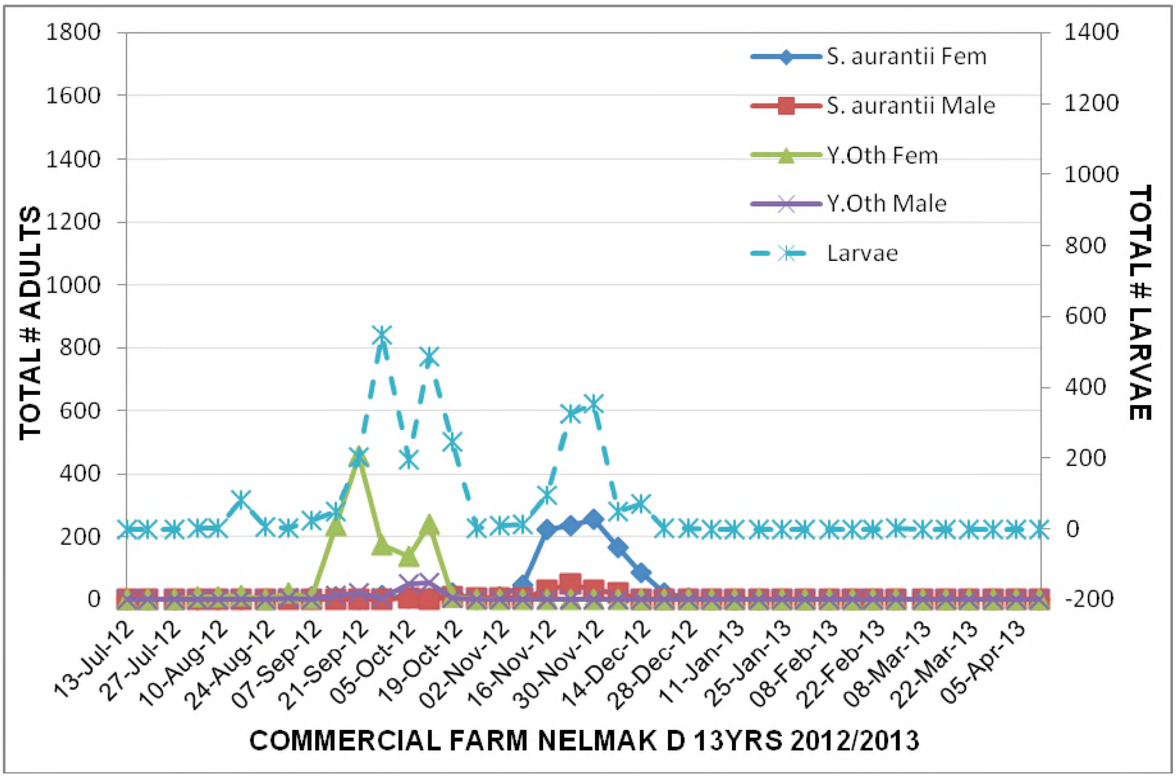


Figure 5.33 2012/2013 Thrips species phenology in the Commercial Farm Nelmak D (13-year-old) orchard.

5.3.9.2 Comparison of the Beaumont sites

The distribution and composition of thrips species in the three Beaumont sites during the 2012/2013 season are shown in Table 5.14 and Fig. 5.34. These three sites also showed a same-cultivar group pattern of thrips population main peaks. The thrips populations in the ARC Variety Orchard Beaumont 14-year-old (Fig. 5.35) and the Commercial Farm Beaumont 13-year-old (Fig. 5.37) orchards peaked on 5 October 2012. Thrips populations in the ARC Friedenheim Beaumont 7-year-old orchard (Fig. 5.36) peaked on 11 October 2012, a week later. At the ARC Variety Orchard Beaumont site, an initial peak occurred on 24 August, followed by a second peak on 21 September, the third (main) peak on 5 October, and a low fourth peak on 23 November 2012. At the Friedenheim Beaumont orchard, only a single peak occurred on 11 October 2012. During the previous season, there was also just the single population peak at this site. The initial peak at the Beaumont 13-year-old site at the Commercial Farm occurred on 5 October and was the main peak, followed by a second lower peak on 30 November 2012.

Table 5.14 2012/2013 Comparison of thrips population peaks and composition of species at the Beaumont cultivar sites.

Site	**1st Peak**	**2nd Peak**	**3rd Peak**	**4th Peak**
ARC Var Orch Beaumont 14 Yrs	24 Aug 2012	21 Sept 2012	**5 Oct 2012***	23 Nov 2012
1st peak – larvae, very low numbers of 'yellow other' adult ♀ and ♂; 2nd peak – larvae, 'yellow other' adult ♀ and ♂; 3rd (main) peak – larvae, 'yellow other' adult ♀ and ♂; 4th peak - larvae, *S. aurantii* adult ♀ and ♂.				
ARC Friedenheim Beaumont 7 Yrs	**11 Oct 2012***	--	--	--
1st (main) peak – larvae, 'yellow other' adult ♀ and ♂.				
Comm Farm Beaumont 13 Yrs	**5 Oct 2012***	30 Nov 2012	--	--
1st (main) peak – mostly larvae, low numbers of 'yellow other' adult ♀; 2nd peak – larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the 'main' peak event.

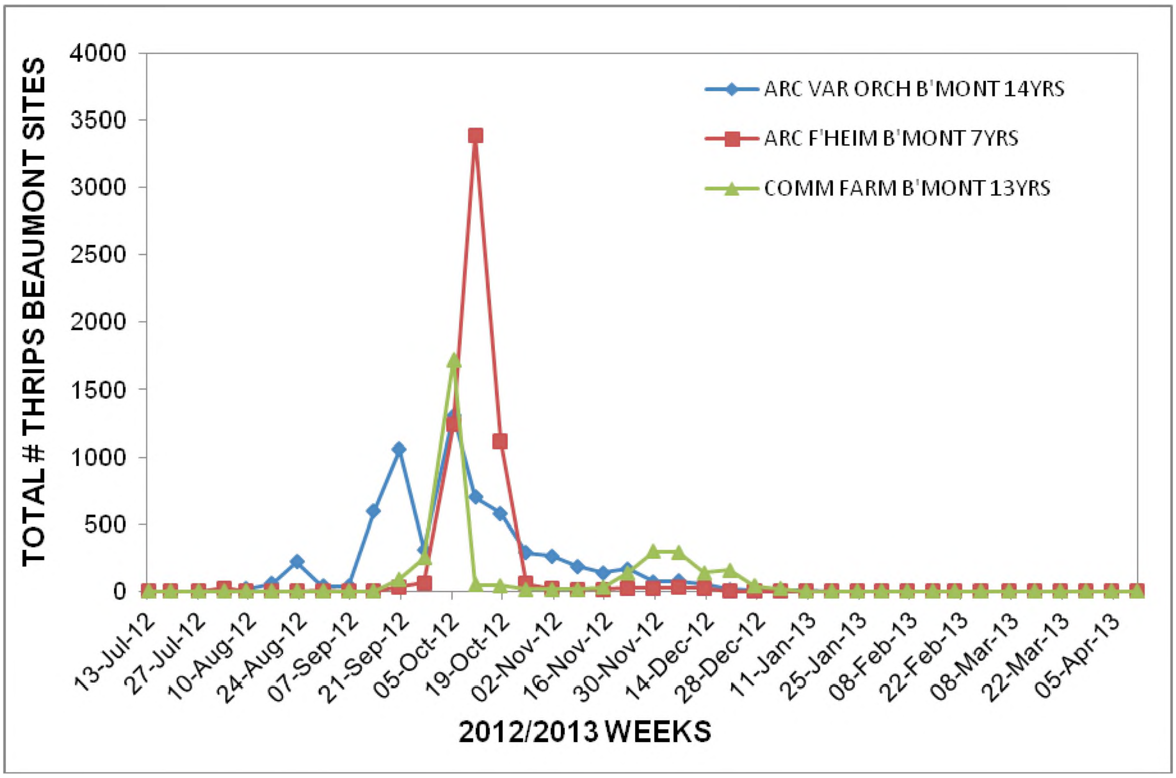


Figure 5.34 2012/2013 Total number of thrips collected from all three Beaumont sites.

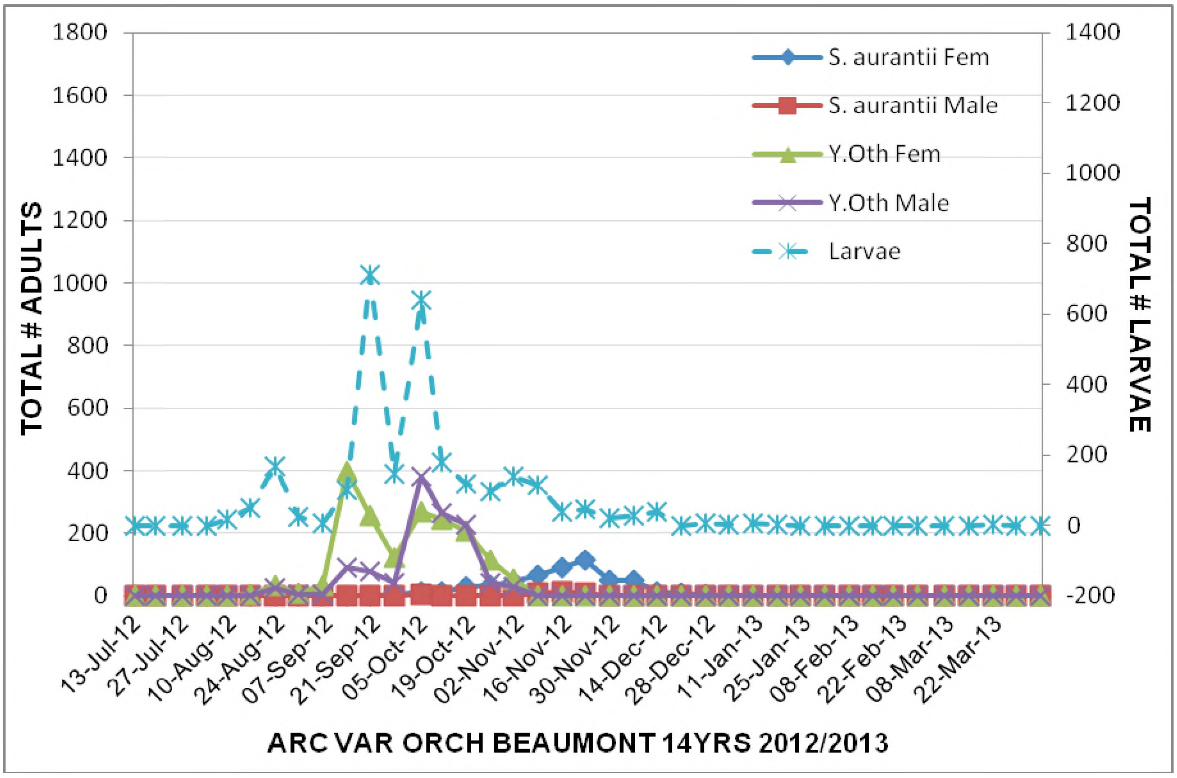


Figure 5.35 2012/2013 Thrips species phenology in the ARC Variety Orchard Beaumont (14-year-old) site.

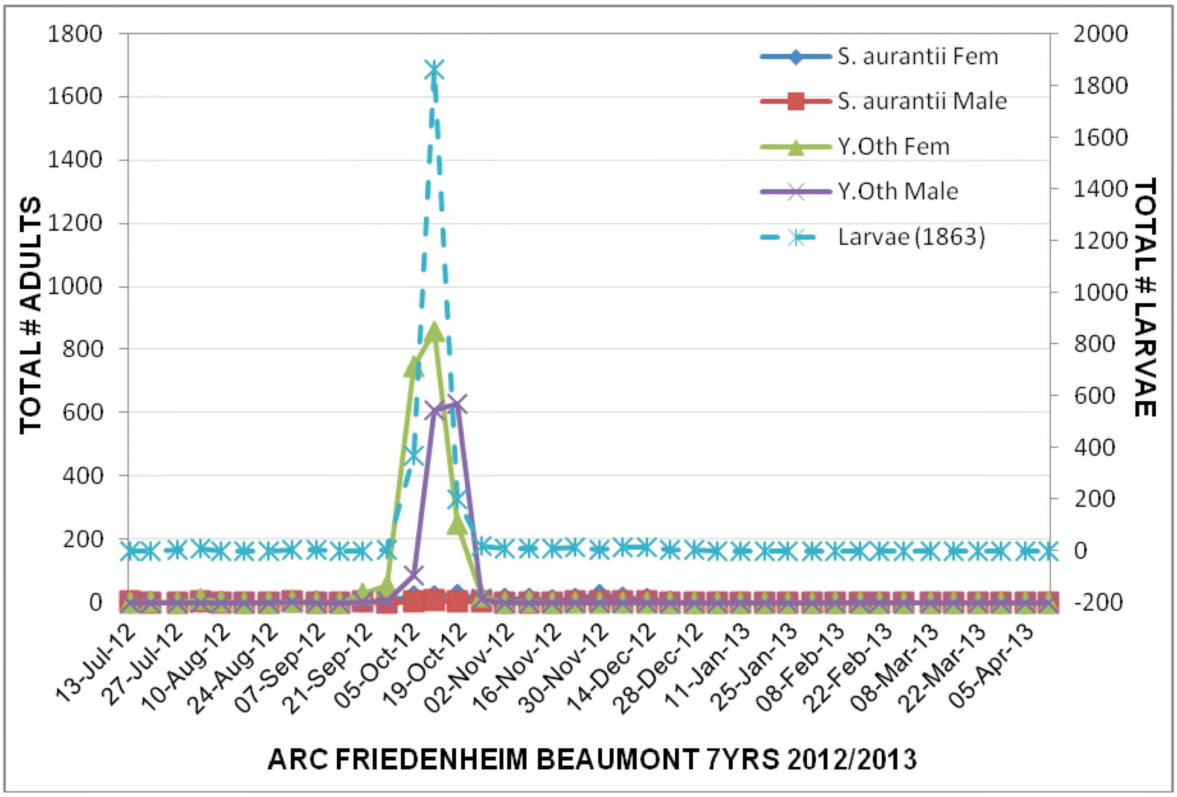


Figure 5.36 2012/2013 Thrips species phenology in the ARC Friedenheim Beaumont (7-year-old) orchard.

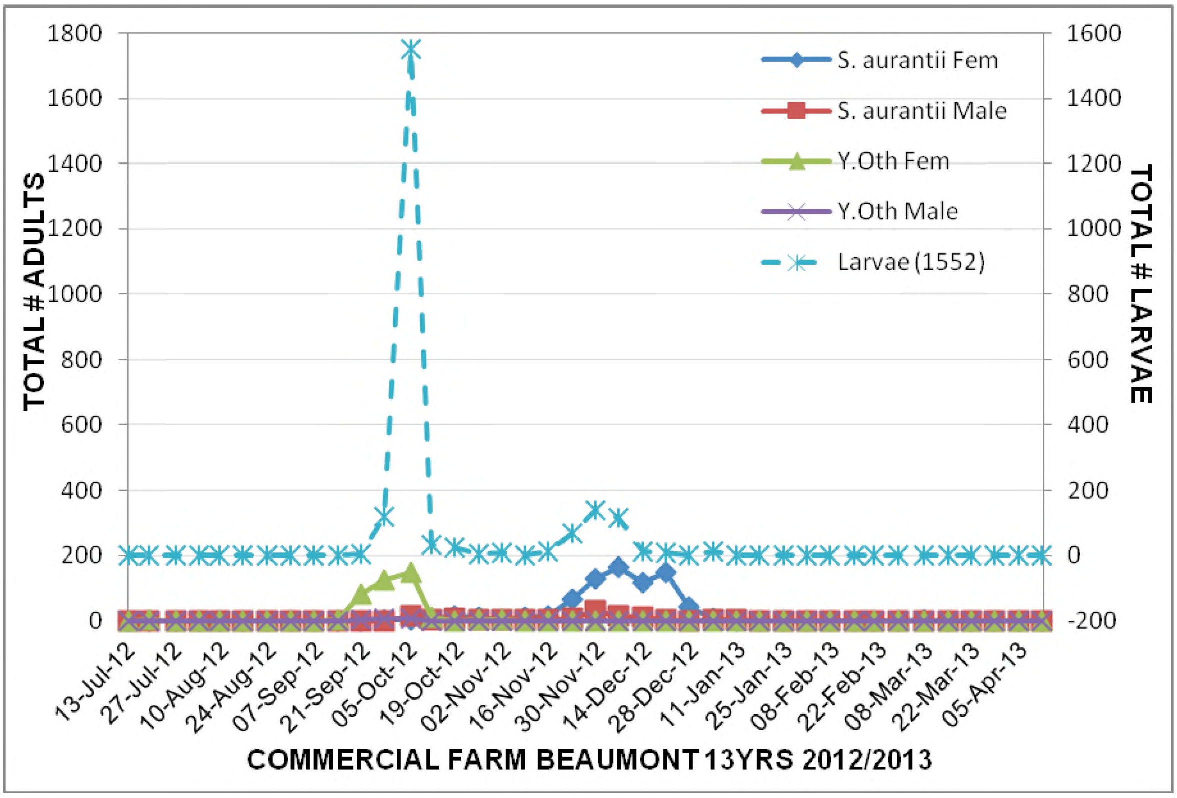


Figure 5.37 2012/2013 Thrips species phenology in the Commercial Farm Beaumont (13-year-old) orchard.

5.3.9.3 Comparison of the 788 sites

The composition and distribution of thrips species in the 788 cultivar site located at the Commercial Farm is shown in Table 5.15 and Fig. 5.38. Thrips populations were already present when sampling commenced on 13 July 2012. The first peak occurred on 10 August, the second (main) peak on 21 September, a third peak on 5 October and a fourth peak on 16 November 2012.

Table 5.15 2012/2013 Thrips population peaks and composition of species at the 788 cultivar site.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
Comm Farm 788	10 Aug 2012	**21 Sept 2012***	5 Oct 2012	16 Nov 2012

1st peak – larvae, 'yellow other' adult ♀; 2nd (main) peak – larvae, 'yellow other' adult ♀ and ♂; 3rd peak – low numbers of larvae, 'yellow other' adult ♀ and ♂; 4th peak – low numbers of larvae, *S. aurantii* adult ♀ and ♂.

*Dates in bold reflect the 'main' peak event.

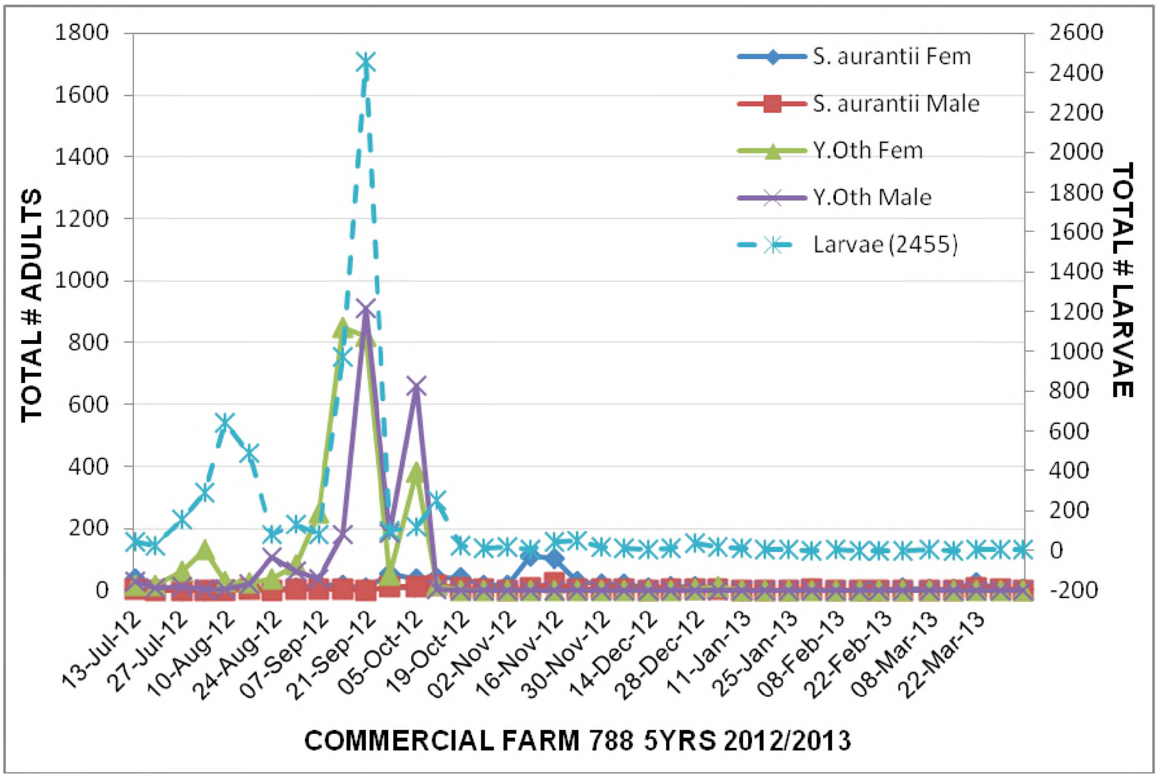


Figure 5.38 2012/2013 Thrips species phenology in the Commercial Farm 788 (5-year-old) orchard.

5.3.9.4 ARC Variety Orchard A16 site

During the second season the new data collected from this early-bearing cultivar was compared to the previous season. The first thrips population peak was on 27 September, the second (main) peak on 11 October, and the third and final peak on 23 November 2012. The distribution and composition of the thrips populations are shown in Table 5.16 and Fig. 5.39.

Table 5.16 2012/2013 Thrips population peaks and composition of species at the ARC Variety Orchard A16 cultivar site.

Site	**1st Peak**	**2nd Peak**	**3rd Peak**	**4th Peak**
ARC Var Orch A16 14 Yrs	27 Sept 2012	**11 Oct 2012***	23 Nov 2012	--

1st peak – mainly larvae, very low number of 'yellow other' adult ♀ and ♂; 2nd (main) peak – mainly larvae, 'yellow other' adult ♀ and ♂, very low number of *S. aurantii* adult ♀ and ♂; 3rd peak – low number of larvae, *S. aurantii* adult ♀ and very low number of ♂.

*Dates in bold reflect the 'main' peak event.

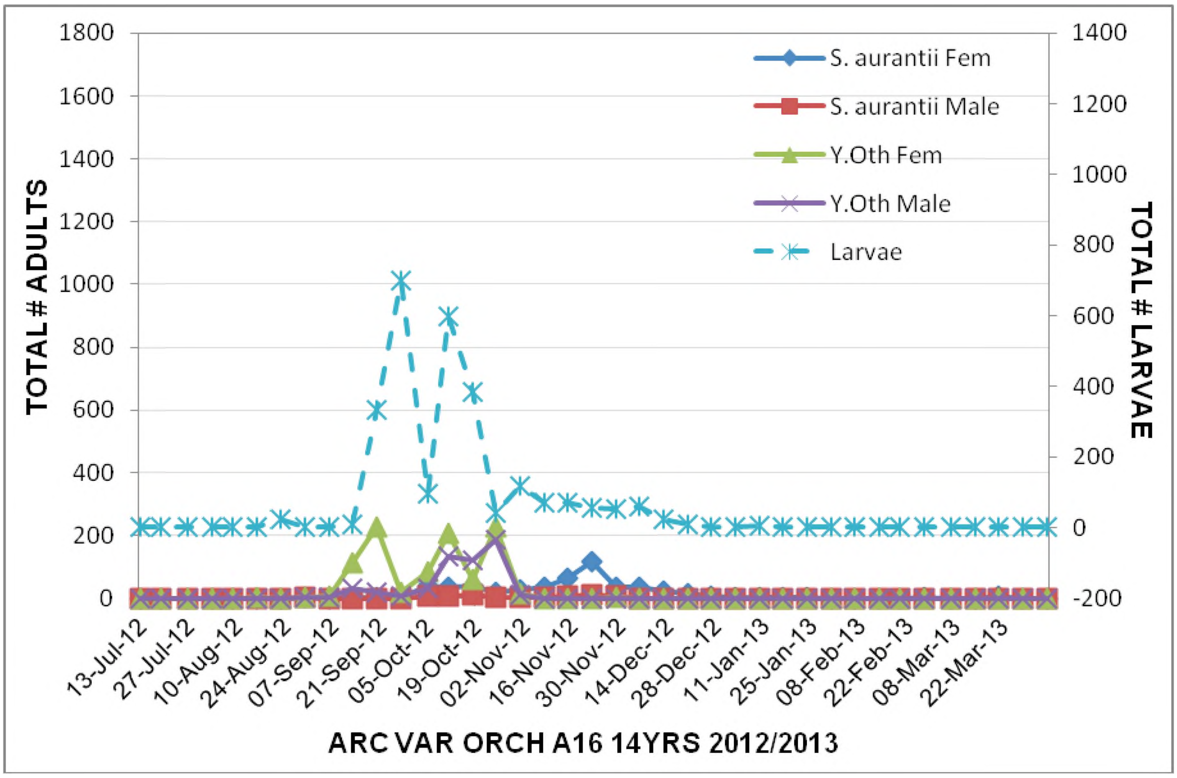


Figure 5.39 2012/2013 Thrips species phenology in the ARC Variety Orchard A16 (14-year-old) orchard.

5.3.9.5 Commercial Farm 816 site

Due to the extremely low nut-set and poor performance of the 816 cultivar at the ARC Variety Orchard it was not included for the second season as data collected would not give an accurate representation of the true potential of this cultivar. Therefore, in the second season data was only collected for the 816 cultivar site at the Commercial Farm. The initial (main) population peak occurred on 15 September, followed by a second, lower peak on 10 November 2012. Only the two peaks occurred at this site; composition of the thrips species is shown in Table 5.17 and Fig. 5.40.

Table 5.17 2012/2013 Thrips population peaks and composition of species at the Commercial Farm 816 cultivar site.

Site	1st Peak	2nd Peak	3rd Peak	4th Peak
Comm Farm 816 5Yrs	**15 Sept 2012***	10 Nov 2012	--	--
1st (main) peak – mainly larvae, 'yellow other' adult ♀ and ♂, very low number of *S. aurantii* adult ♀ and ♂; 2nd peak – very low number of larvae, *S. aurantii* adult ♀ and ♂.				

*Dates in bold reflect the 'main' peak event.

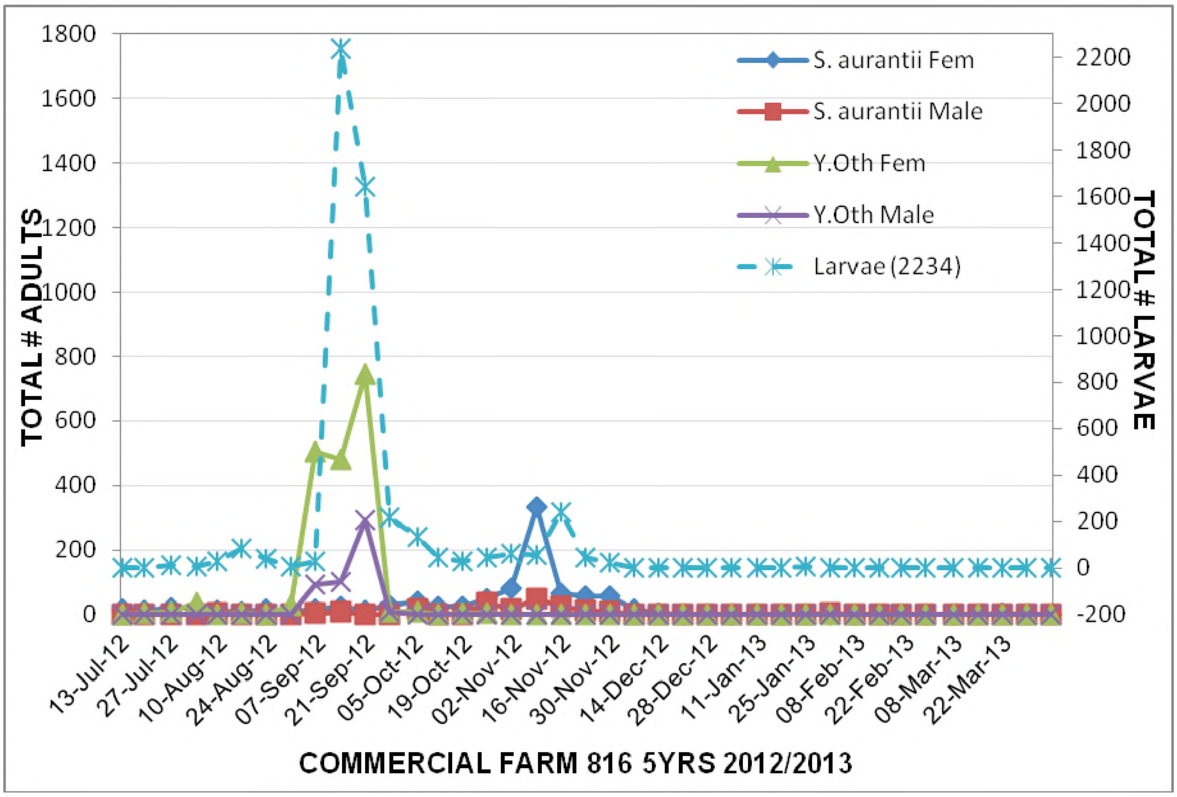


Figure 5.40 2012/2013 Thrips species phenology in the Commercial Farm 816 (5-year-old) orchard.

5.3.10 Chemical spray applications (2012/2013)

As in the previous season, spray applications at the Commercial Farm orchards were applied according to locality and age, based on weekly *B. distincta* scouting data. The 788 5-year-old, Nelmak D 7-year-old, and 816 5-year-old sites (Fig. 5.41) were sprayed with copper to control any fungal outbreak on 30 August 2012. Endosulfan applications were applied on 11 October, 29 November 2012 and 14 January 2013. A synthetic pyrethroid (Alpha-cypermethrin) insecticide was applied on 13 February and 11 March 2013. There did not appear to be any affect on the increasing thrips numbers at these orchards even though one of the endosulfan sprays was applied on 11 October just prior to a thrips peak on 19 October at the Nelmak D 7-year-old site.

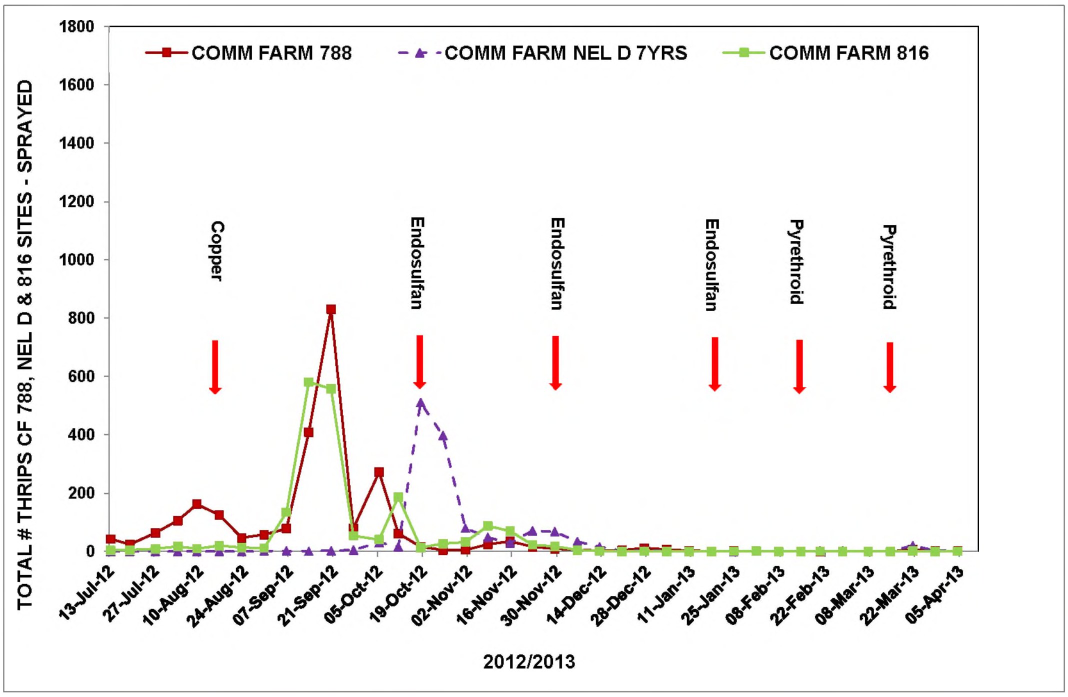


Figure 5.41 2012/2013 Commercial Farm spray application dates at the 788, Nelmak D, and 816 sites.

On 29 August 2012 a copper spray was applied at the Beaumont 13-year-old and Nelmak D 13-year-old cultivar orchards (Fig. 5.42). Fungicidal sprays were applied during the flowering period on 16 October, 25 October and 3 December 2012. Three applications of a synthetic pyrethroid (Alpha-cypermethrin) were applied on 10 January, 11 February and 13 March 2012. During this season chemical applications were once again based on *B. distincta* weekly scouting data and whether thresholds had been breached. As thrips numbers were at extremely low levels when the insecticide applications were applied, there is no evident impact of these sprays having any affect on the populations present.

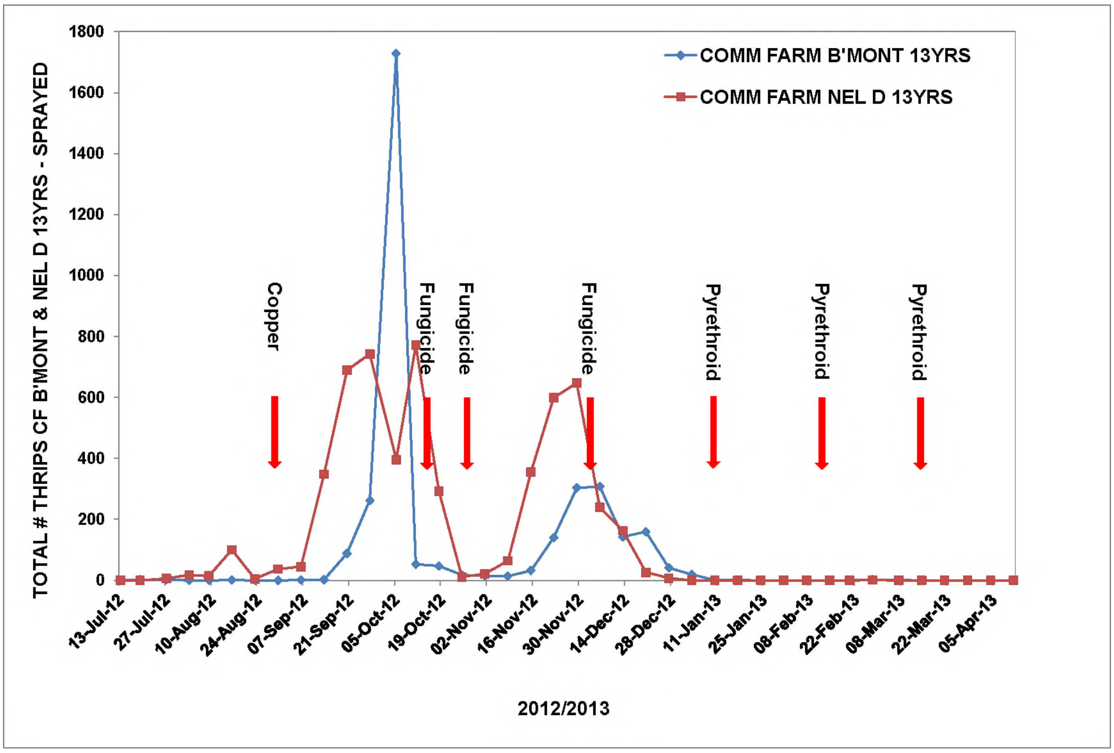


Figure 5.42 2012/2013 Commercial Farm spray application dates at the Beaumont and Nelmak D (13-year-old) sites.

5.3.11 Occurrence of thrips and macadamia phenology

Data on the phenology of macadamia (Chapter 4) was compared to the periods of thrips abundance at each site for both seasons. Without exception, the highest number of thrips occurred when the “closed buds” and “open flowers” stages were present, often whilst some of the other developmental stages occurred simultaneously (Table 5.18). Any patterns between the remaining five developmental stages were less definitive. At three of the sites (ARC-ITSC Old Nelmak 2 43-year-old, ARC-ITSC Nelmak D 9-year-old and Commercial

Farm Beaumont 13-year-old), all seven of the developmental stages were present when the highest numbers of thrips were recorded.

When comparing data for the highest number of thrips during the 2011/2012 season (see Table 5.3) and the 2012/2013 season (see Table 5.11) with the growth points available during the main thrips peak (Table 5.18), there does not seem to be any correlation.

Table 5.18 Macadamia study sites, grouped by cultivar, showing developmental stages (present/absent) when main thrips population peaks occurred during the 2011/2012 and 2012/2013 growing seasons.

Study Site and Growing Season	Season	New Flush	Closed Buds	Open Flowers	Nut Set	Small Nuts	Med Nuts	Large Nuts
ARC Old Nel 2 43Y	2012/13	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ARC Nel D 8/9Y	2011/12	No	Yes	Yes	Yes	Yes	Yes	No
	2012/13	Yes	Yes	Yes	Yes	Yes	Yes	Yes
CF Nel D 6/7Y	2011/12	No	Yes	Yes	No	No	No	No
	2012/13	Yes	Yes	Yes	Yes	No	No	No
CF Nel D 12/13Y	2011/12	Yes	Yes	Yes	Yes	No	No	No
	2012/13	Yes	Yes	Yes	Yes	No	No	No
ARC VO Nel 2 13Y	2011/12	No	Yes	Yes	Yes	No	No	No
ARC VO B’mont 13/14Y	2011/12	No	Yes	Yes	No	No	No	No
	2012/13	Yes	Yes	Yes	Yes	Yes	No	No
ARC F.Heim B’mont 6/7Y	2011/12	No	Yes	Yes	No	No	No	No
	2012/13	Yes	Yes	Yes	Yes	No	No	No
CF B’mont 12/13Y	2011/12	Yes	Yes	Yes	Yes	No	No	No
	2012/13	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ARC VO A4 13Y	2011/12	No	Yes	Yes	No	No	No	No
ARC VO A16 13/14Y	2011/12	Yes	Yes	Yes	No	No	No	No
	2012/13	Yes	Yes	Yes	Yes	Yes	No	No
ARC VO 788 13Y	2011/12	Yes	Yes	Yes	No	No	No	No
CF 788 4/5Y	2011/12	Yes	Yes	Yes	Yes	Yes	No	No
	2012/13	Yes	Yes	Yes	Yes	Yes	Yes	No
CF 816 4/5Y	2011/12	No	Yes	Yes	Yes	No	No	No
	2012/13	Yes	Yes	Yes	Yes	Yes	No	No
ARC VO 816 13Y	2011/12	No	Yes	Yes	Yes	No	No	No

5.4 Discussion

The thrips communities in macadamia over the two growing seasons yielded records of more than 15 species. A number of Panchaetothripinae, *Haplothrips* and *Scolothrips*, were not identified to species level, thus only 15 species were positively identified in this study. The Panchaetothripinae are leaf-feeding species, Thripidae flower-associated species, *Haplothrips* species (Tubulifera: Phlaeothripidae) pollen or spore-feeders, and *Scolothrips* predators. Surplus specimens from this study have been stored in 90% ethyl alcohol which will enable future studies to be conducted using genetic analyses to classify specimens to species level. Timm *et al.* (2008) published a molecular identification key for nine of the most important thrips species of southern Africa.

The yellow group was by far the most abundant over both seasons and probably feed on leaves, pollen, parts of macadamia flowers and small nuts (M. Stiller, pers. comm.) The brown group probably feed on parts of macadamia flowers and small nuts, and the black thrips are generally not known as pestiferous and feed on pollen or fungal spores (M. Stiller, pers. comm.).

It was also important to relate larval presence and abundance to establish which species may be breeding (Terry 1997), using macadamia as a host plant. Mound (2013b) emphasised the importance of identifying host plants which, for thrips species "… is a plant on which the insect is able to rear its young". It is widely known that large populations of adult thrips are highly dispersive; a number of scientific and ecological publications name certain "host records" which are misleading as the species are unable to reproduce and sometimes even to feed on these plants. Another point Mound (2013b) raises is when both adults and larvae are found together, this does not necessarily mean the larvae and adults are of the same species; to be able to positively identify the larvae to species would require rearing them to adults or identification by DNA sequencing. It is also of vital importance to incorporate the total feeding population, which includes both the immature and adult stages (Mound 2013b), to establish populations and generations within orchard crops.

Out of the total number of thrips collected in the 2011/2012 (n ≈ 44,000) and 2012/2013 (n ≈ 98,000) seasons, only 84 pre- and pro-pupae individuals (57 and 27 respectively), were collected; thus, indicating that these developmental stages do not usually occur on the plant and most probably inhabit the soil (Palmer 1990, Parrella and Lewis 1997). Similar observations were made by Grové *et al.* (2001) in mango, *Mangifera indica* L. (Anacardiaceae), orchards in South Africa; their study was conducted in the same region as this present study on macadamia. Dispersal / emergence traps were used in their study, sampling both pre-pupae as they dropped to complete their developmental cycle in the soil, and emerging adults. Many of the species identified by Grové *et al.* (2001) in mango orchards also occurred in the macadamia orchards in this study.

During both study periods, the highest number of thrips was present when the trees were in full flower, with many species occurring simultaneously. It has been well documented that certain thrips species facilitate pollination (Kirk 1984, Mound 2005, Sakai 2001 in Mound 2005, Terry 2001 in Mound 2005, Williams *et al.* 2001 in Mound 2005, Zerega *et al.* 2004 in Mound 2005). Given the complexity of cross-pollination in macadamia (Urata 1954, Ito *et al.* 1970 in Wallace *et al.* 1996 in Trueman 2013, Trueman and Turnbull 1994a in Trueman 2013), thrips may in fact play a major beneficial role as pollinators, which has not been seriously considered.

As the crop seasons progressed, community structure changed and the numbers of thrips species and individuals fluctuated. For instance, the number of species occurring when flowers were in full-bloom was higher than when, for example, the small, medium and large nuts were present (Author, pers. obs.). Thrips populations were never constant, with possibly many biotic and abiotic factors contributing to these fluctuations. The specimens collected during this study were from mixed samplings of growth points; should the sampling be exclusively concentrated on, for instance new flush, this would probably show specific species to be dominant on their preferred choice of “growth point”.

5.4.1 2011/2012 Season

During the 2011/2012 season, between 1 and 4 peaks of abundance were recorded when looking at the data on an individual site-basis. When sampling began the thrips numbers in most of the sites were already increasing, forming what would be the initial main peak. The seasonal peaks appeared to be naturally-occurring as they were evident at all sites regardless of cultivar type, and whether chemical control methods were implemented or not.

Data from same-cultivar sites were grouped and compared; the peaks of abundance were evident and very similar within these cultivar groups. The later, lower peaks usually reflected the increase in abundance of *Scirtothrips aurantii* Fauré in the orchards; this usually occurred once the “yellow other” thrips populations had decreased.

The ARC Friedenheim Beaumont study site differed quite significantly from the other study sites in that throughout the 33- week study, a total of fifteen (twelve female and three male) *S. aurantii* adults were collected. At all other sites, *S. aurantii* adults were present at the beginning of the season (8 September 2011), albeit at extremely low numbers, the counts mostly below 10 individuals and increasing to over 10 within two weeks (26 September 2011).

5.4.2 2012/2013 Season

During the 2012/2013 season significantly more thrips were collected from the 10 sites, albeit over a longer study period (40 weeks). The ARC Friedenheim Beaumont site once again only showed a single population peak throughout the season, even though the number of *S. aurantii* had increased to a total of 204 (178 female and 26 male) individuals. In the remaining 9 study sites between 2 and 4 population peaks occurred. Due to collections starting earlier, one can see the number of thrips increased gradually over time from mid-August and mid-September at most of the sites; seasonal peaks were more widely distributed this season.

Grouping of same-cultivar sites were again compared and even though thrips populations at all the study sites were not as concentrated over time as in the first season, these appeared to be cultivar-related. This result was irrespective of farming practices or chemical control.

5.4.3 Conclusion

By understanding more fully the various macadamia cultivar growth phases during a season, we now have an idea of when thrips populations occur and which species may potentially cause damage. One should bear in mind that for this study, mixed samplings were taken of the seven macadamia growth points, giving a broad representation as to which thrips species occur in the orchards. However, when conducting studies to clarify which species cause damage to a particular growth point (e.g. new flush), sampling should be exclusively collected from that stage. Several species have specific, preferred feeding and breeding sites on a host plant; by studying these it is quite possible that different conclusions would be arrived at with regards to presence and damage on macadamia.

It is likely that *Thrips tenellus* and *T. subnudula*, the two most abundant species at flowering, feed on the flowers, pollen and perhaps even early nut-set (M. Stiller, pers. comm.). The next most prevalent species, *Scirtothrips aurantii*, were present at very low numbers whilst flowering occurred; their numbers increasing only once flowering had finished and *T. tenellus* and *T. subnudula* populations had decreased. It is possible that *S. aurantii* feed on new flush, husks and to a lesser extent blossoms.

Of importance was the presence and number of larvae when sampling began; this indicates that thrips use macadamias as a host plant to reproduce, and which are foraging for resources. It may be plausible that larval development was delayed by low spring ambient temperatures and the required amount of heat units necessary for rapid development took longer to accumulate. This may explain the extremely high larval populations at the commencement of the study at some of the sites. At the onset of summer, when daily temperatures began to rise, the number of heat units would thereby increase and quickly accumulated, which in turn would promote the rapid increase of subsequent thrips generations.

Low populations of *S. aurantii* occurred concurrently with the "yellow other" group of thrips, and could only be seen when looking at the raw data spreadsheets. In the line graphs derived from these data spreadsheets, one cannot clearly distinguish the presence of *S. aurantii* early in the seasons because their numbers were extremely low. Only once the number of "yellow other" thrips populations declined did the *S. aurantii* population peak, although one can, in some instances, verify from the line graphs that their numbers were slowly increasing. These smaller, later peaks showed the change of the thrips phenology in macadamia; *S. aurantii* became the more abundant species, even though their numbers did not reach the same level as the "yellow other" group.

This posed a few questions: once the "yellow other" thrips populations decreased, did the "resident" *S. aurantii* populations opportunistically take over the niche created in macadamias due to the alleviation of competition pressure from the "yellow other" species; or did other *S. aurantii* populations migrate into the macadamias from nearby citrus orchards?

Nelspruit, Mpumalanga, is one of the main citrus and subtropical fruit producing areas in South Africa. *Scirtothrips aurantii* is a species of major economic agricultural importance. Phytophagous insect pest species move between host plants to feed and breed depending on available resources. To ascertain whether *S. aurantii* moved into macadamias as an alternate host crop after the citrus season, we needed to check when the citrus season occurs and the duration of time *S. aurantii* populations are present in citrus orchards.

The citrus growing season is from April through to September. *Scirtothrips aurantii* populations in citrus are at their height during the six-month period, September to January. Gravid females lay their eggs singularly in the soft leaf tissue of the first of the season's new flush. Larvae derived from those eggs become the first generation on citrus; subsequently females lay in any soft tissue (i.e. new flush, new growth tips, flowers and tiny fruitlets) (Gilbert and Bedford 1998). *Scirtothrips aurantii* does not undergo diapause in the major citrus producing areas due to the mild climatic conditions; however, in the cooler regions of South Africa, where harsher cold conditions are experienced, *S. aurantii* populations are reduced to very low levels during winter (Gilbert and Bedford 1998).

The line graphs depicting macadamias phenology data by site for 2011/2012 were checked to see if new flush was present at the commencement of the study (8 September); indeed, at five of the sites new growth flush did occur at that time. At the remaining eight sites, no new flush was present (and would not be until October - January), but alternate "soft tissue" was available early September in the form of "closed buds" and "open flowers".

The 2012/2013 macadamia phenology data line graphs showed that at five sites new flush was present when the study began (13 July 2012), and at a further two sites new flush events occurred within the following two weeks (19 July - 27 July 2012). At the remaining four sites, no new flush was present at the commencement of the study, as new flush events only occurred from August – October. There was however soft tissue available as "closed buds" and "open flowers" were present.

From assessing the population and phenological data of thrips in macadamia and comparing it to the citrus season in Mpumalanga, it seems feasible that *S. aurantii* populations were present, albeit at low numbers from the commencement of sampling and that these populations are "resident" in macadamia orchards. There was no obvious *S. aurantii* population outbreak or large migration event during either of the growing seasons, only the gradual increase in the number of *S. aurantii* present.

This could mean that *S. aurantii* populations are out-competed by the "yellow other" group whose numbers dominate just before and during the flowering period. However, it could also mean that the "yellow other" group and *S. aurantii* populations do not feed on the same developmental stages; that once the flowers and racemes abscise, the "yellow other" group populations either decrease in number or migrate out of the orchards, but there are still oviposition and feeding sites for *S. aurantii* to utilize.

6 Fruit abscission in *Macadamia* (Proteaceae) in Southern Mpumalanga, South Africa

6.1 Introduction

The premature abscission of macadamia, other than natural abscission, results in loss of income for growers, and it has been suggested that thrips (Thysanoptera) are contributing to this abscission. Macadamias flower prolifically and the abscission of flowers, racemes and nut-set is phenomenal given that a 15-year-old tree produces about 10 000 racemes a season, each of which bear between 100 and 300 flowers (Urata 1954), yet only 0.3% of these 1 to 3 million flowers per tree reach maturity (Ito 1980). A good average nut-set in South African orchards is 1.5 nuts per raceme (L. Hobson pers. comm.). It is extremely difficult to identify the cause(s) of so much abscission and ultimately apparent loss of yield, but the potential for higher yields is possible by using pollinators, such as the honeybee, *Apis mellifera* L. (Apidae: Hymenoptera), and interplanting using a different cultivar in a 'pollinator row'. Self-incompatibility of pollination is a trait found in many macadamia cultivars and is regarded as the major reason for low nut-set (Moncur *et al.* 1985); this may be one of the factors influencing the excessive amounts of flowers produced.

Extensive research on potential causes of abscission was undertaken in Hawaii (Nagao and Sakai 1985, Sakai and Nagao 1985), which included investigating the increase of natural ethylene production by racemes. Ethylene is a volatile natural phytohormone that is present usually at low concentrations, and plays an important regulatory role in several physiological processes. Increased ethylene production by the plant occurs following stress induced by either abiotic or biological events such as insect injury and disease (Childers 1997). Sakai and Nagao (1985) showed that even though abscission of both blossoms and fruit occurred continuously from anthesis through to maturity, this period can be separated into three phases during which the rates of abscission differ. Phases of abscission also occur in almonds (Garcia *et al.* 1980 in Sakai and Nagao 1985) and pecans (Woodroof *et al.* 1928 in Sakai and Nagao 1985, Sparks and Heath 1972 in Sakai and Nagao 1985).

From studies on macadamia abscission conducted by Jones (1937), Jones and Shaw (1943), Urata (1954), Sedgley (1981 in Sakai and Nagao 1985), Sakai and Nagao (1985), the three stages of abscission are as follows. The first phase involves the rapid abscission of flowers, which takes place during the first two weeks after anthesis, and is a naturally-occurring, self-thinning event dependant on available carbohydrates and nutrients stored by the tree during the previous season (Urata 1954). More than 90% of flowers abscise during this period (Urata 1954); which were mostly pollinated but unfertilized (Sakai and Nagao 1985).

The second phase takes place 3 to 8 weeks after anthesis, during which time the size of the macadamia nut increases significantly; 80% of the initial nut-set abscises. Urata (1954) and Sedgley (1981 in Sakai and Nagao 1985) reported almost all abscised nuts during this time contained normally-developing embryos, indicating that fertilization had taken place. Many of the abscised nuts turned yellow, which was initially thought to be due to a nutritional imbalance (Urata 1954). During this second phase, ethylene production increased preceding the highest rate of macadamia nut abscission (Sakai and Nagao 1985). The rate of abscission during this phase is more likely to be a consequence of the plant's self-thinning according to the resources it has available, together with any concurrent stress to the plant (Sakai and Nagao 1985).

The third and final phase of abscission is that of larger, immature nuts and occurs gradually from around 9 weeks after anthesis until maturity at around 28 to 30 weeks (Sakai and Nagao 1985). This stage may reflect competition for photosynthates during the period when fruit dry weight and total oils increase (Jones 1937 in Hardner *et al.* 2009, Jones and Shaw 1943), or from accumulated pest pressure and damage.

Not all leaves, flowers and fruit exhibit ethylene-enhanced abscission, although approximately 40% of plant species studied abscise as a response to an increase in ethylene concentrations (Childers 1997). Studies conducted on abscission in other crops (apricot and pistachio - Crane 1971 in Sakai and Nagao 1985, cotton - Rodgers 1981 in Sakai and Nagao 1985, and oranges - Zucconi *et al.* 1978 in Sakai and Nagao 1985), indicate that the second phase is more likely to be caused by internal developmental changes. The period during which the most active growth and rapid increase in fruit enlargement occurs is highly and positively correlated to the highest frequency of abscission (cotton - Davis and Addicott 1972 in Sakai and Nagao 1985, cherries - Wittenbach and Bukovac 1974 in Sakai and Nagao 1985). It has also been shown that ethylene production increases in immature fruits during periods of high abscission frequency (cotton - Lipe and Morgan 1972, 1973, apple, raspberries, cherries - Blanpied 1972 in Sakai and Nagao 1985, cherries - Wittenbach and Bukovac 1974 in Sakai and Nagao 1985).

Ethylene is the proximate mechanism behind abscission, but physiological stress, disease and insect damage may be the ultimate mechanisms.

To assess the relative significance of thrips damage in causing fruit abscission in macadamia, abscised nuts were collected over two consecutive growing seasons, 2011/2012 and 2012/2013, from study sites in and around Nelspruit, Mpumalanga Province, South Africa, (Chapter 1). Data from this study show that thrips are virtually absent in the orchards 12-weeks post anthesis, so there is virtually no additional thrips damage to the fruit past this period.

6.2 Materials and methods

6.2.1 Study sites

Details of the study sites and localities are given in Chapter 1.5 (Table 1.2).

6.2.2 Weather data

The temperature and rainfall data were obtained from the ARC-ITSC weather station in Nelspruit. The data for both seasons were analysed to see if weather had any significant effect on the abscission of nuts. Because the duration of the study periods differed (33 and 40 weeks), temperature and rainfall data over 44-weeks for both years were assessed. This was necessary as the first season lasted longer (until 10 May 2012), and the second season began earlier (13 July 2012). The mean weekly temperature data were plotted against the total number of abscised nuts collected during the 2011/2012 and the 2012/2013 seasons.

6.2.3 Assessment of abscission rates

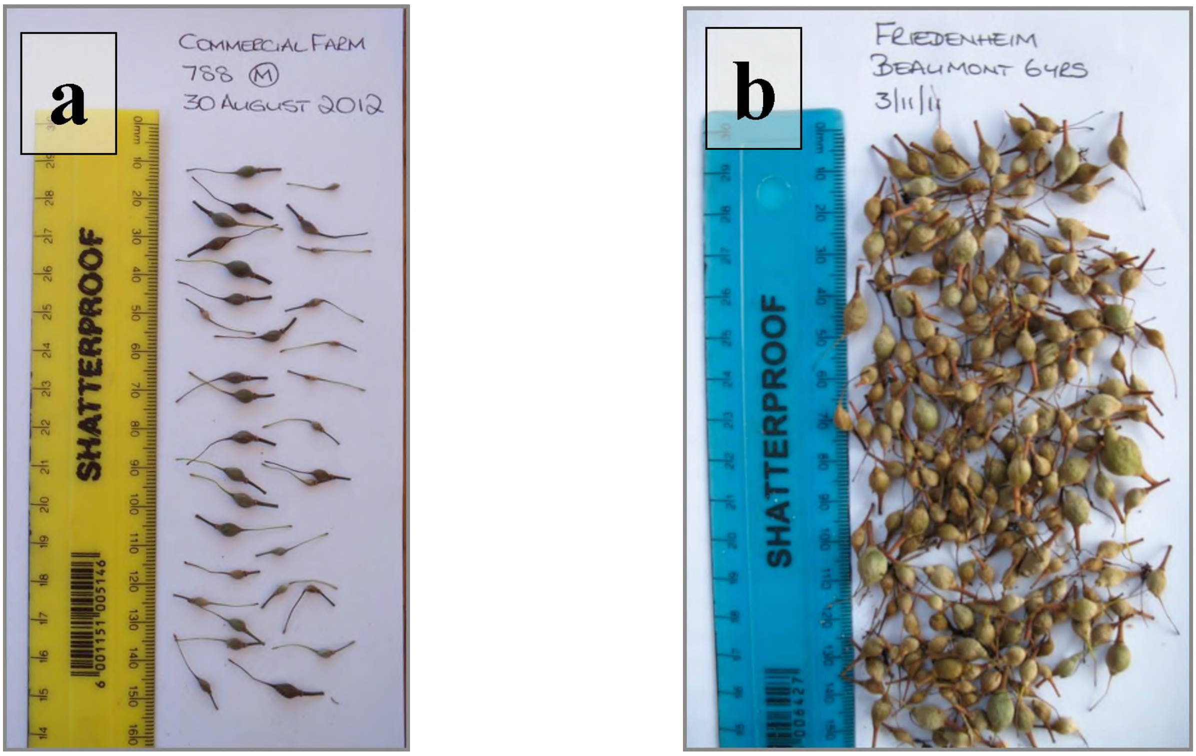
Weekly collections of abscised macadamia nuts were collected beneath 5 data trees at each site, over both seasons. To determine the period of natural nut abscission and abscission due to thrips damage, the leaf litter beneath each of the data trees was cleared to facilitate the weekly collection of fallen nuts (Fig. 6.1). Abscised nuts were collected by study site; nuts from all 5 data trees were placed in a marked paper bag for analysis (Fig. 6.2). The collected abscised nuts from each of the sites were sorted according as to whether thrips damage to the husks was present or not (thrips damage was determined as discussed in Chapter 1.8.1), and counted. The counts were compared between damage classes (present / absent), cultivars, management practices and the two growing seasons.

Digital, calibrated photographs were taken to quantify the phenological stages of the plant (Figs. 6.3 a-b), and representative samples of abscised nuts (Figs. 6.4 a-b, 6.5 a-b). These calibrated photographs were cross-referenced with the photographs taken of the phenological development at each study site (Chapter 4) to quantify the phenological stages of the plant and development of the nuts.

Figure 6.1 Leaf litter cleared beneath the data trees.

Figure 6.2 Weekly abscised nuts collected from the study sites (abscised nuts from some sites sometimes filled more than one bag).

Figures 6.3 a. Beaumont, and **b.** Nelmak D cultivars in full flower.



Figures 6.4 a. and **b.** Photographic records of representative samples of abscised nuts.

Figure 6.5 a. and **b.** Callibrated digital photographs of samples of the weekly abscised nuts by site.

The dates of anthesis at each site were calculated using digital photographs taken of the development of the trees (Chapter 4) and the number of abscised nuts collected weekly. The period (in weeks) between anthesis and the initial, immature nut-drop was determined; the dates when initial nut-drop occurred, and the duration of this period were established (Chapter 4, Table 4.4).

At the beginning of the season, when the abscised nuts were still tiny, it was impossible to see any thrips damage even when using a dissecting microscope (Figs. 6.4 a-b). Until the nuts reached about 1 cm in width, the husks were covered with trichomes (hairs), and thrips damage could not be determined. In various smooth-husked cultivars, such as 788 and 816, thrips damage was evident sooner, as opposed to Beaumont, which retained its trichome covering for longer.

6.2.4 Assessment of thrips damage

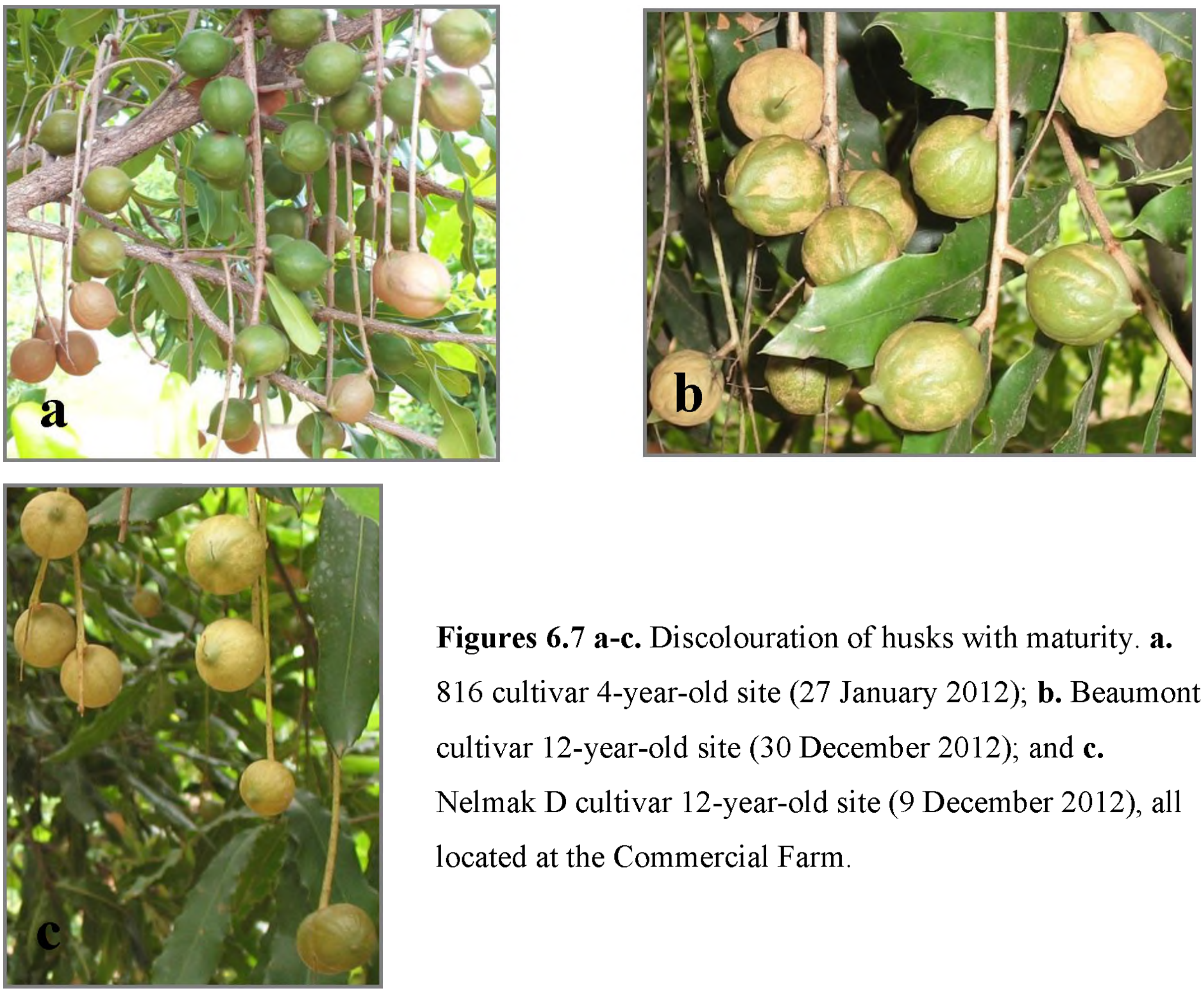
Early in this study quantifying the damage thrips makes to the husks was difficult due to a lack of experience, so digital photographs of South African nuts were sent to colleagues and their opinions sought with regards to the range and pattern of husk damage (Chapter 1, Figs. 1.5 a-d).

Thrips damage to macadamia nut husks appears as “scribbled” or “silvered” damage marks that are not uniformly distributed over the entire husk. The term “bronzing” is commonly used in macadamia literature and in South Africa it seems to always be interpreted by farmers as thrips damage.

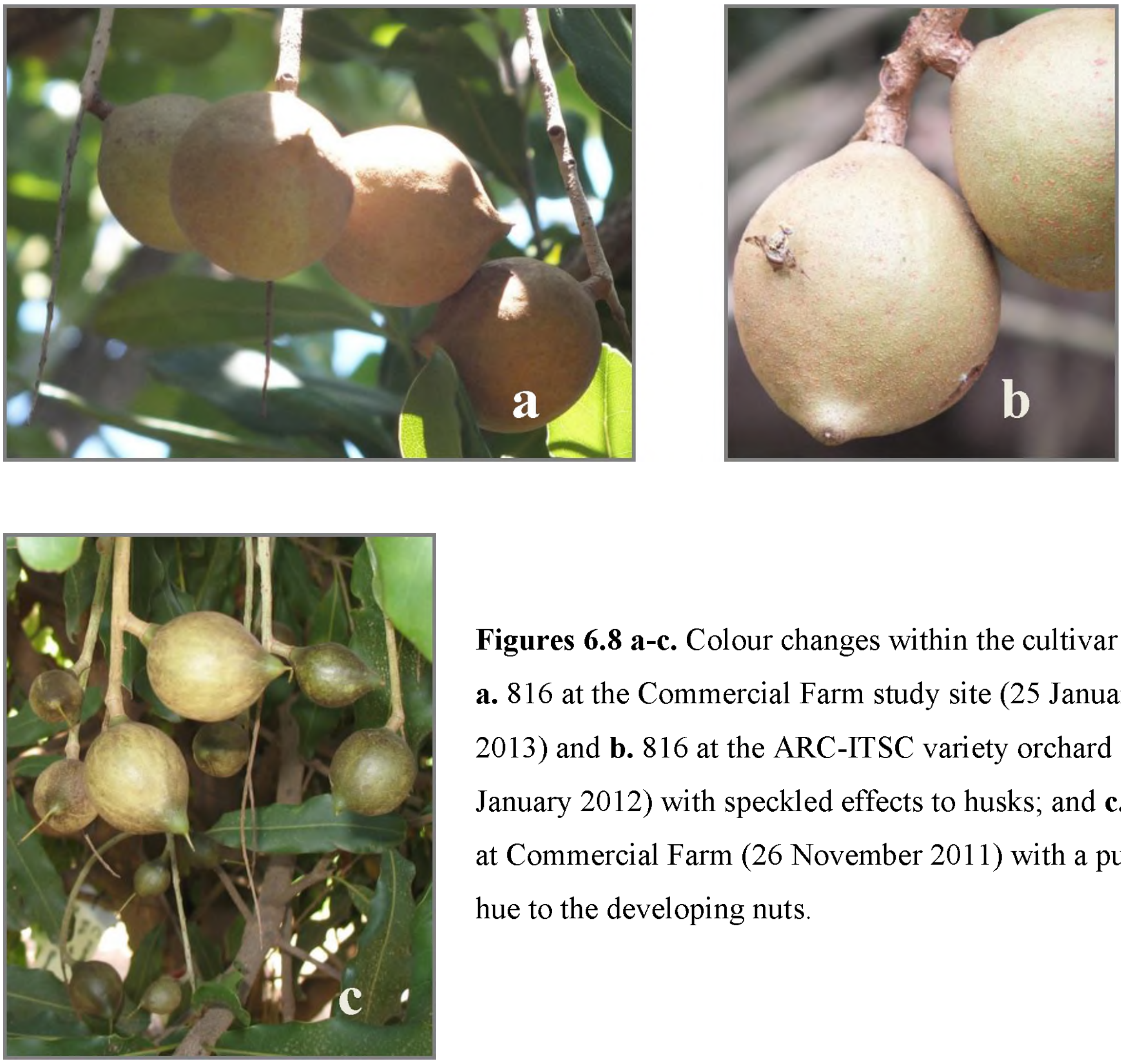
Other husk discolouration may be due to cultivar differences: some cultivars have shiny, glossy husks (i.e. “smooth-shelled” cultivars) (Figs. 6.6 a-b), and others dull, matt husks (i.e. “rough-shelled” cultivars) (Fig. 6.6 c). Over time the husk surface becomes dull, sometimes paler, near maturity as shown in photos of the 816, Beaumont and Nelmak D cultivars at the Commercial Farm (Figs. 6.7 a-c). Cultivars may go through quite a few different “finishes” during their development and growth; in the 816 cultivar this ranged from glossy (Fig. 6.6 b) to speckled (Figs. 6.8 a-b) and with a purple hue (Fig. 6.8 c).

Figures 6.6 a-b. Smooth shelled cultivars with a glossy finish to husks **a.** Cultivar 788 (11 November 2012), and **b.** Cultivar 816 (13 October 2012), both study sites situated at the Commercial Farm.

Figure 6.6 c. Beaumont cultivar husks (22 November 2012), ARC Friedenheim Research Station study site, with a matt finish to the husk.



Figures 6.7 a-c. Discolouration of husks with maturity. **a.** 816 cultivar 4-year-old site (27 January 2012); **b.** Beaumont cultivar 12-year-old site (30 December 2012); and **c.** Nelmak D cultivar 12-year-old site (9 December 2012), all located at the Commercial Farm.



Figures 6.8 a-c. Colour changes within the cultivar 816. **a.** 816 at the Commercial Farm study site (25 January 2013) and **b.** 816 at the ARC-ITSC variety orchard (20 January 2012) with speckled effects to husks; and **c.** 816 at Commercial Farm (26 November 2011) with a purple hue to the developing nuts.

6.3 Results

Quantitative analyses could not be run as not all cultivars were replicated; and when they were, the replicates were insufficient in number, the size of the study sites, duration of the study periods, and management practices also differed. However, the data gathered can be assessed on a qualitative basis (Table 6.1, Figs. 6.9-6.21).

Table 6.1 The total number of abscised nuts, nuts with thrips damage as a percent of the total number of abscised nuts, for both management practices over both seasons.

Unmanaged					**Managed**				
Study Site / Cultivar	**Age (years)**	**Abscised Nuts**			**Study Site / Cultivar**	**Age (years)**	**Abscised Nuts**		
		Total	**Thrips**	**% Thrips**			**Total**	**Thrips**	**% Thrips**
2011/2012									
ARC VO Nelmak 2	13	4 579	1 526	33.3%	CF 816	4	4 417	203	4.6%
ARC VO A16	13	4 454	3 097	69.5%	CF Nel D	6	1 410	20	1.4%
ARC VO A4	13	3 092	709	22.9%	CF Nel D	12	6 432	877	13.6%
ARC VO 816	13	3 053	1 806	59.2%	CF 788	4	1 140	45	4.0%
ARC Nelmak D	8	2 044	367	18.0%	CF Beaumont	12	11 329	265	2.3%
ARC VO 788	13	2 012	776	38.6%					
ARC VO Beaumont	13	1 763	494	28.0%					
ARC Friedenheim Beaumont	6	811	0	0.0%					
Grand Totals		**21 808**	**8 775**	**40.2%**			**24 728**	**1 410**	**5.7%**
2012/2013									
ARC Nelmak 2	43	17 583	666	3.8%	CF 816	5	4 272	332	7.8%
ARC VO A16	14	9 516	3 264	34.3%	CF Nel D	7	469	4	0.9%
Nelmak D	9	3 188	99	3.1%	CF Nel D	13	4 663	222	4.8%
ARC VO Beaumont	14	5 339	1 180	22.1%	CF 788	5	4 215	430	10.2%
ARC Friedenheim Beaumont	7	3 605	69	1.9%	CF Beaumont	13	1 579	56	3.5%
Grand Totals		**39 231**	**5 278**	**13.5%**			**15 198**	**1 044**	**6.9%**

6.3.1 Weather data

The average maximum weekly temperatures (Fig. 6.9) and accumulated rainfall (Fig. 6.10) are plotted against the total number of abscised nuts during the 2011/2012 season. The same comparison was made for the 2012/2013 season; temperature (Fig. 6.11) and rainfall (Fig. 6.12) respectively. Temperature data for the first (Fig. 6.13) and second (Fig. 6.14) seasons was plotted against the total number of thrips and approximate date of anthesis; this was to see whether there was an impact on the amount of abscission, giving an overall view of how temperatures related to anthesis and the occurrence of thrips populations. The temperatures for both seasons were evaluated, and a very similar pattern was evident; there were only 39 accumulated degrees (°C) difference between the two seasons over the 44-week (308-day) period assessed, the slightly higher temperatures occurred during the first season. It was also noted that, in both seasons, a couple of weeks prior to date of anthesis, the average maximum weekly temperatures dropped. Moncur *et al.* (1985) reported that lower temperatures are required to break bud dormancy and promote flower development (Chapter 2.3.4.2).

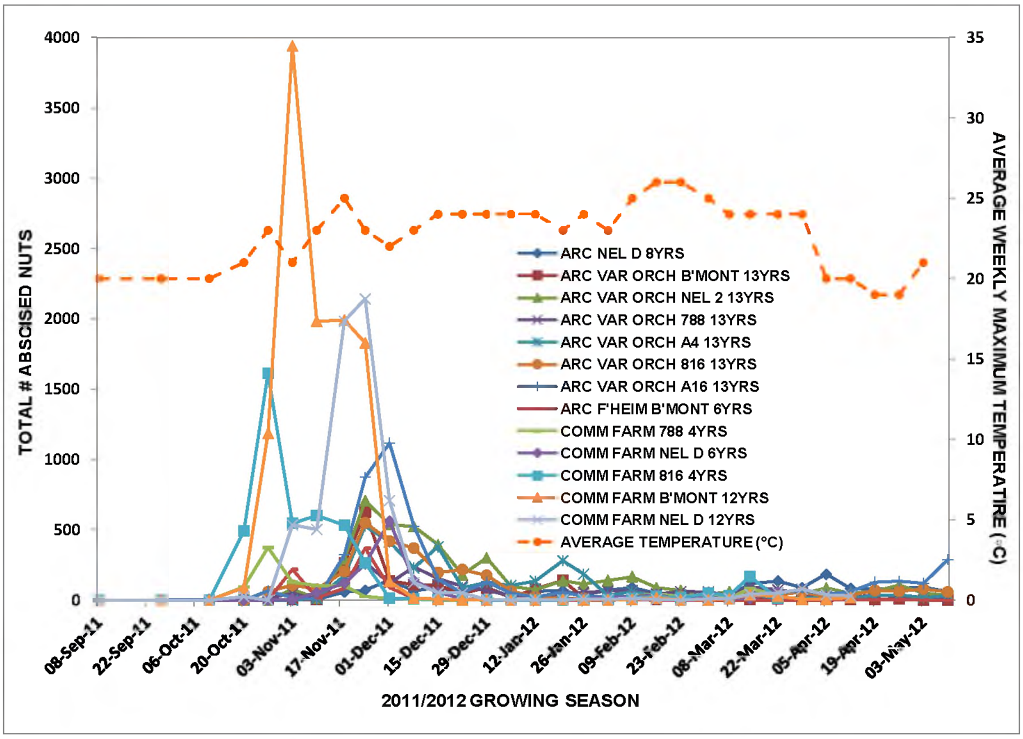


Figure 6.9 2011/2012 Total number of abscised nuts for all study sites, showing average weekly temperatures along the secondary axis.

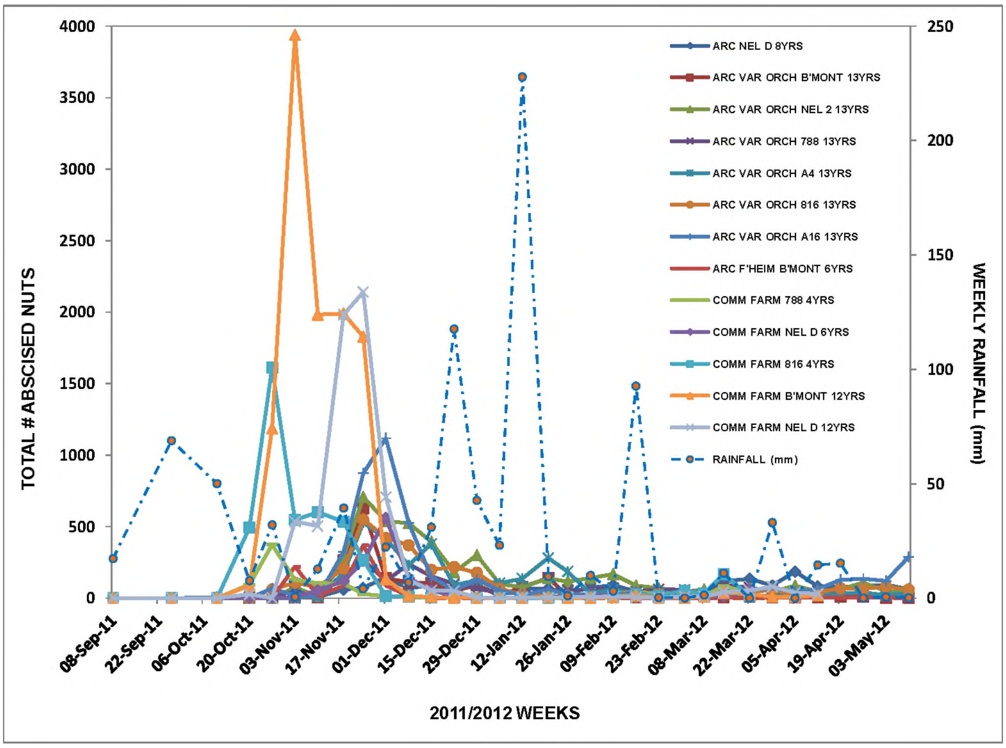


Figure 6.10 2011/2012 Total number of abscised nuts for all study sites, showing weekly rainfall along the secondary axis.

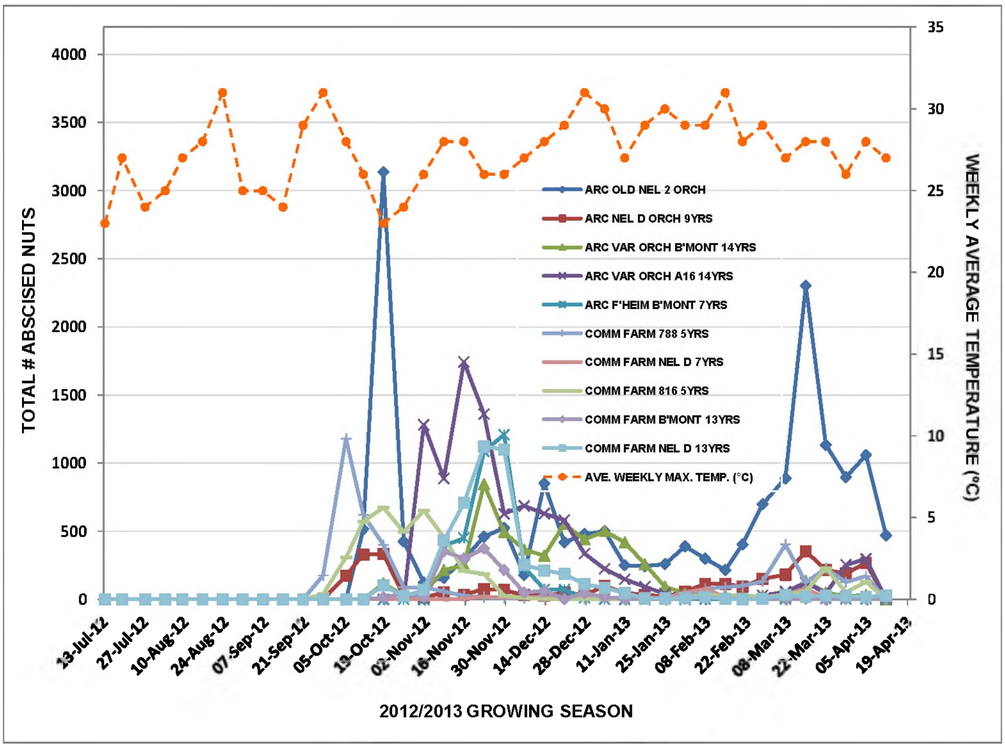


Figure 6.11 2012/2013 Total number of abscised nuts for all study sites, showing average weekly temperatures along the secondary axis.

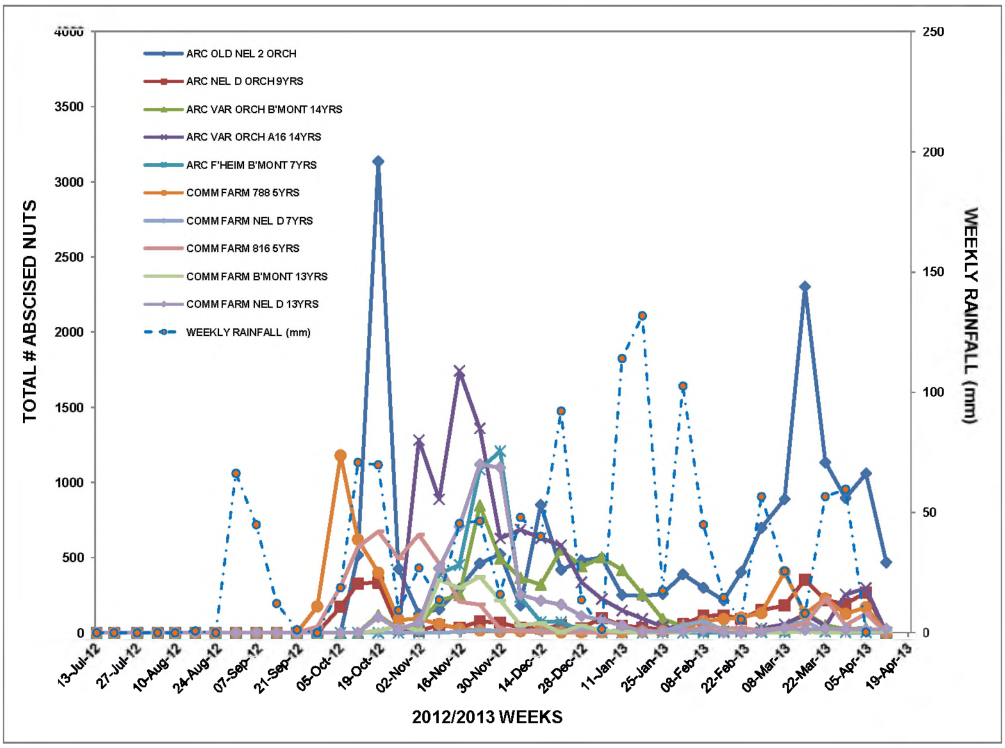


Figure 6.12 2012/2013 Total number of abscised nuts for all study sites, showing weekly rainfall, along the secondary axis.

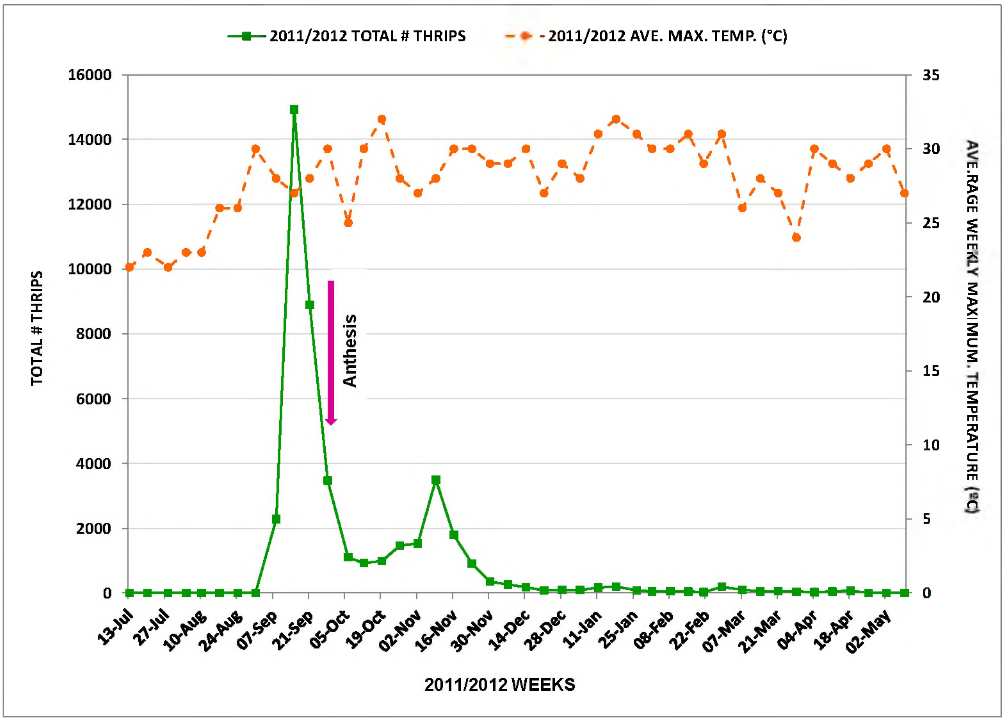


Figure 6.13 2011/2012 The total number of thrips collected over all sites, date of anthesis and average weekly maximum temperatures along the secondary axis.

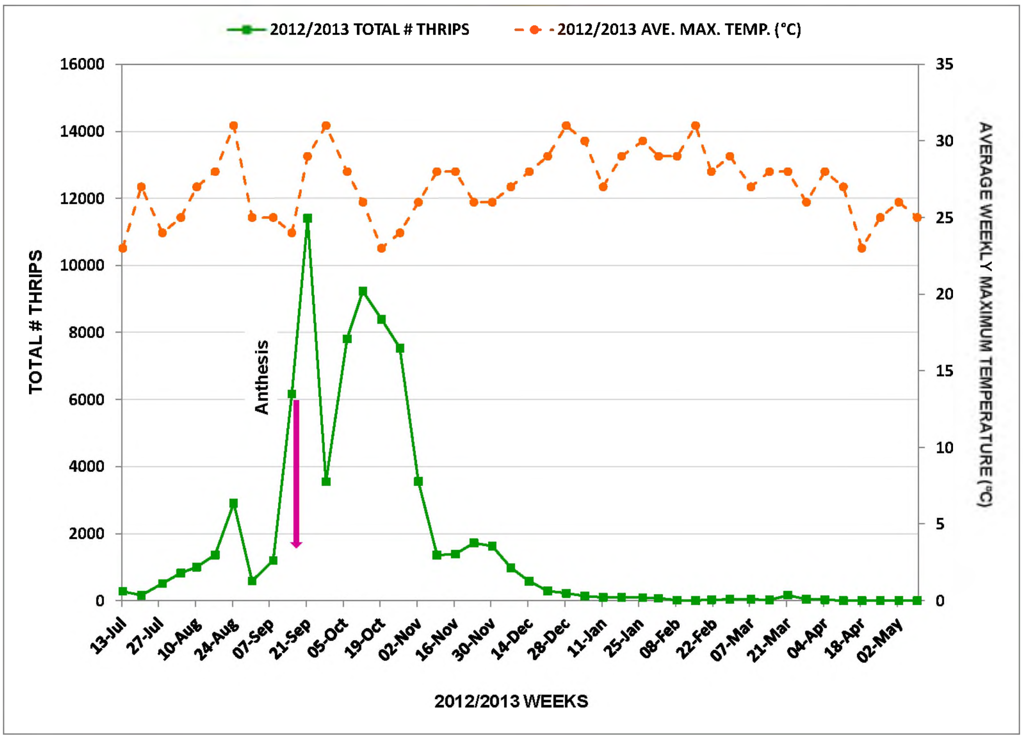


Figure 6.14 2012/2013 The total number of thrips collected over all sites, date of anthesis and average weekly maximum temperatures along the secondary axis.

Looking at weekly rainfall (mm) for both seasons (Figs. 6.10 and 6.12), less rainfall fell during the 2011/2012 (914 mm) than in the 2012/2013 (1344 mm) season; a difference of 430 mm, or 30%. Not only was there an increase in the amount of rainfall during the second season, but it was also more widely-distributed throughout the season.

There was a slight difference in the dates of anthesis for the two seasons; during the first season the approximate date of anthesis was calculated as 25 September 2011, and for the second 14 September 2012. These estimated dates of anthesis seem to be strongly correlated to the first high weekly rainfall in both seasons (i.e. > 65 mm).

6.3.2 Nut abscission during the 2011/2012 season

Eight weeks from the initiation of the project (8 September-3 November 2011), only very few abscised nuts had any evident thrips damage, even when checked under the microscope. From this time on, the number of nuts with husk damage gradually increased.

Estimating from the total number of abscised nuts for all sites, abscission started around 20 October; at the Commercial Farm sites the rate of abscission decreased around 8 December, and two weeks later at the ARC sites, around 22 December 2011. These data include natural nut-drop events. Lower rates of abscission continued at most sites until the end of the season, 10 May 2012.

The total number of abscised nuts collected throughout the season is shown in Table 6.1. The Beaumont 12-year-old site at the Commercial Farm had by far the highest number of abscised nuts. However, this may have been partially due to excessive overwatering at this site, and the adjacent Nelmak D 12-year-old site.

Over a 5-week period 10,927 nuts (an average of 2,185 immature nuts per site/week) abscised. Initially the high rate of abscission was thought to be caused by three possible factors: a) the Beaumont cultivar bears prolifically; b) the trees in this orchard are 12-years old and mature; and c) commercially managed orchards, provided with the necessary nutrients, produce a better nut-set and consequently a greater number of nuts would abscise compared to an unmanaged orchard. However, during the 2012/2013 season the number of nuts to abscise over the initial four-week period of immature nut-drop was 1,243 nuts (an average of 311 nuts per site/week), a substantial decrease from the previous season’s number.

After asking the manager of the commercial farm whether there was any change in management practices, any reason which may be a contributing factor in the significant difference in nut-drop between the two seasons, a very likely reason was revealed. The irrigation system supplying both the Beaumont and Nelmak D 13-year-old orchards, which are adjacent and on the same irrigation line, was set incorrectly and overwatering occurred throughout the 2011/2012 season. Drainage in the orchards was not able to handle the excessive amount of water, causing the orchards to become partially water-logged. At the Nelmak D orchard, during the 2011/2012 season, 5,869 nuts (an average of 1,174 nuts per site/week) abscised over the five-week period of immature nut-drop, and for the 2012/2013 season 3,615 nuts (an average of 723 per site/week) also over a period of five weeks, abscised. Because these two orchards abut one another, this may indicate that Beaumont prefers well-drained soil and is possibly more susceptible to water-logged conditions, whereas the Nelmak D orchard seemed more tolerant.

These same orchards showed a marked decrease in the number of abscised nuts for 2012/2013.

To clarify the amount of damage to the husk caused by thrips, the total number of abscised nuts, and nuts with and without thrips damage, throughout the study period are shown in Fig. 6.15. The first signs of thrips damage, albeit at a low level, occurred on 3 November, two weeks following the start of nut abscission on 20 October 2011. Nuts with thrips damage increased on 18 November and peaked during the next fortnight, 24 November to 8 December; the number of abscised nuts decreased around 22 December 2011.

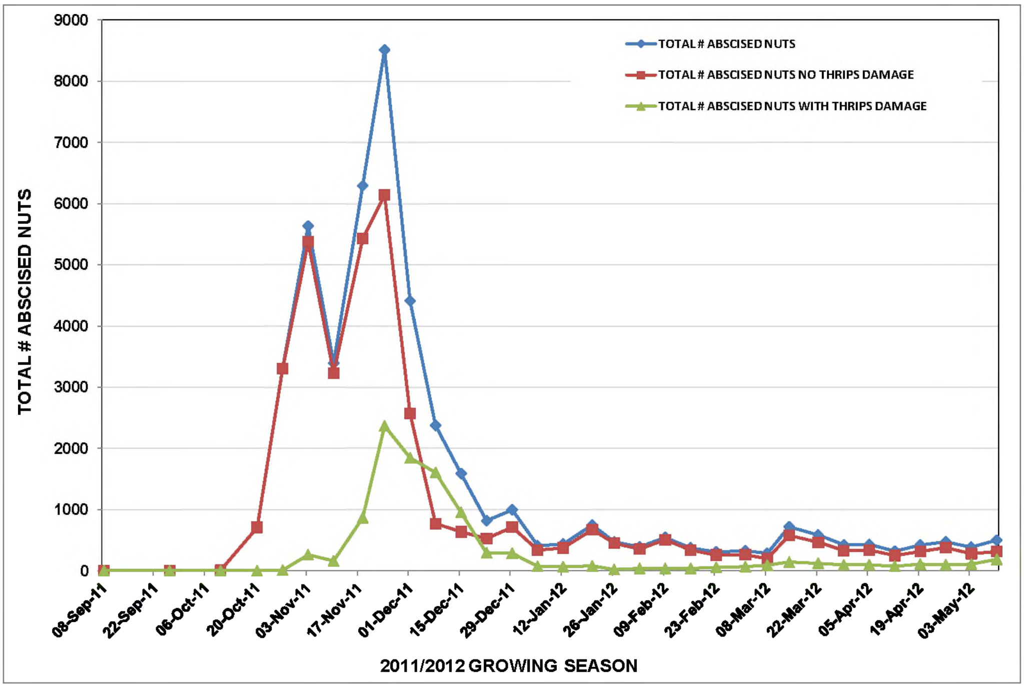


Figure 6.15 2011/2012 Accumulated **a)** total number of abscised nuts; **b)** abscised nuts with no thrips damage; and **c)** abscised nuts with thrips damage, over time.

Abscised nuts with thrips damage began in 7 of the 13 study sites on 3 November 2011; this was also the first instance when the presence of mites was recorded. At the 6 study sites located at the ARC Variety Orchard, the number of nuts with thrips damage increased considerably on 24 November, and remained at a high level for three weeks (Fig. 6.16). The total number of abscised nuts with thrips damage during the 2011/2012 season are also shown in Table 6.1.

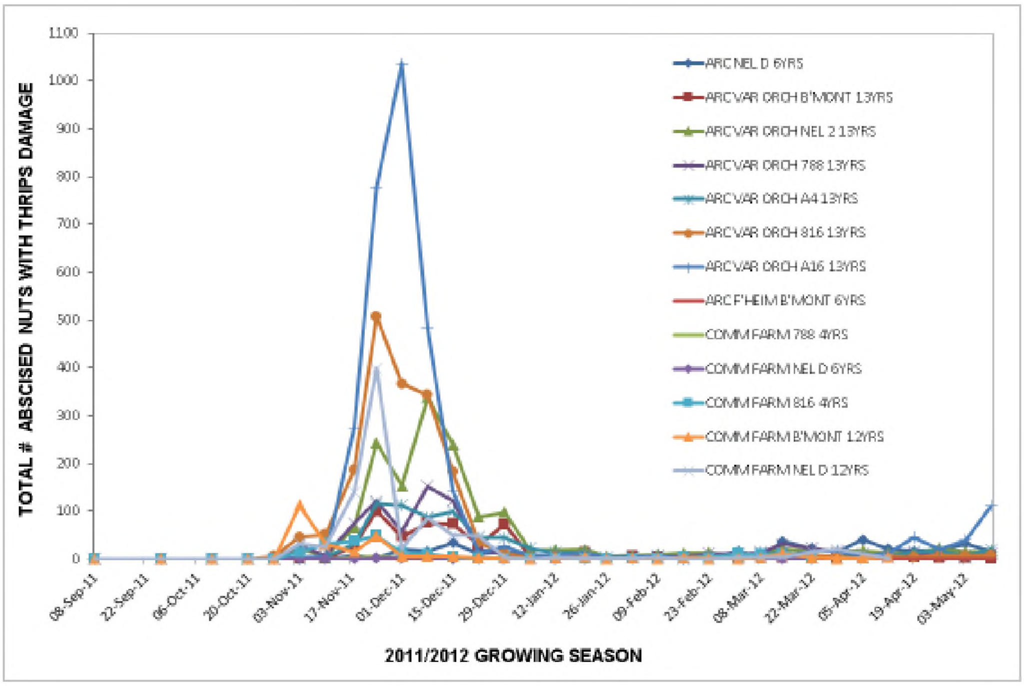


Figure 6.16 2011/2012 Total number of abscised nuts with thrips damage to the husk, by study site.

6.3.3 Nut abscission during the 2012/2013 season

Sampling for the second season began on 13 July 2012; the first abscission of nuts was recorded on 27 September, 11 weeks later. Thrips damage to husks was also recorded on a few nuts on 27 September 2012. The occurrence of abscised nuts differed in that immature nut-drop peaks recurred, yet showed no obvious synchrony to the first season with regards to cultivars or management practices.

The total number of abscised nuts for all study sites during the second season is presented by study site in Table 6.1. Temperature and rainfall data were plotted against the abscised nuts, and shown in Figs. 6.11 and 6.12 respectively. Abscission began on 27 September 2012 and, at some sites, only decreased around 3 January 2013.

In the 2012/2013 season the Nelmak 2 43-year-old orchard located at the ARC-ITSC had the highest abscission rate of all the study sites. This orchard was a "replacement" Nelmak orchard for the site used the previous season (ARC-ITSC Variety Orchard Nelmak 2 13-year-old), which did not bear sufficient nuts to give a true representation of the cultivar. This site had the opposite effect in that the crop and abscission rate of nuts far exceeded any other site. These trees are amongst the oldest macadamias at the ARC, are extremely tall with an extensive canopy area. As with the other sites at the ARC, this site is not managed, and numerous phenological stages were present throughout the season. Nut abscission was 1.55-fold higher than at any other orchard for either season. Abscission at this site began on 11 October and a high number of nuts dropped weekly throughout the season; peaks and troughs were consistent, the lowest number of nuts collected weekly was 125, the highest 3,137 at the peak of the initial, immature nut-drop stage.

The total number of abscised nuts, and abscised nuts both with and without thrips damage, are presented in Fig. 6.17. The first occurrence of thrips damage to husks was at the Commercial Farm 788 5-year-old site on 27 September 2012, although there were only very few nuts (n = 8). Damage increased from 5 October and was widely distributed over a longer period of time than the first season. The total numbers of abscised nuts with thrips damage by site during the 2012/2013 season are shown in Fig. 6.18.

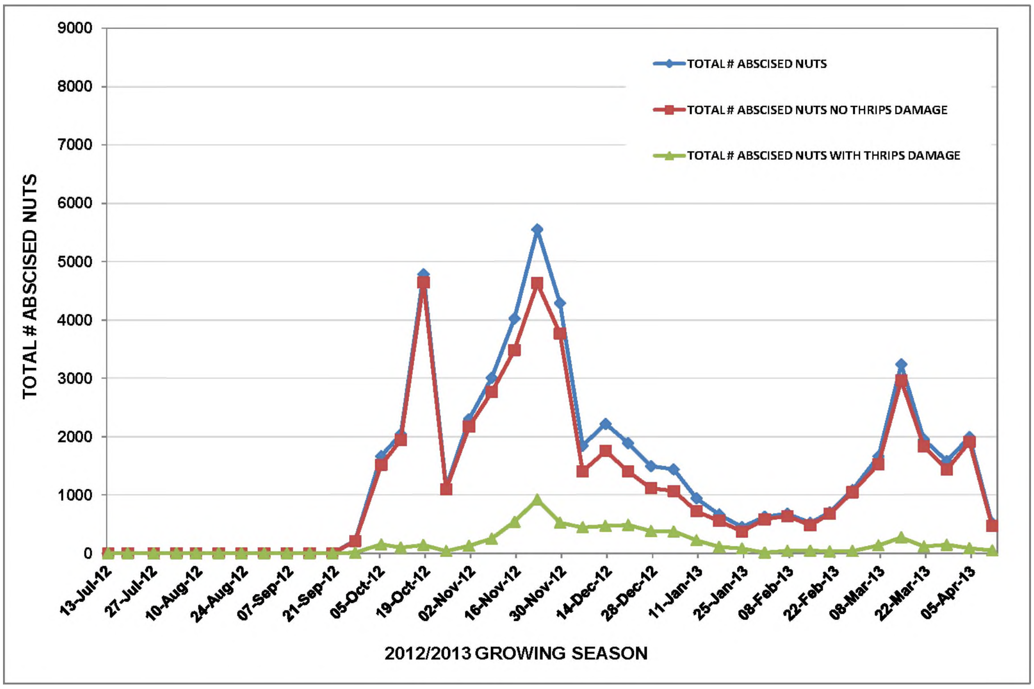


Figure 6.17 2012/2013 Accumulated **a)** total number of abscised nuts; **b)** abscised nuts with no thrips damage; and **c)** abscised nuts with thrips damage, over time.

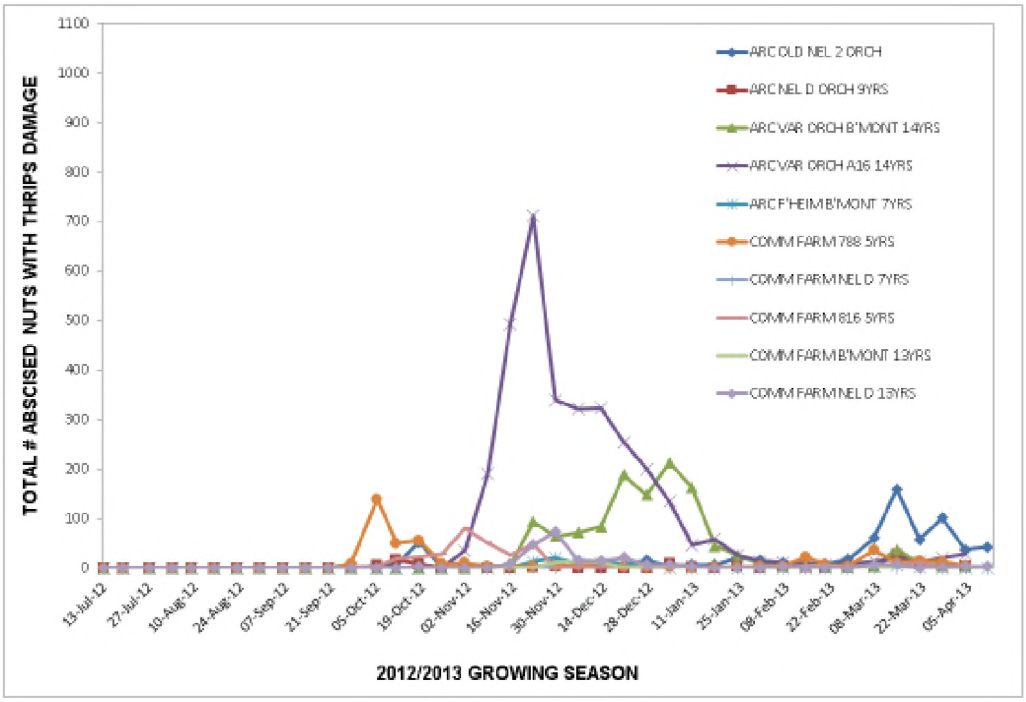


Figure 6.18 2012/2013 Total number of abscised nuts with thrips damage to the husk, by study site.

6.3.4 Analyses of abscission data

Examination of the abscission rate of thrips-damaged nuts (Fig. 6.19) suggested no significant difference between most cultivars; or between managed and unmanaged sites; a consistent difference between the two seasons; and little consistent interaction between these explanatory variables.

Many interactions could not be estimated due to incomplete crossing between levels in the treatment factors (Fig. 6.20), and so formal ANOVA was not attempted. However, pairs of means may be compared for particular combinations of levels of factors by assessing whether their 95% confidence intervals overlap; if they do not, the means may be interpreted as significantly different. If conducted in the same way as planned comparisions, the risk of error inflation can be minimised. Doing this suggests that management practice does not significantly affect the abscission rate of thrips-damaged nuts; that cultivar has no practical significance (except for A16); and that the two seasons were different. There is little evidence of any interaction between the explanatory variables.

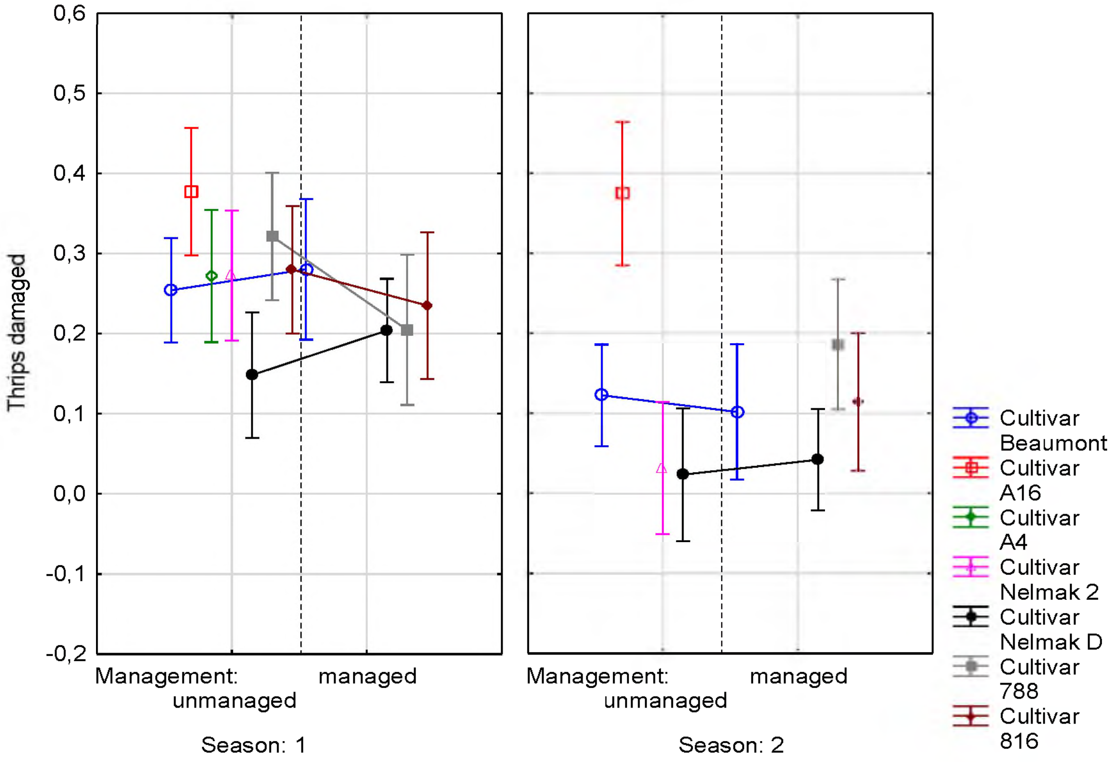


Figure 6.19 Means and 95% confidence intervals for the effects of cultivar, management practice and crop season on the percentage of abscised nuts that were damaged by thrips.

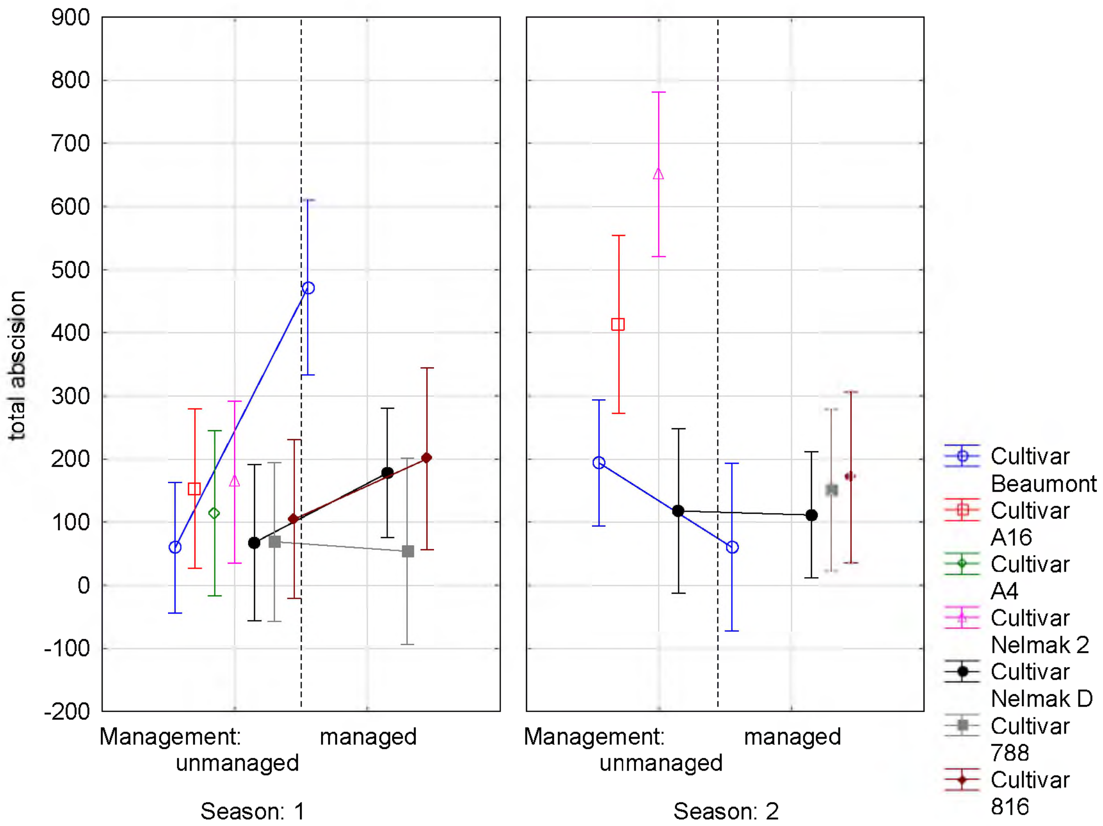


Figure 6.20 Means and 95% confidence intervals for the effects of cultivar, management practice and crop season on the absolute total number of abscised nuts.

6.3.5 Thrips damage to abscised nuts

During the 2011/2012 season the Commercial Farm Beaumont 12-year-old site had the highest amount of abscission (n = 11,329), yet was ranked the fifth-lowest site in terms of percentage with thrips damage (2.3%) (Table 6.1). The high level of abscission may indeed have been as a result of excessive overwatering at this site and the adjacent Nelmak D 12-year-old site. During the following season, the total number of abscised nuts at the same Beaumont site declined substantially (n = 1,579), and the percent with thrips damage was rated second-lowest at 3.5% (Table 6.1).

Transforming the number of abscised nuts with thrips damage to the husk as a percentage of the total number of all abscised nuts, provides a more accurate representation of damage caused by thrips. The number of nuts on a tree also varies considerably with size and cultivar; larger trees may drop more nuts but a smaller percent of the total crop.

Nuts with thrips damage to the husk, from both managed and unmanaged sites, are shown as a percentage of the total number of abscised nuts for both seasons in Fig. 6.21. The results show a lower incidence of nuts with husk damage (5.7%) at the managed sites and, apart from the high abscission rate of the Commercial Farm Beaumont 12-year-old site in 2011/2012 possibly due to overwatering, there was a lower percent of abscission than at the unmanaged sites. At the Commercial Farm during the second season, fewer nuts abscised over a longer period (40-weeks as compared to 33-weeks), and thrips damage to the husks marginally increased (6.9%) (Table 6.1).

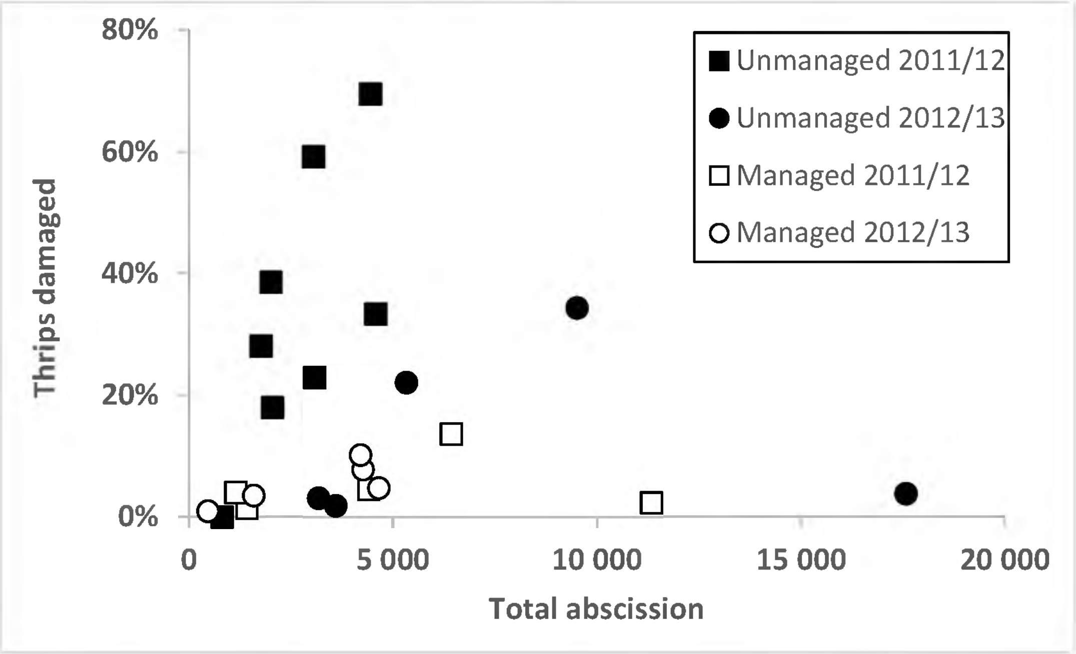


Figure 6.21 Total number of abscised nuts, showing the percent with thrips damage to the husks, at both managed and unmanaged sites, over both seasons.

At the unmanaged sites during the 2011/2012 season, the percentage of nuts with thrips damage (40.2%) was much higher than the second season (13.5%). The outlier was the ARC Nelmak 2 43-year-old site where, although the percentage of thrips damage was low (3.8%), the total number of abscised nuts was extremely high at 17,583 (Table 6.1).

6.4 Discussion

6.4.1 Comparison between the two seasons

It is worth bearing in mind that during the 2011/2012 study period, from when nuts began to abscise until the highest level of thrips damage was recorded, included the period during which natural nut abscission and immature nut-drop occurred, therefore nuts with thrips damge to the husks could not be wholly attributed to having dropped because of damage by thrips. These figures are based on the average of all 13 study sites, so the total number of abscised nuts collected from the Commercial Farm Beaumont 12-year-old site on 3 November 2011 (n = 3,940) where over-irrigation occurred, will have increased the overall average quite considerably.

During both seasons, at most of the study sites (excluding the ARC Nelmak D 8-year-old in 2011/2012, and the Nelmak D 9-year-old and Nelmak 2 43-year-old in 2012/2013), the number of abscised nuts with thrips damage to the husk peaked within the initial nut-drop period; we are therefore unable to quantify how much abscission was caused by "natural" thinning and the amount due to thrips damage.

At the three previously mentioned ARC sites, a peak did occur during this time period, but a slightly higher peak of abscission followed towards the end of the season; Nelmak D 8-year-old (on 5 April 2012), Nelmak D 9-year-old and Nelmak 2 43-year-old (on 14 March 2013); this later peak can probably be attributed to mature nut-drop. The period over which abscission occurred during the second season (Fig. 6.11) was more widely distributed than the first season (Fig. 6.9).

Looking at the total numbers of abscised nuts, the numbers with thrips damage to husks, and those without, the trends over the two seasons are fairly similar (Figs. 6.15 and 6.17). The increased rate of abscission at the ARC-ITSC Old Nelmak 2 at the end of the second season, 20 February to 11 April 2013, is thought to be due to mature nut-drop as 11 April marked 30 weeks post-anthesis.

The total number of abscised nuts, collected from the 13 sites over the 33-week study in 2011/2012, totalled 46,536. This number increased quite considerably during the 40-week study period of the 2012/2013 season from the 10 sites to 54,429. The total number of abscised nuts by study site for the 2011/2012 and 2012/2013 seasons are shown in Table 6.1. During the first season, the Commercial Farm 12-year-old Beaumont site had the highest number of abscised nuts. This may in part have been caused by overwatering. In 2012/2013 the ARC-ITSC Old Nelmak 2 site had by far the highest number of nuts abscise, which may have been partially attributable to the vast canopy and age of the trees at this site.

However, the number of abscised nuts with thrips damage during the 2011/2012 season was 10,185, whereas during the 2012/2013 season the number decreased to 6,322 (Table 6.1). During both seasons the ARC-ITSC Variety Orchard A16 site had the highest number of nuts with thrips damage; possibly indicating that certain cultivars are more susceptible to thrips damage.

During the 2011/2012 season, the number of abscised nuts with thrips damage increased on 17 November 2011. The average weekly temperatures had risen during the preceding weeks and conditions would have been ideal for thrips development and reproduction, facilitating faster generation times.

The 2012/2013 season differed considerably; at four sites nuts with thrips damage increased on 11 October, at one site on 8 November, at three sites on 22 November, at one site 29 November and at one site on 6 December 2012. This followed the same pattern as that of the total number of abscised nuts during this season.

Generally, thrips damage was less prevalent in the second season.

6.4.2 Abscission: flowers, nut-set, immature and mature nuts

The average number of abscised nuts and thrips population data, for both seasons, were combined to determine the approximate time of natural abscission and abscission caused by other factors (Table 6.1 and Fig. 6.22). The dates used for this comparison give a general idea as to when these events take place and are likely to change slightly with season and by region.

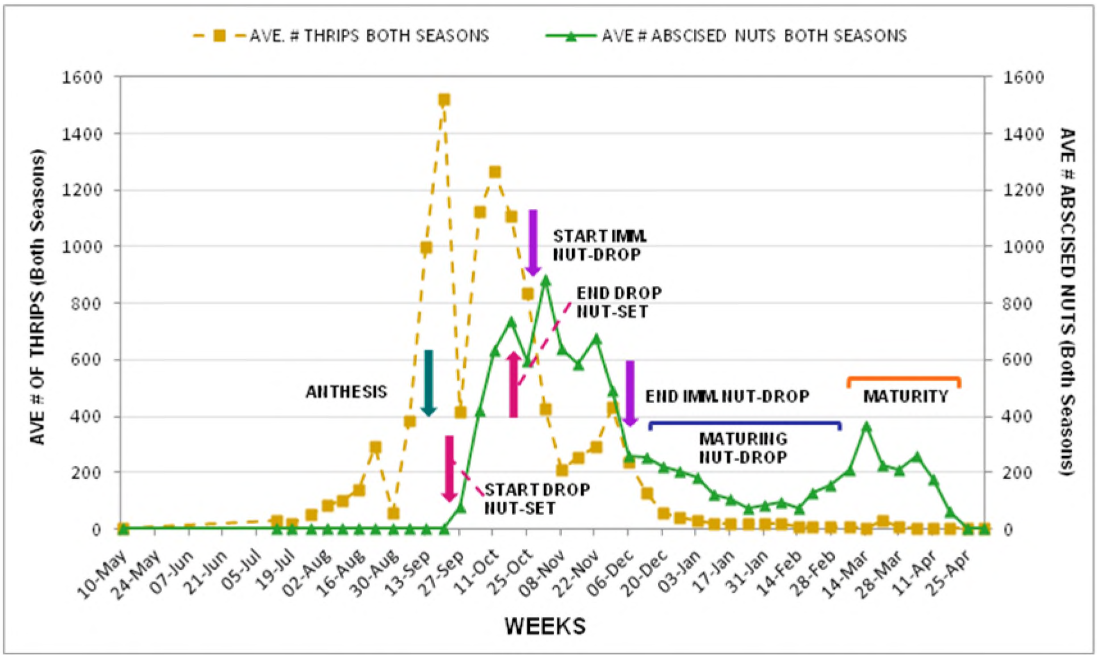


Figure 6.22 Combined anthesis, abscission and thrips data over the 2011/2012 and 2012/2013 macadamia growing seasons showing approximate phenological phases of both macadamia and thrips communities.

The first phase of abscission is that of the flowers, which begins approximately 2-3 weeks after anthesis and lasts for approximately 5 weeks. The second phase begins approximately 2 weeks post-anthesis for approximately 3 weeks (24 September-15 October); comprising small, fertilized fruit which is part of the initial nut-set, and believed to be a natural thinning event. The third phase starts with immature nut-drop, 6-11 weeks after anthesis (18 October-26 November), commonly known as 'November nut-drop'. Nut abscission then gradually diminishes until nuts reach maturity, from around 23 weeks post-anthesis (13 February), until harvest.

The start of the third phase of nut-drop is of larger, immature nuts which abscission is caused by a culmination of an increase in the plant's production of ethylene, the adjustment to crop load before biomass accumulation, reducing fruit-set according to availability of resources, physiological stress, disease, insect damage and/or environmental effects. This final phase extends over the periods of shell hardening, and the accelerated oil accrual in the kernel. Taking into account the quite considerable changes in the plant at this stage, it is suggested that the majority of nut-drop during this final period is due to normal physiological effects. However, this may also be the opportune time when the plant responds most readily to any defects, which would include insect damage, by the abscission of such defective/damaged nuts.

6.4.3 Thrips damage and abscised nuts data for 2011/2012 and 2012/2013

The composition of thrips species communities occurring just prior to the main peaks of abscission was the "yellow" group, comprising mainly *Thrips tenellus* Trybom, *Scirtothrips aurantii* Fauré, *Thrips subnudula* (Karny), *Thrips pusillus* Bagnall, *Thrips microchaetus* Karny and *Thrips acaciae* Trybom. As *T. tenellus* and *T. subnudula* were the most commonly occurring species at the commencement of flowering, it is possible that they feed on pollen, flowers and / or small nut-set. As *S. aurantii* numbers increased long after flowering had ceased (Chapter 5), it is more likely that they feed on new flush and the husks of the nuts.

Looking at the combined number of sites for both seasons (n = 23), *S. aurantii* populations occurred at 17 sites, no *S. aurantii* individuals were collected from 6 sites (Chapter 4, Table 4.4). *Scirtothrips aurantii* populations peaked once the numbers of other yellow species had decreased, which was mostly later in the growing seasons (Chapter 5, Tables 5.5-5.10, 5.13-5.17). At eight sites *S. aurantii* populations were present at low numbers before or at the commencement of immature nut-drop (Chapter 4, Table 4.4).

Quantifying thrips damage to husks as the cause of nut abscission will be extremely difficult. When abscised nuts were processed and tested for maturity, both with and without damage to the husk, as well as a 20-nut random sample picked from the data trees at the study sites, an excessive amount of stink bug damage to the kernels was evident, which may in fact have been the major reason why the nuts abscised (Chapter 7, Figs. 7.3 a-c).

Using the macadamia phenological data as the basis on which to plot the combined average number of (a) thrips collected over both seasons, and (b) abscised nuts, the trends can clearly be seen (Fig. 6.22). Abscission of nut-set, the trees natural fruit-thinning event, occurred around 3 weeks after anthesis. Immature nut-drop took place 6-11 weeks after anthesis, when thrips numbers were already in decline. The fact that nuts with thrips damage to the husk were still hanging in the trees and most of the abscised nuts did not have any thrips damage to the husk, suggests that damage to the husk may be cosmetic and does not lead to abscission.

7 Testing Kernel Maturity of *Macadamias* With Thrips (Thysanoptera) Damage to the Husks

7.1 Introduction

A key question for the South African macadamia nut industry is whether thrips damage is purely superficial and restricted to the husk, or whether it affects the maturity of the kernel, causing economic loss. Quantifying loss of yield attributable to thrips damage, whether direct (abscission of buds, flowers, nut-set and maturing nuts), or indirect (feeding damage to new flush), is extremely difficult if not almost impossible without further in-depth studies targeting these specific focal points. The one damage class which was briefly addressed in this study was that of damage to the outer husks and whether this affected the maturity of the kernel.

7.2 Materials and methods

7.2.1 Study sites

This study was conducted over two growing seasons, 2011/2012 and 2012/2013, in Mpumalanga Province, South Africa. The study sites are described in Chapter 1.5 (Table 1.2).

7.2.2 Abscised nuts

Abscised nuts during both growing seasons were collected from the study sites weekly and sorted according to whether thrips damage to the husk was present or absent; the nuts for each group were counted and recorded (Chapter 6).

7.2.3 Orchard maturity - 20-nut picked sample

To evaluate whether there was any difference in the maturity of the crop still on the trees at each site and the nuts which had abscised (Fig. 7.1 a), a 20-nut sample was picked at random from the five data trees at each site (Fig. 7.1 b). This was done during the final seven weeks of the 2011/2012 season (29 March to 10 May 2012), and the final five weeks of the 2012/2013 season (14 March 2013 to 11 April 2013), immediately before harvest (Table 7.1).

Figure 7.1 a-b. Photographic records of representative samples of **a.** abscised nuts; and **b.** 20-nut sample picked from the ARC-ITSC Nelmak D (8-year-old) site on 14 March 2013.

Table 7.1 Locality and description of study sites where 20-nut samples were picked, and the number of weeks, for comparison maturity tests on abscised nuts, both with and without thrips damage to the husks (for both growing seasons).

Site and Cultivar	**Age of Orchard (Yrs)**		**20-Nut Samples Picked**	
	2011/2012	**2012/2013**	**2011/2012**	**2012/2013**
ARC-ITSC Variety Orchard 788	13	Site not used	No - too few nuts	Site not used
Commercial Farm Orchard 788	4	5	No - 29/3 harvested	Yes - 4 wks 14/3 - 4/4
Commercial Farm Orchard 816	4	5	No - 29/3 harvested	Yes - 4 wks 14/3 - 4/4
ARC-ITSC Variety Orchard 816	13	Site not used	No - too few nuts	Site not used
ARC-ITSC Variety Orchard A16	13	14	Yes - 7 wks 29/3 - 10/5	Yes - 4 wks 14/3 - 4/4
ARC-ITSC Variety Orchard A4	13	Site not used	No - too few nuts	Site not used
ARC-ITSC Variety Orchard Beaumont	13	14	Yes - 7 wks 29/3 - 10/5	Yes - 4 wks 14/3 - 4/4

Site and Cultivar	Age of Orchard (Yrs)		20-Nut Samples Picked	
	2011/2012	2012/2013	2011/2012	2012/2013
ARC Friedenheim Orchard Beaumont	6	7	Yes - 7 wks 29/3 - 10/5	Yes - 5 wks 14/3 - 11/4
Commercial Farm Orchard Beaumont	12	13	Yes - 3 wks 29/3 - 12/4	Yes - 5 wks 14/3 - 11/4
ARC-ITSC Variety Orchard Nelmak 2	13	Site not used	Yes - 7 wks 29/3 - 10/5	Site not used
ARC-ITSC Old Nelmak D Orchard	Site not used	43	Site not used	Yes - 5 wks 14/3 - 11/4
ARC-ITSC Nelmak D Orchard	8	9	Yes - 7 wks 29/3 - 10/5	Yes - 4 wks 14/3 - 4/4
Commercial Farm Orchard Nelmak D	6	7	No - 29/3 harvested	Yes - 4 wks 14/3 - 4/4
Commercial Farm Orchard Nelmak D	12	13	Yes - 3 wks 29/3 - 12/4	Yes - 5 wks 14/3 - 11/4

7.2.4 Sample testing

During the first season the total number of all abscised nuts was processed: a) with no thrips damage to the husk; and b) with thrips damage to the husk. These were to be compared with: c) a 20-nut sample picked from the five data trees at each study site.

Because of the large fluctuations in the numbers of abscised nuts between the different sites in the first season, during the second season 20 individual nuts were randomly chosen from each of groups a) and b) above for maturity testing. In some instances, when there were fewer than 20 abscised nuts, the 20-nut picked sample was tested against as many abscised nuts as there were available, and the data analyses adjusted accordingly.

7.2.5 Testing kernel maturity

The maturity of kernels depends on their oil content. Samples from each of the cultivar orchards were processed separately. Nuts were de-husked, dried in an oven at 70°C for >4 hours to decrease the moisture content (Fig. 7.2), and then cracked by hand. The kernels were removed from the shells and their maturity assessed by placing them in a water bath: mature kernels high in oil content float, immature kernels with less oil content sink (Penter and Kruger 2003). The processed nuts were floated and counts of mature and immature kernels recorded (Figs. 7.3 a-c).

Figure 7.2 De-husked samples prepared for drying to reduce the moisture content, before cracking and floating to check kernel for maturity.

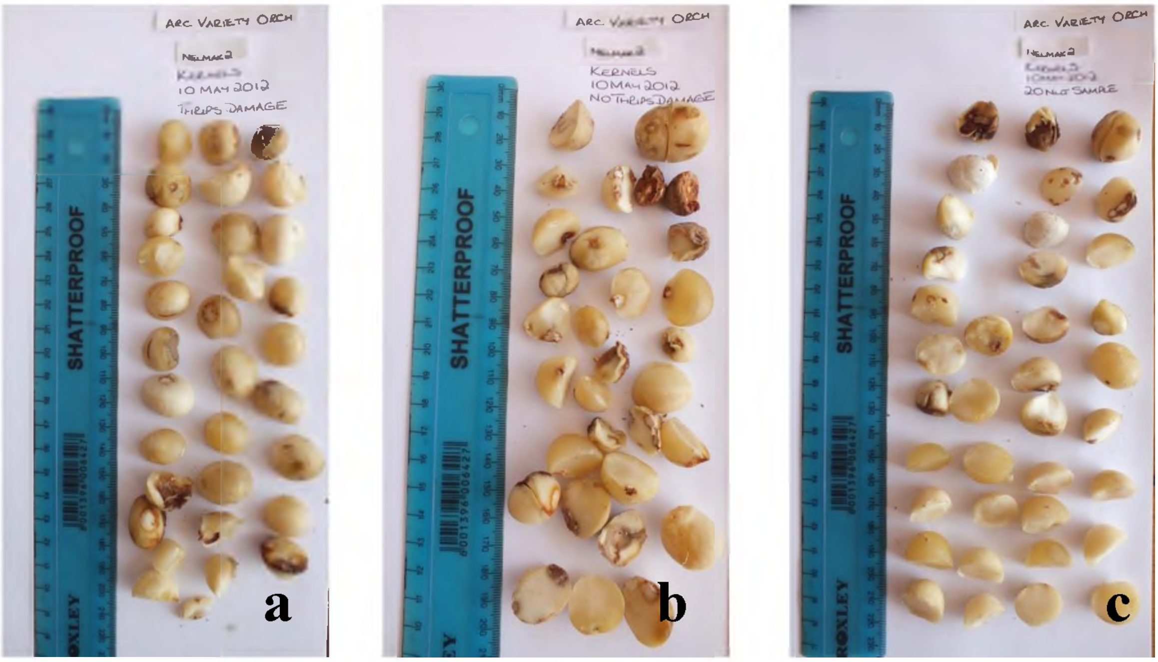


Figure 7.3 Examples of the mature kernels processed from samples collected from the ARC Variety Orchard Nelmak 2 Orchard on 10 May 2012: **a.** with thrips damage to husks; **b.** no thrips damage to husks; and **c.** 20-nut sample picked off the data trees. (Note the extensive damage caused by stink bugs).

7.3 Results

These results are based on qualitative findings, as mentioned previously, logistical constraints as to replication of sites, sampling, time and labour were limiting factors. It was difficult to establish a starting point at which to begin sampling for maturity given the differences in cultivars; early-bearing (788 and 816), mid-bearing (Nelmak 2, Nelmak D and A16), and late-bearing (A4 and Beaumont). This would mean maturity would largely depend on the type of cultivar and the time at which the samples were taken. To achieve 100% maturity was therefore not expected.

The data were calculated as a percentage due to the variation in the number of nuts tested in the two seasons. The percentage of abscised nuts collected over both seasons that had no thrips damage to the husks are shown in Figures 7.4 and 7.8.

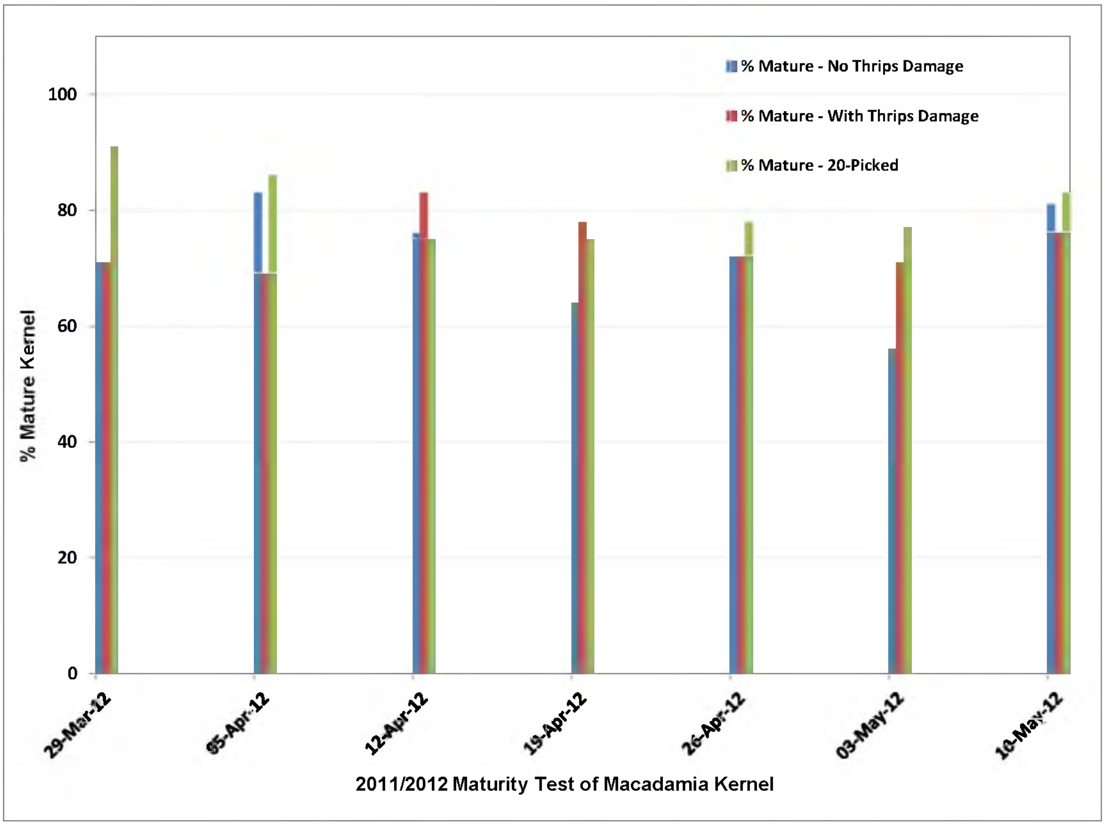


Figure 7.4 2011/2012 Average of mature, abscised nuts with **a.** no thrips damage to the husks; **b.** with thrips damage to the husks; and **c.** a 20-nut sample picked from the data trees and tested over a period of seven weeks prior to harvest, shown as a percentage.

7.3.1 2011/2012 Season

During the first season, data trees at the 788, A4 and 816 13-year-old sites at the ARC-ITSC Variety Orchard bore an insufficient number of nuts for the weekly 20-nut sample for maturity testing. The Commercial Farm 788 4-year-old, Nelmak D 6-year-old and 816 4-year-old sites had already been harvested before the maturity testing began on 29 March 2012. The 20-nut picked samples were collected from the Commercial Farm Beaumont (12-year-old) and Nelmak D (12-year-old) sites for three weeks, prior to the crop being harvested on 18 April 2012 (Fig. 7.4).

Comparisons of the maturity of the nuts were made between damage classes, cultivars, management practice and seasons: a) abscised with no thrips damage (Fig. 7.5), abscised with thrips damage (Fig. 7.6); and c) a 20-nut picked sample (Fig. 7.7).

The data were calculated as a percentage due to the variation in the number of nuts tested in the two seasons. Over 60% of abscised nuts, with no thrips damage, reached maturity; this percent was higher during the second season (Fig. 7.5).

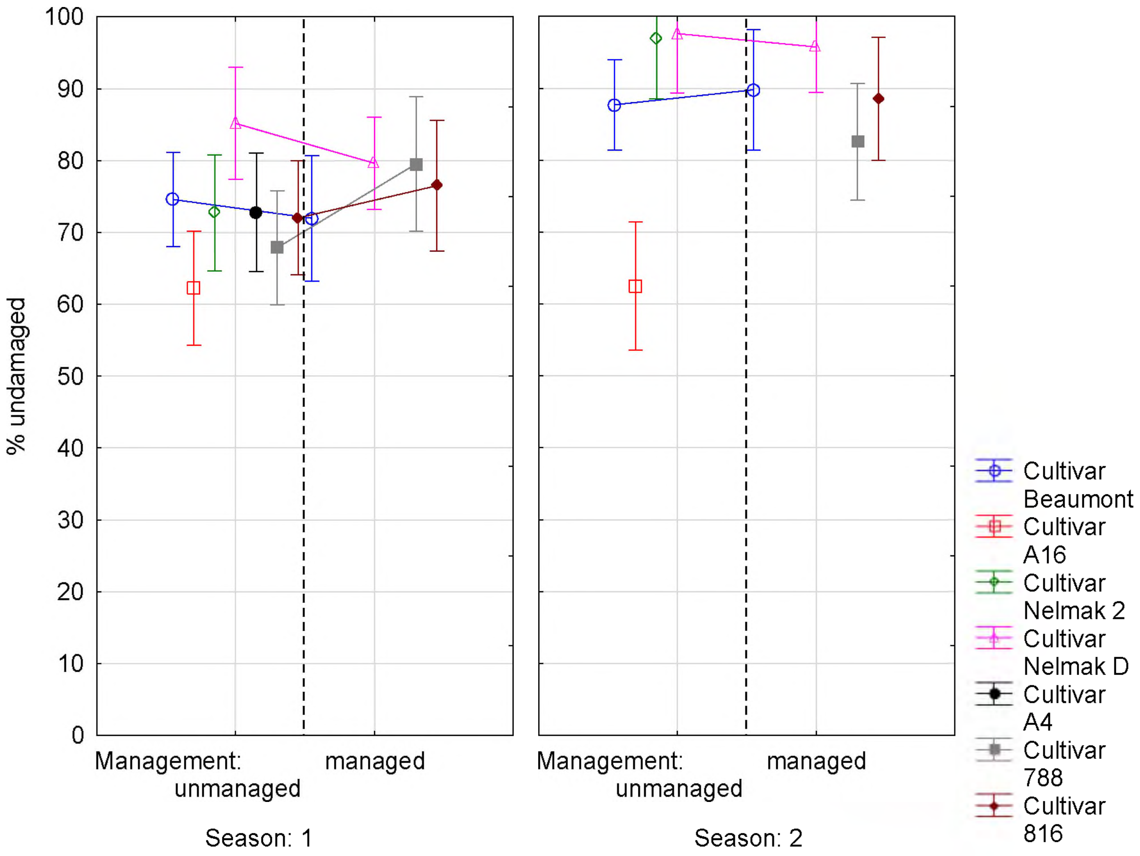


Figure 7.5 Means and 95% confidence intervals for the percent of abscised nuts, by cultivar, and management practice, over both growing seasons, that had no thrips damage and reached

maturity. Pairs of means which have overlapping confidence intervals are not statistically different.

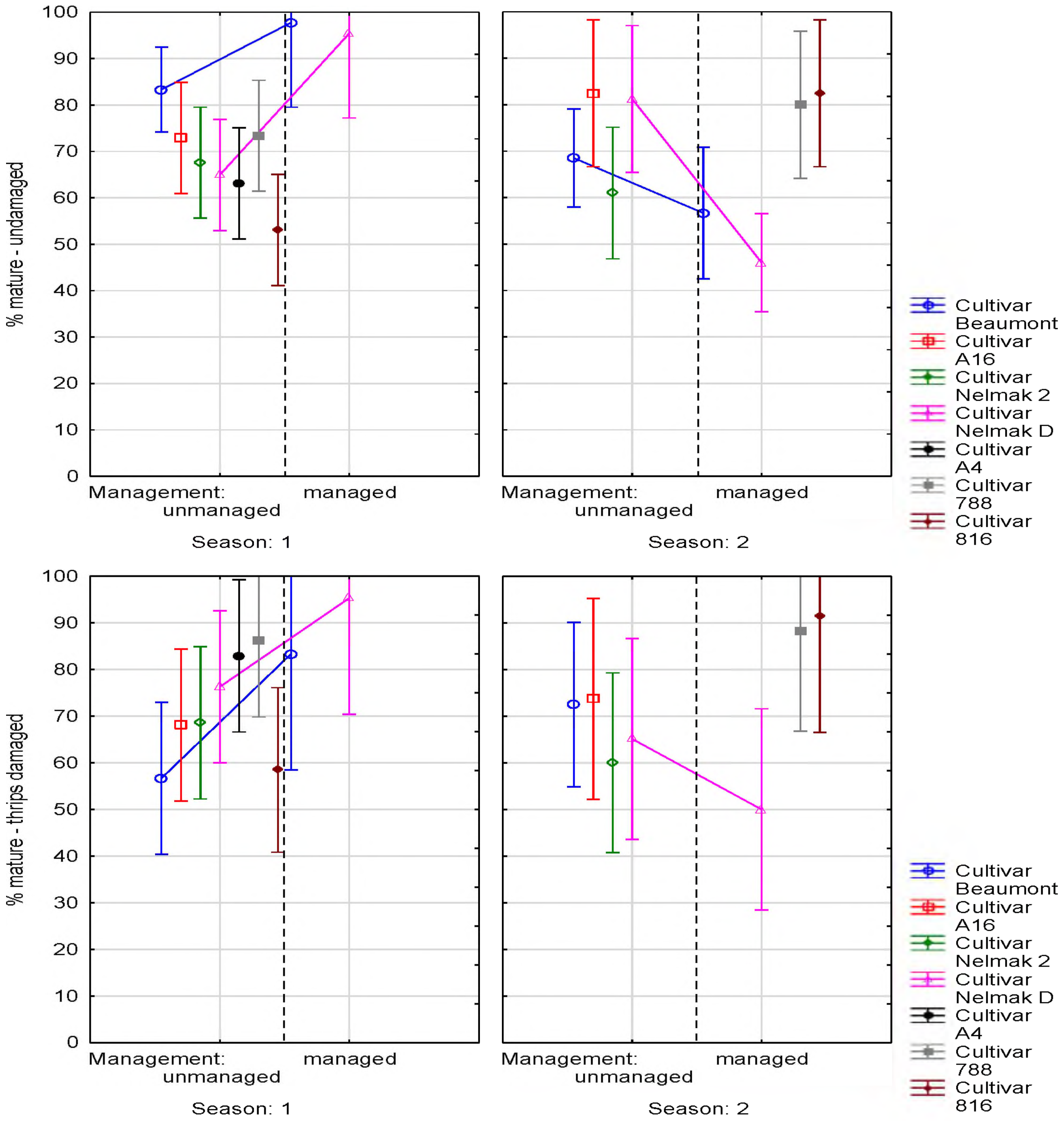


Figure 7.6 Means and 95% confidence intervals for the percent of abscised nuts that were mature, separated by presence of thrips damage, cultivar, management practice, and by season. Pairs of means which have overlapping confidence intervals are not statistically different.

On average, over 50% of abscised nuts reached maturity irrespective of whether thrips damage was present or not.

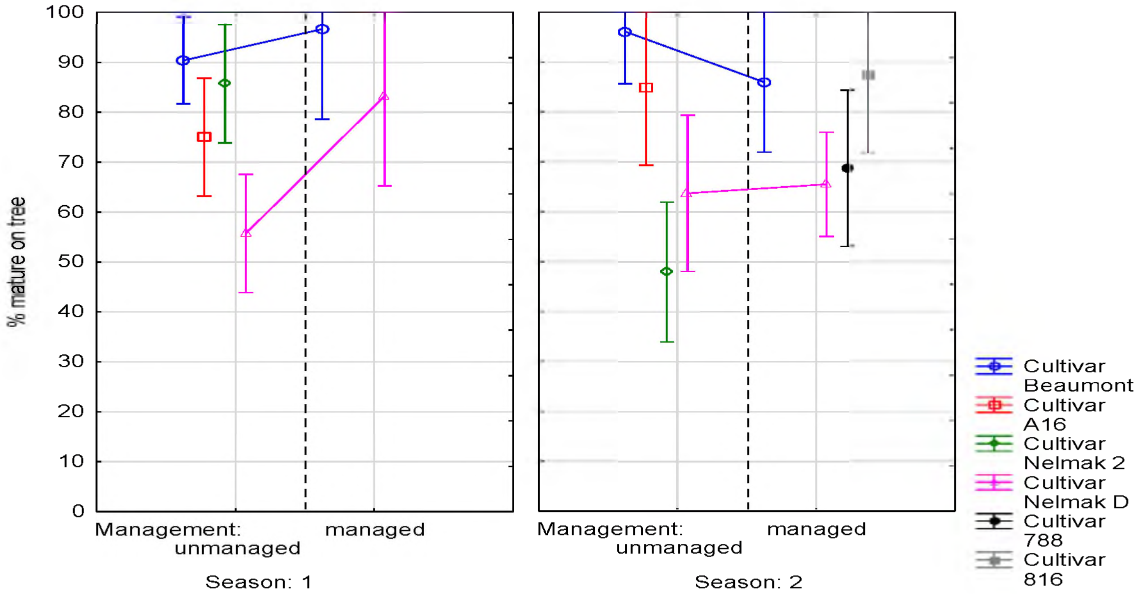


Figure 7.7 Means and 95% confidence intervals for the percent of nuts on the tree that were mature (20-nut picked sample), separated by cultivar, management practice and season. Pairs of means which have overlapping confidence intervals are not statistically different.

The ARC Friedenheim Beaumont 6-year-old site was the only site at which the maturity of kernel from macadamias with no thrips damage to the husks reached 100% for each of the weeks sampled (Annexure II). During the first season this site had the least number of thrips present (Chapter 5, Table 5.3).

Kernel maturity of nuts with thrips damage to the husks reached 100% at the ARC Variety Orchard sites; Beaumont for 2 weeks, and 816 for 1 of the 7 weeks during which maturity was tested. No abscised nuts with thrips damage occurred at the ARC Friedenheim Beaumont 6-year-old site (Annexure II).

The 20-nut picked samples from within the sites showed a high consistency of kernel maturity from ARC Friedenheim Beaumont 6-year-old site over the 7 weeks. Even though the Beaumont 12-year-old site at the Commercial Farm was only tested for maturity over a 3-week period, this site also showed a high percentage of mature kernel (Annexure II).

7.3.2 2012/2013 Season

During the second season, samples were collected earlier, from 14 March 2012, to try and ensure maturity tests could be conducted before harvesting commenced at the Commercial Farm. However, this could only be undertaken for four weeks at the 788 5-year-old, Nelmak D 7-year-old, and 816 5-year-old sites before harvesting began on 10 April, a full month earlier than the previous season. Samples from the Beaumont and Nelmak D 13-year-old sites were collected for a further week before harvesting commenced on 15 April 2013.

At the ARC sites maturity sampling was made over five weeks. Normally no management practices are undertaken at these sites, however during this season the Nelmak D 9-year-old site was harvested and the trees at the Variety Orchard, Beaumont and A16 14-year-old sites, were severely pruned removing all the large branches (and crop) so no further collections could be made after the initial four weeks.

Figures showing the percentage of mature kernel by damage classes during the 2012/2013 season are as follows: a) abscised with no thrips damage; b) abscised with thrips damage; and c) a 20-nut picked sample (Fig. 7.8).

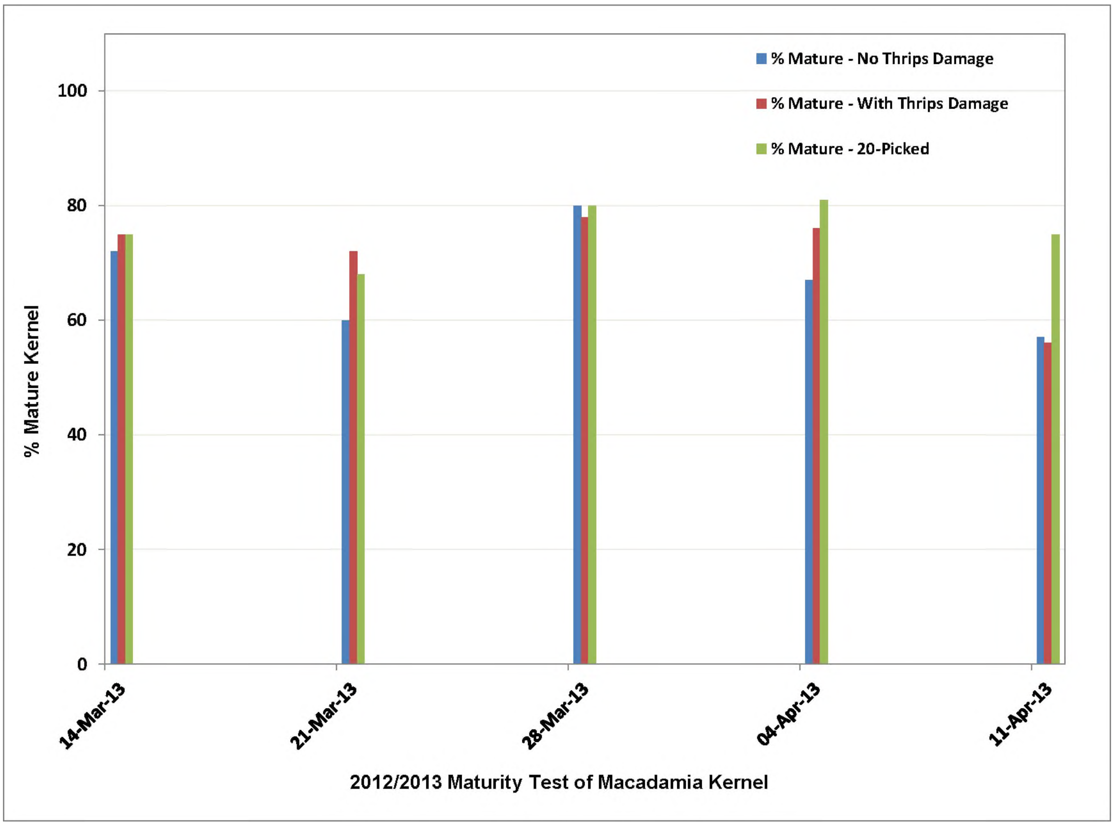


Figure 7.8 2012/2013 Average of mature, abscised nuts with **a.** no thrips damage to the husks; **b.** with thrips damage to the husks; and **c.** a 20-nut sample picked from the data trees over a period of five weeks prior to harvest, shown as a percent.

Maturity of kernel from nuts with no thrips damage reached 100% for one week only; at the Commercial Farm Beaumont 13-year-old site. Maturity levels were however still high, but not as consistent as the previous season. This may possibly have been due to the immaturity of the crop as the Commercial Farm sites were harvested one month earlier than the first season (Fig. 7.5 and Annexure II).

Nuts with thrips damage to the husks reached maturity at a number of sites; however during some weeks no nuts with thrips damage were collected (Fig. 7.6 and Annexure II).

The 20-nut picked samples from each site showed moderately high kernel maturity at the ARC Variety Orchard Beaumont and A16 14-year-old sites, the ARC Friedenheim Beaumont 7-year-old site, and the Commercial Farm 816 5-year-old and Beaumont 13-year-old sites (Figs. 7.7 and 7.8, Annexure II).

7.4 Discussion

Although these results are based on qualitative findings, and data were calculated as a percent, there is no inference that thrips damage affected kernel maturity; and indeed, no significant difference between any of the 3 damage classes. The results show that variety and management practices played no major role, and thrips damage to the husk does not appear to have any effect on the maturity of the kernel. It was also observed that at harvest, a vast majority of the nuts still hanging in the trees had thrips damage and had not abscised.

During the first season, over 60% of all abscised nuts had no thrips damage present; these percentages increased during the second year.

Irrespective as to whether the husks of the abscised nuts were damaged by thrips, on average more than 50% reached maturity.

After processing the nuts for maturity tests, a large percent of both damage classes and the 20-nut picked samples had an extensive amount of stink bug damage (Figs. 7.3 a-c). The main pest causing ‘late-stink bug’ damage is *B. distincta*, and it is most likely that this damage was the major causal factor as to why the nuts abscised (Chapter 5, 5.3.8).

8

Discussion: The Phenologies of *Macadamia* (Proteaceae) and Thrips (Insecta: Thysanoptera) Communities in Mpumalanga Province, South Africa

Summary

This study documents basic information on the phenology of a number of cultivars, their performance under commercial farming practices or at unmanaged orchards, under South African climatic conditions, and the occurrence of thrips on the crop. Approximations of the times at which anthesis and the phases of abscission occurred were calculated using an average of the dates when these events occurred over the two-year study period, together with the identification of a number of thrips species, their abundance and seasonal distribution.

A clearer picture of the thrips communities in macadamias enhances our knowledge of when thrips occur, the time at which to monitor / scout, and which species are more likely to cause damage. During this study, thrips numbers were virtually absent in the sites 12-weeks post-anthesis. Damage to new flush was minimal during this time; flower abscission, premature nut-drop and abscission could not be attributed to thrips as a number of other factors may have contributed towards these events.

Further studies on thrips in macadamias have been suggested at the end of this chapter. It is essential that South African scientists working on macadamia collaborate; synthesizing their data from past and current projects to assemble a comprehensive data set from which an extensive IPM programme can be established. An initiative, suggested by Jones (2002), is that scientists from inter-related disciplines should be invited to collaborate, resulting in a more holistic study of any applied research project.

8.1 Summary: Chapter 1 – Introduction, Aims and Selection of Study Sites

Over the past 80 years, macadamias have been planted in South Africa; many cultivar selections have been assessed to find out which cultivars are best-suited and more productive under these conditions. South Africa is now a major contributor of macadamia nuts on an international basis, with production increasing more than 23-fold over the past 20 years (Nortjé 2012, Anon. 2013a).

Most of the macadamia cultivars grown in South Africa are of Hawaiian, and to a lesser extent Australian origin, with a few hybrid cultivars developed in South Africa. A "general" phenology of macadamia grown under South African conditions was known (Wiid-Hobson 2003a, Anon. 2007), but the variation within and between cultivars less so. Any introduced plant needs to adapt to the environmental conditions and resources of the adoptive country to reach its yield potential. Many selections have been tested to ascertain which the most productive cultivars are under South African conditions. Presently the cultivar which makes up 31% of the total plantings in South Africa is 695 (Beaumont), which seems to adapt more readily to the climatic and environmental conditions.

It is important that any agricultural entomological study be conducted over an extended period to establish the seasonal cycles of both plant and pest(s). Research over a longer period will also identify those pests that persistently cause economically significant damage season after season. In this study, data were gathered on thrips species reproducing on macadamia as a host plant, and those species that were purely incidental, occurring rarely. Many phytophagous thrips species are recognised as serious, sporadic or minor pests of numerous plants worldwide, yet their pest status can differ remarkably from one area to another. Therefore to be able to identify which species cause damage to macadamia in South Africa, to which part(s) of the plant and at what time, will help determine whether thrips need to be controlled.

To begin to understand the interactions between the thrips species using macadamia as a host plant, the structure of this thesis was based on addressing the following points, the chapters where these points are addressed is shown in brackets:

1. Find out what thrips damage in macadamias looks like (Chapter 1);
2. Review the botany and history of macadamia and its cultivation in South Africa (Chapter 2);
3. Review thrips biology and pest species associated with other South African crops (Chapter 3);

4. Characterize the phenology of macadamia cultivars used in this study (Chapter 4);
5. Determine thrips species present in macadamia in South Africa (Chapter 5);
6. Characterize the seasonal occurrence and phenology of key thrips species in macadamias and relate it to host plant phenology (Chapter 5);
7. Ascertain whether premature macadamia nut-drop and subsequent nut abscission can be attributed to thrips damage (Chapter 6);
8. Determine whether thrips damage to outer husk is “cosmetic” damage, or if maturity of the kernel is affected (Chapter 7).

A comprehensive understanding of the cultivation of macadamia in South Africa is crucial to coordinating an IPM programme for the control of pests in this crop. A basic understanding of how some of the most commonly grown cultivars performed under South African conditions needed to be addressed. The phenology of these cultivars, whether early-, mid-, or late-bearing, if out-of-season flowering and nut-set occurred, the timing and duration of nut-drop and maturity were some of the biological factors required to evaluate the impact thrips had, if any, on these natural events (Chapter 4).

The sites were chosen depending on accessibility and availability of comparison cultivar blocks. Where possible, sites were used during both seasons. To understand the natural occurrence of thrips, unmanaged study sites located at the ARC-ITSC, Nelspruit, were used whilst the remaining sites were located at a commercial farm. This was done to assess whether thrips infestations and subsequent damage would be higher at the unmanaged sites, and what affect this would have on cultivar performance.

Due to minimal thrips damage to new flush during the two seasons, an extensive survey was not carried out. To attain upper and lower thresholds for thrips damage to new flush, a study should be conducted over minimally five years in orchards where this problem persists.

Thrips damage, determined as an irregular silvering or scribbling pattern on the husks, does not affect the entire surface area of the husk, as mite damage does. Historically, thrips species on macadamia in Hawaii (Jones 2002) and Australia (Gallagher *et al.* 2003) was considered a minor pest that normally does not require any chemical intervention, but recently in Australia it has been reported that thrips species are causing damage (Craig Maddox, 2015, pers. comm.).

8.2 Summary: Chapter 2 – Macadamia (Proteaceae): Origin, Botany and History of Cultivation in South Africa

Extensive research has been conducted on the botany of macadamia in Hawaii and Australia, the countries where it has been grown commercially the longest. The manipulation and implementation of best practice to establish and maintain long-term productivity in orchards has been ongoing since the 1800s. However some botanical aspects cannot be altered; both the initiation and termination of certain stages of macadamia phenology are climatically-driven. Temperatures play a pivotal role; the optimal minimum and maximum temperatures for new growth are between 16-25°C (Stephenson *et al.* 1986). Temperatures below 10°C inhibit new growth and temperatures above 30°C have an abnormal affect (Trochoulias and Lahav 1983 in Stephenson *et al.* 1986), substantially lowering the rate of photosynthesis in the leaves (Allan and de Jager 1978). According to Moncur *et al.* (1985), temperature changes in subtropical regions are of greater significance than changes of rainfall and moisture. The authors reported that after a rise in temperature and some rainfall, raceme elongation began and bud dormancy was broken.

Anthesis marks the period (of about five weeks) when trees are in full flower; the macadamia season is divided into "weeks post-anthesis" and lasts approximately 30 weeks (in the southern hemisphere – Australia and South Africa), until nuts mature and harvesting begins. In Hawaii (the northern hemisphere), anthesis may extend over a protracted period, sometimes lasting months, during which time numerous developmental stages occur simultaneously in an individual tree. The onset of flowering was more variable within and between trees of a cultivar orchard than among different cultivar orchards (Nagao and Hirae 1992 in Trueman 2013). Significant genetic variation exists for the onset and duration of flowering, nut-set and the beginning of nut-drop. The least amount of genetic variation was found in the duration of nut-drop; most variation in all traits among racemes was found within the same tree and not between cultivars (Boyton and Hardner 2002).

The prolific numbers of flowers and racemes produced by macadamias may be due to self-incompatibility and therefore indicate dependence on cross-pollination. Macadamia flowers are protandrous; this means that the stamens of the flower mature and release their pollen before the stigma becomes receptive, therefore increasing the odds of out-crossing over self-pollination. Wind pollination in macadamia is limited (Urata 1954, Scholefield

1982). The presence of small nectaries in the flowers strongly indicates that insects are the primary pollinators of macadamia (McGregor 1976 in Scholefield 1982).

Nut retention is strongly correlated to the available carbohydrate levels in the tree and a large proportion of abscission can be attributed to the plant adjusting to the crop load prior to biomass accumulation (Trueman 2013). Studies conducted in Hawaii on potential causes of abscission determined that the natural production of ethylene by racemes plays an important regulatory role in several physiological processes in macadamia (Nagao and Sakai 1985, Sakai and Nagao 1985). Even though abscission occurs from anthesis to maturity, it can be resolved into three phases:

1. The rapid abscission of flowers; which depends on successful fertilization and the tree's available nutrients and stored resources;
2. The initial, immature nut-set; an increase in the natural ethylene production precedes the highest rate of nut-drop, which is most likely an adjustment to crop load before biomass accumulation, reducing the fruit-set according to the trees available resources (Sakai and Nagao 1985). The production of ethylene also increases when the plant is put under stress, which can be induced by either abiotic or biological events, such as insect injury and disease (Childers 1997).
3. The abscission of larger immature to mature nuts. Many physiological changes occur during this time, which includes the periods of major biomass accumulation, shell hardening, and accelerated oil accrual in the kernel, causing a reduction of the photosynthates (Jones 1937 in Hardner *et al.* 2009, Jones and Shaw 1943). This may also be the period within which the plant most readily responds to cumulated pest pressure and damage.

8.3 Summary: Chapter 3 – Thrips (Thysanoptera): Their Biology and a Review of Thrips in Tropical and Subtropical Crops in South Africa

Scientists became interested in studying thrips only around the 1900s, and many species were described and named during the 1920s and 1930s. In 1927 Pittman discovered that some species transmitted a "spotted-wilt" disease to plants, which then initiated extensive research on thrips as vectors of viral plant diseases (Lewis 1997a). Over time some thrips species have spread worldwide, partially facilitated by trade routes and the import / export of plants, plant material, fruit and vegetable produce. Whilst some exotic species have exploited new territories, endemic species have also adapted to the new host plants (Mound 1983). Thrips can synchronize their reproduction to fit into recently-colonised ecosystems (Morse and Hoddle 2006). They are not pre-disposed to diapause, produce numerous generations per season, and their high fecundity and short life cycles promotes year-round populations (Chapter 3).

Feeding guilds include species which are carnivorous, herbivorous, mycophagous, saprophytic and sporophagous, sometimes even in combination, depending on the resources available (Palmer *et al.* 1989, Palmer 1990, Lewis 1997a, Mound 2005). Species within the herbivorous group may feed at specific sites on the plant; species in flowers may feed on pollen and plant tissue (Kirk 1984); others may damage buds or new flush (Lewis 1973). It is important to define which species are causing damage to the plant and which are not.

Thrips are also known to facilitate, through mechanical dissemination, numerous microbial pathogens which result in mildews, moulds and rusts on plants. Fitzel (1994) published a list of 23 fungi recorded on *Macadamia integrifolia* from the New South Wales and Queensland Herbarium Records (Chapter 3, Table 3.3).

Many of the insecticides previously used to control pest populations have been banned to meet international export regulations, or their usage reduced to comply with Maximum Residue Levels (MRLs). The newer chemicals on the market tend to have lower persistence, the advantage of which is a lower impact on the environment, natural enemies and parasitoids.

However with lower persistence, the timing of the applications has to be precise and this is achieved by regularly monitoring the pest populations. Thrips quickly evolve resistance, and cross-resistance, to chemicals from their exposure to insecticides as either the "target" or "non-target" group; growers need to be made aware of this fact when applying chemical control for other pests in the orchards.

Macadamia growers should carefully consider whether chemical applications are absolutely necessary to prevent the damage thrips cause in orchards before the over-use of yet another active ingredient develops into resistance in a far more damaging pest. If the percent of thrips damage to new flush is minor, no chemical applications should be made (Chapter 1). Thrips damage to the husk does not affect kernel maturity (Chapter 7), so chemical applications to prevent "bronzing" are not only uneconomical but also irresponsible as the over-use of pesticides causes knock-on effects to non-target insects and could increase the chances of resistance evolving.

8.4 Summary: Chapter 4 - Phenology of Macadamia Cultivars in Southern Mpumalanga, South Africa

Good farming practices are essential to increase and maintain production levels. Orchard management, including pruning, ensures the balance between vegetative flush and fruit-set to sustain high yields and long-term productivity; this is achieved by manipulation, retaining sufficient new growth to provide future bearing-wood and enough foliage for photosynthesis and the accumulation of carbohydrate reserves for the following season (Stephenson *et al.* 1986).

Orchard maintenance and hygiene also play a vital role; mature nuts from out-of-season nut-set are generally left on the orchard floor or in the trees, and may be incorporated with the subsequent "new" seasons' nuts, thereby reducing the quality of the crop (Nagao *et al.* 1994). These "old" mature nuts are exposed to pests, pathogens and environmental conditions that can manifest in secondary infestations (Stephenson and Gallagher 2000 in Trueman 2013).

This study established that the occurrence of a secondary nut-set event is a more accurate indication of whether a cultivar set a supplementary crop than that of out-of-season flowering. During this study, periodic flowering in some of the cultivars occurred, yet resulted in no subsequent nut-set. Over both seasons, no secondary nut-set occurred at any of the Beaumont cultivar sites, whether the sites were managed or unmanaged. During the 2011/2012 season the two Nelmak cultivar sites under management practices at the commercial farm did not set a secondary nut-set, but during the 2012/2013 season only one of the sites did not bear a subsequent crop. It appears that Nelmak hybrids cultivated using proper management strategies do not set a secondary crop, but if no management practices are implemented, a secondary nut-set occurs. Apart from the ARC-ITSC A4 site during the 2011/2012 season, a secondary nut-set occurred at all the study sites.

Because pest populations are sometime synchronous with specific host plant developmental stages, it was necessary to include the seasonal occurrence of thrips communities with the macadamia phenological data to accentuate this point. Protracted flowering, extended developmental periods, and the presence of various growth stages on a host plant simultaneously, affects the immigration, tenure and reproduction of pest populations (Stephenson and Gallagher 2000 in Trueman 2013), resulting in an increase of the amount of economic damage to the crop. These overlapping periods will also cause logistical problems when planning / implementing IPM programmes.

During the first season, no thrips peaks occurred at any of the study sites prior to anthesis. At four sites during the second season thrips numbers peaked, but these were not the main peaks. This may have been partially attributed to the difference in climatic conditions experienced over the two seasons. With data collected for only two growing seasons it is difficult to establish an annual performance model. When looking at all of the sites ($n = 23$) collectively over the two-year period, the major thrips peaks occurred after anthesis (Chapter 4, Table 4.4). At 21 of the 23 sites, the major thrips peaks had occurred before initiation of abscission and had concluded before the end of initial nut-drop.

The phenological data collected in this study can be utilized as a framework upon which the seasonal data of all pest populations in macadamia can be plotted. By determining which developmental stage(s) of the plant is targeted by a specific pest, these data can be incorporated into an IPM programme to: a) contain these populations before chemical intervention is required; or if necessary, b) apply timely chemical applications.

8.5 Summary: Chapter 5 - Identification and Phenology of Thrips (Thysanoptera) Species in Macadamia Orchards, Southern Mpumalanga

8.5.1 Identification

During the two-year study period, 15 species of thrips were identified to species-level in macadamia orchards in Mpumalanga Province, South Africa. In addition, various Panchaetothripinae (leaf-feeding), *Haplothrips* (spore-feeding) and *Scolothrips* (predatory) species were also found but were not identified further (Chapter 5). Thrips were collected from seven macadamia growth points which included new flush, closed buds, open flowers, nut-set, small, medium and large nuts.

Of the colour groups that the thrips species were sorted into for identification, the "yellow group" was by far the most abundant during both seasons (Chapter 5). The highest densities occurred when open flowers were present; given this, thrips may in fact play a major beneficial role in the cross-pollination of macadamia, an important factor that has previously not been considered.

8.5.2 Phenology

The highest number of thrips was present when the trees were in full flower, and a number of species occurred simultaneously. As the season progressed, community structure changed and the numbers of thrips species and individuals fluctuated (Chapter 5). This study did not qualify whether thrips aggregated on the flowers to mate, lay eggs, feed or prey on other arthropods.

The presence of larvae established that some species were reproducing on macadamia as a host plant, whilst other species may have been only visiting the plant. Only very few taxonomic keys for the identification of immature thrips species exist; to be able to positively identify which species were breeding in macadamia, the immatures would have to be reared through to adults for identification or undergo genetic analyses. These components were not included in this study.

It is important to study thrips distribution, abundance and population dynamics to be able to understand, and perhaps predict, these occurrences (Kirk 1997b). This study is the first step towards beginning to understand these important aspects regarding the thrips community in macadamias.

Prior to the main peaks of abscission, the thrips species were mainly those of the "yellow group" (Chapter 5). As the economically important *S. auranti* was one of the most abundant species in the orchards, and was easily identifiable within the "yellow group", accurate data on this species were collected and analysed. However, during both seasons, of the combined number of 23 study sites, no *S. aurantii* individuals were collected from 6 of the sites. At the remaining 17 sites, *S. aurantii* populations only increased after the other species of the "yellow group" declined, towards the end of the season. This could mean that *S. aurantii* populations are out-competed by the "yellow other" group whose numbers dominate just before and during the flowering period.

Robust statistical analyses incorporating cultivar or tree age was not practicable due to incomplete replication of cultivars across seasons and management practices. For this reason, comparisons of cultivars were made qualitatively.

The 2011/2012 season's data from same-cultivar sites were compared; peaks of abundance were very similar within cultivar groups, with the later, lower peak reflecting the increase in abundance of *S. aurantii* populations.

For the 2012/2013 season presence of thrips was more widely distributed than the season before. The build-up of thrips occurred in a chronological-like pattern in same-cultivar sites, all within a few weeks of each other (Chapter 5, Table 5.12). The grouping pattern of the cultivars was irrespective of whether the sites were managed or not.

During the 2011/2012 season applications of an organophosphate and a synthetic pyrethroid were made for the control of *Bathycoelia distincta* stink bug populations. The synthetic pyrethroid spray, applied on 15 November, seemingly had no affect on the subsequent increase in thrips numbers on 24 November and thrips peak on the 1 December 2011 (Chapter 5, Fig. 5.25). The lack of any apparent repression of the thrips numbers may very well imply a lack of susceptibility to the pyrethroid application. During the second season, again one of the chemical applications, this time of endosulfan, was applied on 11 October for the control of *B. distincta*; a thrips peak followed on 19 October at the Nelmak D 7-year-old site. When comparisons were made between sites where no chemicals were applied (unmanaged) and sites which had been treated with chemicals (managed), it was evident that the peaks of abundance were naturally occurring, regardless of whether orchards were managed or not. These seasonal peaks were evident at all cultivar sites.

Future studies could incorporate classifying which species cause damage to specific growth points (e.g. new flush); sampling should be exclusively collected from that stage. Several species have specific, preferred feeding and breeding sites on a host plant, and by studying these it is quite possible that different conclusions would be arrived at with regards to thrips presence and damage on macadamia.

8.6 Summary: Chapter 6 – Fruit Abscission in Macadamia (Proteaceae) in Southern Mpumalanga, South Africa

To assess how much premature abscission was attributable to thrips, abscised nuts were collected from each site over the two growing seasons. The mean weekly temperature and rainfall data were included with the abscission data to see whether there were any climatic effects (Chapter 6).

The data were assessed on a qualitative basis. During the 2011/2012 season, slightly higher temperatures and lower rainfall occurred than during the second season; rainfall during 2012/2013 was more widely-distributed throughout the season. The estimated average dates of anthesis for both study periods were slightly different, approximately two weeks apart; the first season being later than the second. These approximated dates seem to be strongly linked to the first high weekly rainfall (> 65mm) for both seasons (Chapter 6, Figs. 6.10 and 6.12).

The total number of abscised nuts during the 2011/2012 and 2012/2013 seasons, a break-down between cultivars, study sites and percent of nuts with thrips damage to the husks is presented in Chapter 6, Table 6.1. The accumulated a) total number of abscised nuts; b) number of nuts with no thrips damage to the husk; and c) number of nuts where thrips had damaged the husks, over the duration of the first and second study period periods are illustrated in Figs. 6.15 and 6.17 respectively.

Examination of the abscission rate of thrips-damaged nuts (Fig. 6.19) suggested no significant difference between most cultivars; or between managed and unmanaged sites; a consistent difference between the two seasons; and little consistent interaction between these explanatory variables.

By transforming the number of abscised nuts with thrips damage to the husk to a percentage of the total number of abscised nuts gave a more accurate assessment, as the number of nuts produced by a tree varies considerably with size and cultivar. The high incidence of nuts with thrips damage to the husks at the unmanaged ARC sites was more apparent during the 2011/2012 season (40.2%) than the managed sites at the Commercial Farm (5.7%). For the 2012/2013 season damage to husks at the unmanaged sites at the ARC was 13.5%, and at the Commercial Farm 6.9%.

Many of the nuts with thrips damage to the husks did not abscise and were still hanging in the trees close to / at harvesting; another observation which leads to the supposition that thrips damage does not cause abscission (Author, pers. obs.).

8.7 Summary: Chapter 7 - Testing Kernel Maturity of Macadamias with Thrips (Thysanoptera) Damage to the Husks

During the first season, on average, more than 60% of the total numbers of abscised nuts were not damaged by thrips; the percentage during the second season increased considerably. Of the abscised nuts with thrips damage more than 50%, on average, reached maturity (Chapter 7, Figs. 7.5 and 7.6). There was no difference in kernel maturity irrespective as to whether there was thrips damage to the husk or not.

Quantifying loss of yield attributable to thrips, whether direct or indirect damage, is not possible without further in-depth studies which focus on damage to specific structural and physiological stages of the plant. After the abscised nuts and the 20-nut picked sample had been processed, a high percent of stink bug feeding damage was observed; this may quite possibly have been the main cause of abscission.

When testing nuts for kernel maturity, stink bug feeding damage to most kernels was evident. Stink bugs, particularly *B. distincta*, cause a lot of cumulative damage to macadamia, from mid-November until harvest, and it is apparent that these nuts do not all abscise.

Therefore, determining the cause of abscission, whether it is a natural thinning event, physiological stress due to disease, pathogens, nutrient deficiency, over- or under-watering, stink bug feeding, thrips and other insect damage, or a myriad of other possible causes, is extremely difficult.

8.8 Integrated Pest Management (IPM)

Integrated Pest Management (IPM) programmes for macadamias have been conceptualized and developed after extensive research over decades in Hawaii (Jones 2002, Kawate and Tarutani 2006), Australia (O'Hare *et al.* 2004) and South Africa (Bruwer 2004, Schoeman 2009a, b).

Integrated Crop Management (ICM) involves looking at agronomic practices, planting cover crops and using resistant cultivars/varieties. Integrated Pest Management (IPM) falls within ICM, and comprises a number of strategies to develop and maintain a sustainable, broad-based approach towards pest management (Hepburn 2013). Jones (2002) very astutely recommended that scientists in inter-related disciplines, such as entomology, horticulture, plant pathology, weed science and economics, collaborate to achieve this goal.

Preventative pest measures within an IPM framework include scouting and monitoring of pest populations, orchard sanitation, the use of pesticides, bioinsecticides, pathogens, biocontrol agents, mass-trapping, push-pull strategies, trap cropping and the sterile insect technique (SIT). Insect Resistance Management (IRM) should be included as an essential component of IPM. Insecticide resistance is no longer a threat but a reality in South Africa as in many other countries worldwide (Hepburn 2013). At this stage there are too few options left in the chemical "arsenal" and we need to look seriously at conserving and extending the "life" of each of the chemicals which are still effective before we have nothing left to rely on (Hepburn 2013).

One of the most important aspects of IPM is determining the economic decision levels: the Economic Threshold (ET), Economic Injury Level (EIL) and Action Level (AL). It is upon these key criteria that decisions are made, which makes scouting and monitoring of pest populations crucial to any IPM programme, to assess if, and when, chemical control is necessary (Pedigo and Rice 2006). Research conducted on macadamia pests in Hawaii (Jones 2002, Kawate and Tarutani 2006) and Australia (O'Hare *et al.* 2004) have already determined the ALs for the major pests. In South Africa, to date, the only ET calculated for macadamia crops is that of the two-spotted stink bug, *B. distincta*, (P.S. Schoeman, pers. com.), even though extensive research has been conducted on other major macadamia pests. This is in part due to the lack of scientists, resources and information gathered over a number of sequential growing seasons over the past 80 years. Only after a minimum of about five years' worth of data have been collected can we begin to see trends in the pest population phenologies and density and begin to establish thresholds.

8.9 Conclusions

Given the natural cycle of macadamias (i.e. the facultative challenges of pollination and fertilization due to the physiological structure of the blossoms; the excessive production of racemes, of which the majority drop; abscission of early nut-set due to high ethylene levels produced in the racemes, *et cetera*), it is a wonder that this crop is so successfully grown commercially. The stink bug complex causes the most damage in macadamia orchards in South Africa (Schoeman, 2014); the cumulative damage caused by their continual feeding throughout the season on nuts of all sizes is the basis on which chemical spray programmes have been established. Potentially the greatest challenge to date for macadamia growers is the recent development of some *B. distincta* populations no longer being susceptible to pyrethroid products (CH pers. obs.); we do not wish to further exacerbate this problem by applying yet more chemicals having a knock-on effect and cause other pest populations to become resistant to other active ingredients. The use of "soft" insecticides to be applied for pests which are not as damaging as stink bug will have less impact on beneficial insects such as pollinators and natural enemies (O'Hare *et al.* 2004).

Responsible use of chemical insecticides cannot be over-emphasized; the basic rules are to use registered products, apply at the recommended rates, alternate the active ingredients (chemical families) in consecutive sprays, and not to apply more frequently than prescribed and ensure the pre-harvest/withholding period is maintained. All these criteria are printed on chemical labels. These labels are legal documents; any infringement of the use of a chemical in a manner which is not prescribed is unlawful (Jones 2002). Growers should enlist assistance and advice from professionals in their area of expertise (i.e. plant pathologists, entomologists, taxonomists, soil scientists, irrigation and fertigation experts, chemical consultants *et* cetera), before taking a decision, which could have far-reaching as well as economic consequences.

No excessively high thrips infestations occurred during this two-year study. Damage to new flush was minimal; there was no difference in maturity of the abscised nuts whether thrips damage was present or not, and therefore spraying insecticides to prevent “bronzing” is not economically relevant.

During the 2015/2016 season, high numbers of *S. aurantii* decimated growth tips and damaged leaves on the new flush at a commercial farm near Nelspruit; reports were received from other growing regions experiencing the same levels of infestation (Author pers. comm.). This widespread infestation may have been caused by the severe drought experienced in South Africa during the past couple of years. The damage resulted in the stunted growth of new bud-wood with very short gaps between the internodes. Subsequent new flush, and even racemes, were produced from this bud-wood, and in the future, it will be interesting to see whether any nut-set and retention of nuts occur on these young branches.

At the same commercial farm, a high number red spider mite, *Oligonychus coffeae* (Nietner 1861) (Acari: Tetranychidae), were also observed on new flush and apical growth tips; all life-cycle stages were present, from eggs to adults (Author pers. obs.). After applying an insecticide, also registered for the control of *O. coffeae*, the number of mites dropped significantly and no further generations were observed.

Although the author did not encounter this level of thrips and mite infestations during the study period, the following strategy is suggested as a step to determine whether the growth tips are permanently damaged.

- A number of tips that appear “dead” be tagged and numbered;
- Do the same for tips which are green at the apex (using a different coloured tag).
- Use the same number of samples on the same trees, and include tree replicates (i.e. n = 5).
- To be able to have a point of reference, take photographs weekly/fortnightly of the individual numbered and tagged tip, next to a ruler for calibration, and keep records of whether any growth has occurred.

The author is unable to predict whether the “dead” tips will revive or die-back, or whether the green tips will recover from previous damage and develop normally. This strategy will be able to provide an estimation of the percent of permanent damage.

It is vitally important that the cause of damage is correctly identified as numerous other causes, such as mealy bugs and mites; fungi can also cause serious damage to growth points (Author pers. obs.).

8.10 Future Studies

The author recommends that the following be undertaken as future studies. These need to be conducted over a period of at least five consecutive growing seasons, to show trends and gather enough data to analyse on a quantitative basis.

a) A full, in-depth study should be conducted on macadamia with thrips damage to the husks, to quantitatively show that kernel maturity at crack-out is not affected.

b) Closer examination of the thrips (and possibly also mite) species occurring in regions where thrips damage to growth tips and new flush is severe. Attempt to “measure” the amount of damage caused and the long-term effects that may have on the following year’s performance and yield.

c) Determine whether *Thrips tenellus* and *T. subnudula* are in fact causing damage, and if so, how to monitor their populations and presence in the orchards.

d) An assessment of thrips species and damage to nursery stock should be undertaken. There may be a variation in the number of thrips species feeding on the foliage and growth tips which may, in the long-term, affect the potential and future productivity of the seedlings.

e) Establish which thrips species target specific macadamia developmental growth stages, those stages should be sampled separately throughout a full season, rearing out the larvae to adults for identification, and providing irrefutable evidence of which species cause damage to that specific stage.

f) Researchers should also look in to utilizing naturally-occurring pathogens, such as entomopathogenic fungi, to control thrips, targeting the soil-dwelling prepupae and pupae stages through soil applications, and active adults and larvae through foliar applications. This would immediately have an impact on population build-up at the beginning of the season and, once established, the pathogen should control numbers throughout most of the season. However, the non-target effect would have to be carefully looked in to as many entomopathogenic fungi are not species-specific and may have a detrimental effect on pollinators and natural enemies.

g) Studies need to be undertaken to establish Action Levels for damaging thrips species on macadamia. A reliable and practical technique of monitoring and scouting thrips species and densities should be further examined.

GLOSSARY OF TERMS

HEYWOOD, V.H., BRUMMITT, R.K., CULHAM, A., SEBERG, O. (2007) *Flowering Plant Families of the World*. Firefly Books, Ontario, Canada.

PEDIGO, L.P. & RICE, M.E. (2006) *Entomology and Pest Management*. Prentice Hall, Upper Saddle River, New Jersey.

STROHSCHEN, B. (1986) *Contributions to the Biology of Useful Plants. 4. Anatomical Studies of Fruit Development and Fruit Classification of the Macadamia Nut* (Macadamia integrifolia *Maiden and Betche*). *Angewandte Botanik* 60: 239-247.

TRIPLEHORN, C.A. & JOHNSON, N.F. (2005) (Eds.) *Borror and DeLong's Introduction to the Study of Insects*. Thomson Brooks/Cole, Belmont.

abdomen – posterior end of an insect body, where the digestive, excretory and intestines and reproductive organs are located.

abiotic – something affecting growth of insect populations that is not biologically based (i.e. rainfall / temperature).

abscission – the process by which leaves or nuts separate from the tree and fall.

action level (AL) – the level of a pest population which indicate that control measures should be implemented.

anther – the terminal part of the male organs (stamen), usually borne on a stalk (filament) and developing to contain pollen.

anthesis – the period of flowering; from opening of the flower bud to the setting of the seed.

apex – tip of an organ; usually the growing point.

apical – pertaining to the apex.

arrhenotoky – a form of parthenogenesis in which females are produced from fertilized eggs and males from unfertilized eggs.

axis – the main or central stem of a herbaceous plant or of an inflorescence.

basipetally (opening of flowers on a raceme) – proceeding from the apex toward the base.

beneficial insect – a naturally occurring or commercially produced insect, mite, nematode, parasite or predator used to help the control of insect pest populations.

biotic – something affecting insect numbers that is biologically based (i.e. parasitoids, pathogens or predators, as opposed to an abiotic or non-biological variable).

bisexual (of flowers) – containing both male and female reproductive organs in a single flower.

calyx – collective term for all a flowers sepals.

carnivorous – feeds on the flesh of other animals.

carpel – one of the flower's female reproductive organs, comprising an ovary and a stigma, and containing one or more ovules.

cincture – encircling an area, girdling.

clonal – genetically identical to its parent having been developed by vegetative reproduction from a bulb, cutting or other part.

corolla – all the petals of a flower.

cotyledon(s) – the first leaf, or pair of leaves, of an embryo within the seed.

cross-pollination – *see* pollination

cultivar – plant variety that is developed by breeding and has a designated name.

damage (to plant) – measurable loss of host utility, most often including yield quantity, quality or aesthetic appeal.

> **direct damage** – damage that occurs on the marketable part of the crop. In macadamia crops it would be kernel damage or damage that causes immature nuts to drop.
>
> **indirect damage** – damage occurring to the crop which is not marketed (i.e. leaves).

dehiscence – method or act of opening to shed pollen or seeds.

diapause – a period of arrested development and reduced metabolic rate, during which growth, differentiation and metamorphosis cease.

economic injury level (EIL) – the number of insect pests necessary to cause economic loss.

economic threshold (ET) – the number of insect pests at which treatment should be applied to prevent economic losses. The ET is set below the EIL to allow treatment to be applied before the EIL is reached.

exoskeleton – the external skeleton of insects to which the muscles are attached. Also provides protection from the environment and possible natural enemies.

fertigation – the application of fertilizer through the irrigation system.

filament – the anther-bearing stalk of a stamen.

floret – an individual flower bud.

follicle – a dry fruit which is derived from a single carpel and which splits open along one side only. (*See fruit, macadamia* and *nut*).

fruit – strictly the ripened ovary of a seed plant and its contents. Loosely speaking, the whole structure containing ripe seeds, which includes more than the ovary (e.g. the husk, shell and kernel). (*See follicle, macadamia* and *nut*).

fungicide – chemical used to control a fungal disease.

germplasm – genetic hereditary material.

hemimetabolous – *see metamorphosis*.

herbivorous – feeding on plants.

holometabolous – *see metamorphosis*.

husk – *see* pericarp

hybrid – a plant bred from a cross between two plants with different genetic constituents.

inflorescence – any arrangement of more than one flower.

insecticide – chemical used to control insect pest populations.

instar – different immature stages of an insect. This term is used from the youngest (first instar) to the last or final instar. This does not apply to the egg or pupal stage of an insect.

Integrated Pest Management (IPM) – an approach to pest and disease management incorporating aspects of chemical, cultural, physical and biological control methods to prevent pest populations and diseases from reaching damaging levels. Involves the use scouting and monitoring techniques to determine if and when treatments are required.

kernel – the edible content of a nut or fruit stone.

larva (pl., *larvae*) – the immature stage of an insect (i.e. butterflies, moths, beetles, weevils, flies and wasps), which undergoes complete metamorphosis. Commonly known as caterpillars or grubs.

macadamia – a follicle (fruit), colloquially called a 'nut'. The first detailed ontological account definitively classifying macadamia as a type of fruit was published by Strohschen (1986), who described macadamia as "… a dry dehiscent fruit formed from one carpel and having one longitudinal line of dehiscence". (*See follicle, fruit* and *nut*).

metamorphosis – change in body form of an insect as it progresses through its life cycle.

> **complete metamorphosis (holometaboly)** – insects which undergo four stages of development: an egg, larval, pupal and adult stage. The larvae generally do not resemble the adult and this stage is primarily a food-gathering stage. Pupae are usually quiescent and hide away at this time. The adult emerges from the pupal stage. The adult stage is mainly for reproduction; some adults do not feed or only take up nectar or pollen.
>
> **incomplete metamorphosis (hemimetaboly)** – insects that undergo three stages of development: an egg, nymphal and adult stage. The nymphs usually resemble the adult but lack fully developed wings, wing buds may be present and enlarge as the insect moults.

monitoring – systematically checking the tree and abscised fruit for pests and diseases and recording the findings to be able to make decisions on pest and disease management strategies.

multivoltine – producing many generations per year.

mycophagous – fungal feeders.

natural enemies – naturally occurring beneficial organisms.

nectaries – glands which nectar is produced.

node – the point on a stem where one or more leaves are borne.

nut – a dry, single-seeded, indehiscent fruit with a woody pericarp. (*See follicle, fruit* and *macadamia*).

nymph – the immature stage of insects (i.e. true bugs, aphids and mites) with an incomplete metamorphosis.

ocelli - plural of ocellus; a simple eye of an insect or other arthropod.

oogenesis – the production of eggs.

oviparous – produces eggs which are laid and develop outside the maternal body.

ovipositor – a tube-like, egg-laying apparatus; the external genitalia at the tip of a female's abdomen. Insects are capable of piercing their host plants, or the cuticles of host insects, and laying their eggs inside the host.

ovoviviparous – producing eggs which develop within the female's body and hatch within or immediately after extrusion from the female.

ovule – the central part of a plant ovule in which the embryo develops. The ovule develops into the seed after fertilization.

papillae – a small elevated pad on the surface of a stigma, petal or leaf.

parasite / parasitoid – an insect which is parasitic in its immature stages, whilst the adult is free-living. Generally a parasitoid consumes or kills only one host to complete its development. An adult female typically lays many eggs in an organism, the eggs hatch and the larvae feed on the host.

parthenogenesis – development of an egg without fertilization.

pathogen – a broad term used to describe any micro-organism which may cause disease or death to in insect host (i.e. bacteria, viruses, fungi, rickettsia or nematodes).

pedicel – the stalk of a single flower.

perfect flowers – flowers with functional male and female organs.

perianth – the floral envelope whose segments are usually divisible into an outer whorl (calyx) of sepals, and an inner whorl (corolla) of petals. The segments of either or both whorls may fuse to form a tube.

pericarp – the wall of a fruit that encloses the seeds and develops from the ovary wall.

pesticide resistance – when a previously susceptible insect population increases its ability to resist being killed by a pesticide. The evolution of resistance is a process that increases the proportion of individuals in a population that carry resistance genes. Pesticide resistance is a population-level process.

petal – a non-reproductive part of the flower, usually conspicuously coloured; one of the units of the corolla.

phenology – the study of regularly recurring biological phenomena, such as plant budding or animal migrations, especially as influenced by climatic conditions.

photosynthesis – the process by which green plants manufacture sugars from water and carbon dioxide by converting the energy from light into chemical energy with the aid of the green pigment chlorophyll.

phytophagous – feeding on many host plants.

pistil – the female reproductive organ consisting of one or more carpels, comprising ovary, style and stigma.

pollination – the transfer of pollen grains from stamen to stigma. Cross-pollination occurs between flowers of different plants of the same species; self-pollination occurs between flowers of the same plant, or within one flower.

polyphagous – feeding on many types of food.

precocious – an early-developing plant; starts bearing fruit at an early age

predator – an organism that kills and consumes other organisms.

propagules – the portion of a plant or a fungus, such as a seed or spore, from which a new individual can develop.

protandrous (of flowers) – the maturing of stamens and the consequent release of their pollen before the stigmas of the same flower become receptive.

prothorax – the anterior of the three thoracic segments.

pterothroax – the collective name for the mesothoracic and metathoracic segments, to which the wings are borne.

pterygote – winged.

pubescent – downy, covered in soft, short hairs.

pupa (pl., *pupae*) – the developmental stage, usually immobile or quiescent, of an insect (i.e. butterflies, moths, beetles, weevils, flies and wasps), before the final developmental stage of becoming an adult.

quiescent – inactive.

raceme – an inflorescence consisting of an elongated central structure (main axis) called a rachis from which pedicels bear individual flowers.

rootstock – The lower portion of a grafted or budded tree below the graft union.

sample – (biologically) a collection of sampling units; (statistically) a collection of observations.

> **sampling unit** – the smallest part of the environment collected and examined for insect damage or presence.
>
> **artificial sampling unit** – a convenient although unnatural sampling unit (i.e. traps and soil cores).
>
> **natural sampling unit** – some portion of the environment, such as a leaf, twig or fruit which can be easily related back to the plant.

saprophytic – feed on dead, decaying, dissolved organic material.

scion – wood that is used to graft trees. Also used to refer to the upper portion of the graft above the graft union.

scouting (entomology) – methodical inspection of plant material for insect presence or damage.
"selfing" – *see* pollination

self-pollination – *see* pollination.

sepal – a floral leaf or individual segment of the calyx of a flower, usually green.

seta (pl., *setae*) – bristle or hair.

shell – *see* testa.

spinose – spiny.

sporophagous – feed on spores and decaying organic matter.

stamen – the male reproductive organ of a flower. It consists of a usually bilobed anther born on a stalk (filament).

stick-tight nuts – mature nut-in-husk which stay attached to the tree and do not abscise.

tepal – a perianth-segment that is not clearly distinguishable as either a sepal or a petal.

testa – a seed's outer protective covering (shell).

thelytoky – a form of parthenogenesis in which only females are produced from unfertilized eggs, males being very rare or absent.

trichomes – hair on outer layer of plant's epidermis.

uniseriate – arranged in a single row, series or layer.

variety (botany) – taxonomic category of related organisms, especially plants, of a rank below species. Varieties of a species generally have distinguishing characteristics, and may arise naturally or through deliberate plant breeding.

venation – the arrangement of veins.

viviparous – bring forth live young.

whorl (of leaves) – the node or point on the shoot where three (or four) leaves attached to a node on the branch.

References

AHRENS, P. (1991) History and statistics of macadamias in Levubu. In: Proceedings of the Macadamia Mini Symposium, Levubu, 18 - 19 September 1991, pp. 3-4.

ALLAN, P. (1972) Macadamia prospects. In: Proceedings of the Macadamia and Pecan Nut Symposium, Umtali, 9 - 10 November 1971, pp. 15-26.

ALLAN, P. (2006) *Revised Illustrated Guide to Identification of Macadamia Cultivars in South Africa*. Horticultural Science, University of KwaZulu-Natal and SAMAC, Pietermaritzburg.

ALLAN, P. & DE JAGER, J. (1978) Net photosynthesis in macadamia and papaw and the possible alleviation of heat stress. *Californian Macadamia Society Yearbook* 25: 150-157.

ALLAN, P., BLORE, N., CAIRNS, A.L.P. (1999) Cultivar performance at Ukulinga. In: Proceedings of the 1st International Macadamia Symposium in Africa. Mpumalanga Parks Board, Nelspruit, 27 - 30 September 1999, pp. 138-144.

ANANTHAKRISHNAN, T.N. (1993) Bionomics of Thrips. *Annual Review of Entomology* 38: 71-92.

ANANTHAKRISHNAN, T.N. & SURESH, G. (1984) Thrips-fungus interactions with special reference to their vector potential. *In: Proceedings of the Indian Academy of Science* (*Animal Sciences*) 93(4): 315-322.

ANNECKE, D.P. & MORAN, V.C. (1982) *Insects and Mites of Cultivated Plants in South Africa*. Butterworths, Durban.

ANONYMOUS (2007) *Macadamia Phenology: Management Guide*. Poster.

ANONYMOUS (2011) The macadamia industry in South Africa. In: *South Africa Macadamia Growers' Association Growers Handbook*, pp. 8-16.

ANONYMOUS (2013a) Overview of the South African Macadamia Industry. Subtrop, Tzaneen. http://www.subtrop.co.za Accessed 19 April 2014.

ANONYMOUS (2013b) International Fruit and Nut Council. Global Statistical Review 2008-2013. http://www.nutfruit.org Accessed 10 October 2014.

ANONYMOUS (2014) International Fruit and Nut Council. Global Statistical Review 2014.

ARCAMONTE, M. (1995) Thrips resistance management. *Citrograph*, August 1995, pp 3-6.

BARTH, F.G. (1991) *Insects and Flowers: The Biology of a Partnership*. Princeton University Press, New Jersey.

BEDFORD, E.C.G. (1943a) The biology and economic importance of South African citrus thrips, *Scirtothrips aurantii* Fauré. *Publications of the University of Pretoria, South Africa, Series 2, Natural Science* 7: 1-68.

BEDFORD, E.C.G. (1943b) The biology of the citrus thrips. *Farming in South Africa* 18(205): 275-280.

BEDFORD, E.C.G. (1968) Biological and chemical control of citrus pests in the western Transvaal. An integrated spray programme. *South African Citrus Journal* 417: 9, 11, 13, 15, 17, 19, 21-28.

BEDFORD, E.C.G. & DU TOIT, W.J. (1993) Insecticides for thrips sprays affect IPM programmes for citrus. *Information Bulletin, Institute for Tropical and Subtropical Crops* 256: 13-16.

BEDFORD, E.C.G., VERCUEIL, S.W., DEACON, V.E. (1985) A general guide to integrated control of citrus pests with red scale under biological control. *Farming in South Africa, Citrus Series* H. 47: 1-16.

BHALLA, P.L. & MULWA, R.M.S. (2003) Tissue culture and macadamia propatation. *Acta Horticulturae* 616: 343-346.

BINNS, M.R. & NYROP, J.P. (1992) Sampling insect populations for the purpose of IPM decision making. *Annual Review of Entomology* 37: 427-453.

BOYTON, S.J. & HARDNER, C.M. (2002) Phenology of flowering and nut production in macadamia. *Acta Horticulturae* 575: 381-387.

BRINK, T. (1993) Blaaspootjies by mangos. *South African Mango Growers' Association Yearbook* 13: 131-133. [In Afrikaans].

BRINK, T. & MARITZ, M. (1995) Sitrusblaaspootjie by 'n groot verskeidenheid plante. *Institute for Tropical and Subtropical Crops, Information Bulletin* 274: 3-4. [In Afrikaans].

BRUWER, I.J. (2004) Evaluation of integrated pest management programmes for the control of various insect pests on macadamias in South Africa. *Southern African Macadamia Growers' Yearbook* 11: 22-27.

BUTHELEZI, B. (2015) INC World Congress, Turkey. *Subtrop Quarterly Journal* 10: 68-69.

BUTT, T.M. & BROWNBRIDGE, M. (1997) Fungal pathogens of thrips. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CAB International, Wallingford, United Kingdom, pp. 399-433.

CARR, M.K.V. (2013) The water relations and irrigation requirements of macadamia (*Macadamia* spp.): a review. *Experimental Agriculture* 49(1): 74-90.

CARTER, W. (1939) Geographical distribution of Yellow Spot of Pineapples. *Phytopathology* 29: 285-286.

CHILDERS, C.C. (1997) Feeding and oviposition injuries to plants. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CAB International, Wallingford, United Kingdom, pp. 505-537.

CHILDERS, C.C. & ACHOR, D.S. (1995) Thrips feeding and oviposition injuries to economic plants, subsequent damage and host responses to infestation. In: Parker, B.L., Skinner, M. & Lewis, T. (Eds.) *Thrips Biology and Management*. Plenum, New York, pp. 31-51.

COOPER, T. (1980) President's Report for 1980. *California Macadamia Society Yearbook 1980* Vol. 26: 10-11.

CYBERCAPETOWN.COM (2014) Map of Mpumalanga Province, South Africa. http://cybercapetown.com/Maps/Mpumalanga. Accessed 6 October 2014.

DE JABER, K. & DE VILLIERS, E.A. (1993a) Banana thrips. In: Robinson, J.C. (Ed.) *Handbook of Banana Growing in South Africa*. Dynamic Ad: Nelspruit, pp. 115-117.

DE JAGER, K. & DE VILLIERS, E.A. (1993b) Flower thrips. In: Robinson, J.C. (Ed.) *Handbook of Banana Growing in South Africa*. Dynamic Ad, Nelspruit, pp. 117-118.

DE ROOSTER, K., SNYMAN, J.C., SMITH, B.L., FOURIE, P.F., DE VILLIERS, E.A., WILLERS, P., SCHWARTZ, A. (1985) Tea cultivation in South Africa. *Farming in South Africa, Tea Series* A1: p. 7.

DE VILLIERS, E.A. (1990) Blaaspootjies by avokados. *Farming in South Africa, Avocado Series* H: pp. 2. [In Afrikaans].

DE VILLIERS, E.A. (1993) Pests of minor importance. In: *The Cultivation of Macadamias. Bulletin, Institute for Tropical and Subtropical Crops, Agricultural Research Council, Republic of South Africa* 426: 52-57.

DE VILLIERS, E.A. (2001) Thysanoptera – Family Thripidae. *Heliothrips sylvanus* Fauré, guava thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 231.

DE VILLIERS, E.A. & DE JAGER, K. (2001a) Thysanoptera – Family Thripidae. *Hercinothrips bicinctus* (Bagnall), banana thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 232-233.

DE VILLIERS, E.A. & DE JAGER, K. (2001b) Thysanoptera – Family Thripidae. *Thrips exilicornis* Hood, flower thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 240-241.

DE VILLIERS, E.A. & VAN DEN BERG, M.A. (1987) Avocado insects of South Africa. *South African Avocado Growers' Association Yearbook* 10: 75-79.

DE VILLIERS, E.A. & VAN DEN BERG, M.A. (2003) Pests of minor importance. In: De Villiers, E.A. & Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 138-164.

DENNILL, G.B. & ERASMUS, M.J. (1992) Basis for a practical technique for monitoring thrips in avocado orchards. *Crop Protection* 11: 89-91.

DRIESTADT, S.H., PHILLIPS, P.A., O'DONNELL, C.A. (2007) *Thrips*. UC Statewide IPM Program, University of California Davis. Publication No. 7429.

ELMER, P.A.G. & MICHAILIDES T.J. (2004) Epidemiology of *Botrytis cinerea* in orchard and vine crops. In: Elad, Y., Williamson, B., Tudzynski, P., Delen, N. (Eds.) *Botrytis: Biology, Pathology and Control*. Kluwer Academic Publishers, Netherlands, pp. 243-272.

ERICHSEN, C. (1996) *An evaluation of insect pest damage to avocado fruits*. MSc Thesis, University of Pretoria, South Africa.

FAURÉ, J.C. (1929) The South African citrus thrips and five other new species of *Scirtothrips* Shull. *Bulletin of the Faculty of Agriculture, Transvaal University College, Pretoria* 18: 1-18.

FAURÉ, J.C, (1956) South African Thysanoptera. Part 6. *Journal of the Entomological Society of Southern Africa* 19: 313-341.

FERRAR, T.A. & LÖTTER, M.C. (2006) *Mpumalanga Biodiversity Conservation Plan Handbook*. The Mpumalanga Provincial Government, Nelspruit, p. 88

FITZELL, R.D. (1994) *Diseases and Disorders of Macadamias*. Wollongbar Agricultural Institute, Queensland Department of Primary Industries. p. 31.

FRONEMAN, I.J. (2003) Nursery practices and propagation. In: de Villiers, E.A. and Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 46-55.

GALLAGHER, E., O'HARE, P., STEPHENSON, R., WAITE, G. (2003) *Field Guide - Macadamia Problem Solver & Bug Identifier*. The State of Queensland Department of Primary Industries, Brisbane. pp. 128-131.

GARCIA, D.J., CASTILLO, C.F., ORTEGA, E., ESCAMILLA, E., OROZCO-CÁRDENAS, M.L. (2013) In vitro propagation of Macadamia (*Macadamia integrifolia* L.). University of California, Riverside. http://ptrc.ucr.edu/files/**macadamia**-poster-sivb-2013.pdf Accessed 10 October 2014.

GARLICK, G. (1991) History and statistics of the Natal South Coast. In: Proceedings of the Macadamia Mini Symposium, Levubu, 18 - 19 September 1991, pp. 6-7.

GEORGALA, M.B. (1982) Thrips control: comments on registered treatments. *Citrus and Subtropical Fruit Journal* 585: 13, 14, 16-17.

GILBERT, M.J. (1986) The first African record of *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), a potential pest of citrus and other crops in southern Africa. *Journal of the Entomological Society of Southern Africa* 49: 159-161.

GILBERT, M.J. (1990) Relative population levels of citrus thrips, *Scirtothrips aurantii* on commercial citrus and adjacent bush. *South African Journal of Zoology* 25: 72-76.

GILBERT, M.J. (1992) *The ecology of the South African citrus thrips,* Scirtothrips aurantii *Fauré and its economic implications*. PhD Thesis, Rhodes University, Grahamstown, South Africa.

GILBERT, M.J. & BEDFORD, E.C.G. (1998) Citrus thrips, *Scirtothrips aurantii* Fauré. In: Bedford, E.C.G., van den Berg, M.A., de Villiers, E.A. (Eds.) *Citrus Pests in the Republic of South Africa*. Dynamic Ad, Nelspruit, pp. 164-183.

GERTENBACH, W.P.D. (1983) Landscapes of the Kruger National Park. *Koedoe* 26:9-121.

GITONGA, L.N. (2010) Multiplication, Conservation and Genetic Characterization of Selected Macadamia Germplasm in Kenya. PhD Thesis, Jomo Kenyatta University, Kenya.

GORDON, I. (1987) Macadamia varieties and selections in New Zealand. In: Proceedings of the 2nd Australian Macadamia Research Workshop, 15 - 19 September 1987, Bangalow, Australia, p. 225.

GREGORY, G.R. (1987) Second Australian Macadamia Research Workshop Opening Address, Session 1, Paper No. 1. In: Proceedings of the Second Macadamia Research Workshop, Bangalow, New South Wales, 15 - 19 September 1987, pp. 11 – 14.

GROUT, T.G. (1994) The distribution of phytoseiid mites (Acari: Phytoseiidae) on citrus in southern Africa and their possible value as predators of citrus thrips (Thysanoptera: Thripidae). *Experimental & Applied Acarology* 18: 61-71.

GROUT, T.G. (2011) Citrus Thrips *Scirtothrips aurantii* Fauré. Chapter 3: Specific Pests, Part 13. In: T.G. Grout (Ed.) *Integrated Production Guidelines for Export Citrus. Volume III. Integrated Pest and Disease Management.* Citrus Research International, Nelspruit. pp. 1-11.

GROUT, T.G. & RICHARDS, G.I. (1990) Monitoring citrus thrips, *Scirtothrips aurantii* (Thysanoptera: Thripidae) with yellow card traps and the effect of latitude on treatment thresholds. *Journal of Applied Entomology* 190: 385-389.

GROUT, T.G. & RICHARDS, G.I. (1992) *Euseius addoensis addoensis*, an effective predator of citrus thrips, *Scirtothrips aurantii*, in the Eastern Cape Province of South Africa. *Experimental and Applied Acarology* 15: 1-13.

GROUT, T.G. & STEPHEN, P.R. (1993) Predation of alate citrus thrips, *Scirtothrips aurantii* Fauré (Thysanoptera: Thripidae) by *Euseius citri* (van der Merwe and Ryke) (Acari: Phytoseiidae) at low temperatures. *African Entomology* 1(2): 264-265.

GROUT, T.G. & STEPHEN, P.R. (1994) Importation of *Neoseiulus cucumeris*: How will it affect existing thrips control by *Euseius addoensis* on citrus? *Citrus Journal* 4(2): 22-24.

GROUT, T.G. & STEPHEN, P.R. (1995) *Goetheana incerta* parasitizing citrus thrips in southern Africa. *Citrus Journal* 5(4): 30-32.

GROUT, T.G., STEPHEN, P.R., LA CROIX N.J.S. (1996) Citrus thrips (Thysanoptera: Thripidae) in Swaziland develop tolerance to tartar emetic bait. *African Entomology* 4(1): 15-20.

GROVÉ, T. (1999) *Thrips management in Ff* T. (2001) Thysanoptera – Family Thripidae. *Scirtothrips aurantii* Fauré, citrus thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa.* Dynamic Ad, Nelspruit, pp.233-238.

GROVÉ, T. & PRINGLE, K.L. (2000) A sampling system for estimating population levels of the citrus thrips, *Scirtothrips aurantii* Fauré (Thysanoptera: Thripidae), in mango orchards. *African Entomology* 8(2): 223-226.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2000a) Field evaluation of insecticides for the control of citrus thrips, *Scirtothrips aurantii* (Thysanoptera: Thripidae), on mango. *African Plant Protection* 6(1): 9-15.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2000b) Treatment levels for citrus thrips, *Scirtothrips aurantii* (Thysanoptera: Thripidae) in mango orchards. *African Plant Protection* 6: 17-20.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2000c) Efficacy of coloured sticky traps for citrus thrips, *Scirtothrips aurantii* Fauré (Thysanoptera, Thripidae) in mango ecosystems of South Africa. *Fruits* 55(4): 253-258.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2000d) Seasonal abundance of different stages of the citrus thrips, *Scirtothrips aurantii,* on two mango cultivars in South Africa. *Phytoparasitica* 28(1): 43-53.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2001) Thrips (Thysanoptera) species associated with mango trees in South Africa. *African Entomology* 9(2): 153-162.

GROVÉ, T., GILIOMEE, J.H., PRINGLE, K.L. (2003) The relationship between citrus thrips, *Scirtothrips aurantii* (Thysanoptera: Thripidae), abundance and fruit size in mango orchards. *African Entomology* 11(1): 39-48.

HAMILTON, R.A. & ITO, P.J. (1986) Macadamia nut variety improvement in Hawaii. *California Macadamia Society Yearbook* 32: 43-47.

HARDNER, C.M., PEACE, C., LOWE, A.J., NEAL, J., PISANU, P., POWELL, M., SCHMIDT, A., SPAIN, C., WILLIAMS, K. (2009) *Genetic Resources and Domestication of Macadamia. Horticultural Reviews* Vol. 35: 1-126.

HEARD, T.A. (1994) Behavior and pollinator efficiency of stingless bees and honey bees on macadamia flowers. *Journal of Apicultural Research* 33: 191-198.

HEARD, T.A. & EXLEY, E.M. (1994) Diversity, abundance, and distribution of insect visitors to macadamia flowers. *Environmental Entomology* 23(1): 91-100.

HENNING, C. (2014) From the Chairman's Desk. *Subtrop Quarterly Journal, Third Edition 2014*, Vol. 7, pp. 25-26.

HEPBURN, C. (2013) Insecticide resistance: the crucial reality. Subtrop Quarterly Journal 1: 19-22.

HEPBURN, C. & STILLER, M. (2012) Towards understanding the economic impact of thrips: preliminary findings. *South African Macadamia Growers' Association Yearbook 2012*, pp. 6-21.

HEPBURN, C. & STILLER, M. (2013) The thrips complex inhabiting macadamias: An update (2011-2012 and 2012-2013). *South African Macadamia Growers' Association Yearbook 2013*, pp. 26-36.

HEPBURN, C., STILLER, M., VILLET, M. (2014) The thrips complex inhabiting macadamia orchards in Nelspruit: is it a major problem? *South African Macadamia Growers' Association Yearbook 2014*, pp. 66-75.

HEYWOOD, V.H., BRUMMITT, R.K., CULHAM, A., SEBERG, O. (2007) *Flowering Plant Families of the World*. Firefly Books, Ontario.

HIGLEY, L.E. & PETERSON, K.D. (1994) Initiating sampling programs. In: Pedigo L.P. and Buntin, G.D. (Eds.) *Handbook of Sampling Methods for Arthropods in Agriculture*. CRC Press, Baca Raton, Florida, pp. 119-136.

HOBSON, L. (1972) Some macadamia observations: a visit to California. In: Proceedings of the Macadamia and Pecan Nut Symposium, Umtali, 9 - 10 November 1971, pp. 7-10.

HOBSON, L. (1991) The history and statistics of the Letaba (Tzaneen) district. In: Proceedings of the Macadamia Mini Symposium, Levubu, 18 - 19 September 1991, pp. 7-8.

HODDLE, M.S. & ROBINSON, L. (2004) Evaluation of factors influencing augmentative releases of *Chrysoperla carnea* for control of *Scirtothrips perseae* in California avocado orchards. *Biological Control* 31: 268-275.

HODDLE, M.S., NAKAHARA, S., PHILLIPS, P.A. (2002) Foreign exploration for *Scirtothrips perseae* Nakahara (Thysanoptera: Thripidae) and associated natural enemies on avocado (*Persea americana* Miller). *Biological Control* 24: 251-265.

HODDLE, M.S., OEVERING, P., PHILLIPS, P.A., FABER, B.A. (2004) Evaluation of augmentative releases of *Franklinothrips orizabensis* for control of *Scirtothrips perseae* in California avocado orchards. *Biological Control* 30: 456-465.

HOKKANEN, H.M.T. & PIMENTEL, D. (1989) New associations in biological control: theory and practice. *The Canadian Entomologist* 121(10): 829-840.

IMMARAJU J.A., MORSE, J.G., HOBZA, R.E. (1990) Field evaluation of insecticide rotation and mixtures as strategies for citrus thrips (Thysanoptera: Thripidae) resistance management in California. *Journal of Economic Entomology* 83: 306-314.

IRONSIDE D.A. (1996) *Insect Pests of Macadamia in Queensland*. Department of Primary Industries, Queensland, p. 28.

ITO, P.J. (1980) Effect of style removal on fruit set in macadamia. *HortScience* 15(4): 520-521.

IZZO, T.J., PINENT, S.M.J., MOUND, L.A. (2002) *Aulacothrips dictyotus* (Heterothripidae), the first ectoparasitic thrips (Thysanoptera). *Florida Entomologist* 85: 281-283.

JONES, V.P. (1994) Oviposition patterns of koa seedworm and litchi fruit moth (Lepidoptera: Tortricidae) on macadamia nut abortion. *Journal of Economic Entomology* 87: 781-786.

JONES, V.P. (2002) *Macadamia. Integrated Pest Management.* College of Tropical Agriculture and Human Resources, University of Hawaii, Manoa.

JONES, W.W. (1939) A study of the developmental changes in composition of the macadamia. *Plant Physiology* 14: 755-768.

JONES, W.W. & SHAW, L. (1943) The process of oil formation and accumulation in the macadamia. *Plant Physiology* 18:1-7.

KAMBUROV, S.S. (1986) New pests and beneficial insects on citrus in South Africa – Part 1. *Citrus and Subtropical Fruit Journal* 625: 6, 7, 9-11.

KAMBUROV, S.S. (1991) Damage to fruit and the impact on crop set from late infestations of citrus thrips (*Scirtothrips aurantii* Fauré). *Citrus Journal* 1: 33-34.

KAWATE, M.K. & TARUTANI, C.M. (Eds.) (2006) *Pest Management Strategic Plan for Macadamia Nut Production in Hawaii.* Workshop Summary 21 April 2004, University of Hawaii at Manoa, Honolulu, Hawaii.

KIRK, W.D.J. (1984) Pollen-feeding in thrips (Insecta: Thysanoptera). *Journal of the Zoological Society of London* 204: 107-117.

KIRK, W.D.J. (1985) Egg-hatching in thrips (Insecta: Thysanoptera). *Journal of the Zoological Society of London* 207: 181-190.

KIRK, W.D.J. (1997a) Feeding. In: T. Lewis (Ed). *Thrips as Crop Pests.* CAB International, Wallingford, pp. 119-174.

KIRK, W.D.J. (1997b) Distribution, abundance and population dynamics. In: T. Lewis (Ed). *Thrips as Crop Pests.* CAB International, Wallingford, pp 217-257.

KIRK, W.D.J. & TERRY, L.I. (2003) The spread of western flower thrips *Frankliniella occidentalis* (Pergande). *Agriculture and Forest Entomology* 5: 301-310.

LEIGH, D.S. (1968) Propogation and selection of macadamia nut trees. *Agricultural Gazette NSW* 76: 242.

LESLIE, G.W. (2005) Thrips, a new pest of sugarcane in southern Africa. *South African Sugar Journal* 89: 15.

LEWIS, T. (1973) *Thrips, Their Biology, Ecology and Economic Importance.* Academic Press, London.

LEWIS, T. (Ed.) (1997a) *Thrips as Crop Pests.* CAB International, Wallingford, United Kingdom.

LEWIS, T. (1997b) Pest thrips in perspective. In: Lewis, T. (Ed.) *Thrips as Crop Pests*, CAB International, Wallingford, United Kingdom, pp. 1-13.

LIM, U.T., VAN DRIESCHE, R.G., HEINZ, K.M. (2001) Biological attributes of the nematode, *Thripinema nicklewoodi*, a potential biological control agent of western flower thrips. *Biological Control* 22: 300-306.

LIPE, J.A. & MORGAN, P.W. (1972) Ethylene: role in fruit abscission and dehiscence processes. *Plant Physiology* 50:759-764.

LIPE, J.A. & MORGAN, P.W. (1973) Ethylene, a regulator of young fruit abscission. *Plant Physiology* 51:949-953.

LOOMANS, A.J.M., MURAI, T., GREENE, I.D. (1997) Interactions with hymenopterous parasitoids and parasitic nematodes. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CAB International, Wallingford, United Kingdom, pp. 355-397.

MAIDEN, J.H. & BETCHE, E. (1897) On a new species of *Macadamia* together with notes on two plants new to the colony. Proceedings of the Linnaeous Society New South Wales 21: 624-627.

MALAN, E.F. (1954) Pynappelproduksie in Suid-Afrika. *Department of Agriculture, South Africa, Horticultural Series* 18(339) p. 29. [In Afrikaans].

MALAN, E.F. & THOMAS, D.D.S. (1963) *Bananas in South Africa*. Pamphlet No. 351. Government Printer, Pretoria, p. 52.

MANICOM, B.Q. (1997) The current status of fungal diseases of macadamia nuts in South Africa. *South African Macadamia Growers' Association Yearbook* pp. 70-72.

MANICOM, B.Q. (2003) Diseases. In: de Villiers, E.A. & Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. Agricultural Research Council – Institute for Tropical and Subtropical Crops, Nelspruit, pp. 110-116.

McCONACHIE, I. (1980) The Macadamia Story. *California Macadamia Society Yearbook 1980* Vol. 26: 41-75.

McCONCHIE, C.A., MEYERS, N.M., ANDERSON, K.L., VIVIAN-SMITH, A., O'BREIN, S. (1996) Development and maturation of macadamia nuts in Australia. In: Stephenson, R.A., & Winks, C.W. (Eds.) Challenges for Horticulture in the Tropics. Proceedings of the 3rd Australian Society of Horticultural Science Conference 18 - 22 August 1996, Broadbeach, Australia, pp. 234-238.

McCUBBIN, P.D. & LEE, P.F.W. (1996) The comparative performance of two Australian and five Hawaiian macadamia cultivars in South Africa. In: Stephenson, R.A., & Winks, C.W. (Eds.) Challenges for Horticulture in the Tropics. Proceedings of the 3rd Australian Society of Horticultural Science Conference 18 - 22 August 1996, Broadbeach, Australia, pp. 212-216.

MES, M.G. (1957) Studies on the flowering of *Coffea arabica* L. I. Influence of temperature on the initiation and growth of coffee flower buds. II. Breaking dormancy of coffee flower buds. *Portugaliae Acta Biologica* 4: 328-341; 342-354.

MILNE, D.L. (1973) Avocado pests. In: Milne, D.L. (Ed.) *Insect Pests of Subtropical Fruit Crops.* Department of Agricultural Technical Services, South Africa, Entomology Memoir 33: p. 42.

MILNE, D.L. (1977) Biological control of citrus thrips, *Scirtothrips aurantii*: What are the prospects? *The Citrus and Subtropical Fruit Journal* 528: 14, 16.

MONCUR, M.W. (1988) *Floral Development of Tropical and Subtropical Fruit and Nut Species.* CSIRO Publication, pp 138-140.

MONCUR, M.W., STEPHENSON, R.A., TROCHOULIAS, T. (1985) Floral development of *Macadamia integrifolia* Maiden & Betche under Australian conditions. *Scientia Horticulturae* 27: 87-96.

MORITZ, G. (1997) Structure, growth and development. In: Lewis, T. (Ed.) *Thrips as Crop Pests.* CAB International, Wallingford, United Kingdom, pp. 15-63.

MORSE, J.G. & BRAWNER, O.L. (1986) Managing citrus thrips resistance to pesticides. *Citrograph* 71(5): 93, 96-97, 108.

MORSE, J.G. & HODDLE, M.S. (2006) Invasion biology of thrips. *Annual Review of Entomology* 51: 67-89.

MORSE, J. & SCHWEIZER, H. (1996) Citrus thrips resistance – a problem requiring grower and PCA restraint. *Citrograph*, May 1996, pp. 11-15.

MOUND, L.A. (1971) The feeding apparatus of thrips. *Bulletin of Entomological Research* 60: 547-548.

MOUND, L.A. (1983) Natural and disrupted patterns of geographical distribution in Thysanoptera (Insecta). *Journal of Biogeography* 10: 119-133.

MOUND, L.A. (1997) Biological diversity. In: Lewis, T. (Ed.) *Thrips as Crop Pests.* CAB International, Wallingford, United Kingdom, pp. 197-215.

MOUND, L.A. (2005) Thysanoptera: diversity and interactions. *Annual Review of Entomology* 50: 247-269.

MOUND, L.A. (2010) Species of the Genus *Thrips* (Thysanoptera, Thripidae) from the Afro-tropical Region. *Zootaxa* 2423: 1-24.

MOUND, L. A. (2013a) Thysanoptera (Thrips) of the World - a checklist. http://www.ento.csiro.au/thysanoptera/worldthrips.html [Accessed 22 September 2015].

MOUND, L.A. (2013b) Homologies and host plant specificity: recurrent problems in the study of thrips. *BioOne* 96(2): 318-322.

MOUND, L.A. & MARULLO, R. (1996) The thrips of Central and South America: an introduction (Insecta: Thysanoptera). *Memoirs on Entomology, International* 6: 1-488.

MOUND, L.A. & PALMER, J.M. (1981) Identification, distribution and host plants of the pest species of *Scirtothrips* (Thysanoptera: Thripidae). *Bulletin of Entomological Research* 71: 467-479.

MOUND, L.A. & STILLER, M. (2011) Species of the genus *Scirtothrips* from Africa (Thysanoptera, Thripidae). *Zootaxa* 2786: 51-61.

MOUND, L.A. & TEULON, D.A.J. (1995) Thysanoptera as phytophagous opportunists. In: Parker, B.L., Skinner, M. & Lewis, T. (Eds.) *Thrips Biology and Management*. Plenum, New York, pp. 3-19.

MULWA, R.M.S. & BHALLA, P.L. (2007) Assessment of clonal stability of *in vitro* regenerated shoots of *Macadamia tetraphylla* by RAPD analysis. *Australian Journal of Agricultural Research* 58(3): 253-257.

NAGAO, M.A. & SAKAI, W.S. (1985) Effects of growth regulators on abscission of young macadamia fruits. *Journal of the American Society of Horticultural Science* 110:654-657.

NAGAO, M.A., HO-A, E.B., YOSHIMOTO, J.M., YOSHIMURA, E.R. NOTLEY, E., FUCHIGAMI, L.H. (1994) Relationship between vegetative flushing and flowering of *Macadamia integrifolia* in Hawaii. *Scientia Horticulturae* 60: 9-16.

NAKAHARA, S. (2005) Order Thysanoptera. In: Triplehorn, C.A. and Johnson, N.F. (Eds.) *Borror and DeLong's Introduction to the Study of Insects*. Thompson Brooks/Cole, Belmont, pp. 333-340.

NEUENSCHWANDER, P. & MARKHAM, R. (2001) Biological control in Africa and its possible effects on biodiversity. In: Wajnberg, E., Scott, J.K. & Quimby. P.C. (Eds.) *Evaluating Indirect Ecological Effects of Biological Control*. CAB International, Wallingford, United Kingdom, pp. 127-146.

NORTJÉ, G. (2012) Census Report. *South African Macadamia Growers' Association, In a Nutshell, July/August 2012*, pp. 2-4.

O'HARE, P.J., QUINLAN, K., STEPHENSON, R., VOCK, N. (Eds.) (2004) *Macadamia Grower's Handbook*. Queensland Department of Primary Industries, Australia.

OOSTHUIZEN, J.H. (1992) Evaluation of plant densities for macadamia nut trees in a fan design. *Journal of the Southern African Society for Horticultural Sciences* 2: 1-6.

ORWA, C., MUTUA, A., KINDT, R., JAMNADASS R., ANTHONY S. (2009) Agroforestree Database: a tree reference and selection guide. Version 4.0. http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp.

PALMER, J.M. (1990) Identification of the common thrips of Tropical Africa (Thysanoptera: Insecta). *Tropical Pest Management* 36(1): 27-49.

PALMER, J.M., MOUND, L.A., DU HEAUME, G.J. (1989) 2. Thysanoptera. In: Betts, C.R. (Ed.) *Guide to Insects of Importance to Man.* Commonwealth Agricultural Bureau, International Institute of Entomology, The Natural History Museum, London, p. 73.

PARELLA, M.P. & LEWIS, T. (1997) Integrated Pest Management (IPM) in field crops. In: Lewis, T. (Ed.) *Thrips as Crop Pests.* CAB International, Wallingford, United Kingdom, pp. 595-614.

PEDIGO, L.P. & RICE, M.E. (2006) *Entomology and Pest Management*. Pearson Education Incorporated, Upper Saddle River, New Jersey.

PENTER, M. & KRUGER, F.J. (2003) Shelling of macadamia nuts. In: In: De Villiers, E.A. & Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 182-191.

PETTY, G.J. (1978) Pineapple pests: Thrips. *Farming in South Africa, Pineapple Series* H17: p.8.

PETTY, G.J. (2001a) Thysanoptera – Family Thripidae. *Frankliniella schultzei* (Trybom) Kromnek thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 228.

PETTY, G.J. (2001b) Thysanoptera – Family Thripidae. *Thrips tabaci* (Lindeman) onion thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 242-246.

RAVISHANKAR, H., RAO, M.M., BOJAPPA, K.M. (1979) Fruit bud differentiation in mango 'Alphonso' and 'Totapuri' under mild tropical rainy conditions. *Scientia Horticulturae* 10: 95-99.

REIM, C. (1991) Early history of macadamias in South Africa. In: Proceedings of the Macadamia Mini Symposium, Levubu, 18 - 19 September 1991, pp. 1-2.

RUTHERFORD, M.C., MUCINA, L., LÖTTER, M.C., BREDENKAMP, G.J., SMIT, J.H.L., SCOTT-SHAW, C.R., HOARE, D.B., GOODMAN, P.S., BEZUIDENHOUT, H., SCOTT, L., ELLIS, F., POWRIE, L.W., SIEBERT, F.,

MOSTERT, T.H., HENNING, B.J., VENTER, C.E., CAMP, K.G.T., SIEBERT, S.J., MATTHEWS, W.S., BURROWS, J.E., DOBSON, L., VAN ROOYEN, N., SCHMIDT, E., WINTER, P.J.D., DU PREEZ, P.J., WARD, R.A., WILLIAMSON, S., HURTER, P.J.H. (2006) Savanna Biome. *Strelitzia* 19:439-539.

SAKAI, W.S. & NAGAO, M.A. (1985) Fruit growth and abscission in *Macadamia integrifolia*. *Physiologia Plantarum* 64(4): 455-460.

SALTER, B., McCONCHIE, C.A., WILKIE, J.D. (2003) Options for the use of ethephon to promote harvesting in macadamia. In: Proceedings of the 2nd International Macadamia Symposium, 29 September - 4 October 2003, Tweed Heads Australia, pp. 130-133

SAMWAYS, M.J. (1986) Spatial distribution of *Scirtothrips aurantii* Fauré (Thysanoptera: Thripidae) and threshold level for one percent damage on citrus fruit based on trapping with florescent yellow sticky traps. *Bulletin of Entomological Research* 76: 649-659.

SAMWAYS, M.J., TATE, B.A., MURDOCH, E. (1986) Monitoring the citrus thrips and citrus psylla using florescent yellow sticky traps – a practical guide. *The Citrus and Subtropical Fruit Journal* 629: 9-15.

SCHOLEFIELD P.B. (1982) A scanning electron microscope study of flowers of Avocado, Litchi, Macadamia and Mango. *Scientia Horticulturae* 16(1982): 263-272.

SCHOEMAN, P.S. (2009a) *Key biotic components of the indigenous Tortricidae and Heteroptera complexes occurring on macadamia in South Africa*. PhD Thesis, North West University, Potchefstroom, South Africa.

SCHOEMAN, P.S. (2009b) Integrated management of macadamia pests. *Southern African Macadamia Growers' Association 2009 Yearbook* 16: 23-29.

SCHOEMAN, P.S. (2014) Stink bug IPM on macadamias in South Africa: current status and the road ahead. *Southern African Macadamia Growers' Association 2014 Yearbook* 22: 69-75.

SCHORMANN, R. (1991) History and statistics of the southern Lowveld. In: Proceedings of the Macadamia Mini Symposium, Levubu, 18 - 19 September 1991, pp. 4-6.

SCHWARTZ, A. (1983) Sitrusblaaspootjies: Wat van biologiese beheer? *Citrus and Subtropical Fruit Research Institute, Subtropica* 4(2): 14. [In Afrikaans].

SEDGLEY, M. (1983) Pollen tube growth in macadamia. *Scientia Horticulturae* 18: 333-341.

SEDGLEY, M., BLESING, M.A., VITHANAGE, H.I.M.V. (1985) A developmental study of the structure and pollen receptivity of the macadamia pistil in relation to protandry and self-incompatibility. *Botanical Gazette* 146(1): 6-14.

SERFONTEIN, J.J., SERFONTEIN, S., SWART, S.H. (2007) Screening of macadamia nurseries for pathogens with the emphasis on *Pythium* and *Phytophthora* spp. and its impact on dieback in orchards. *The Southern African Macadamias Growers' Association Yearbook* 15: 36-38.

SHELTON, A.M., NAULT, B.A., PLATE, J., ZHAO, J-Z. (2003) Regional and temporal variation in susceptibility to lambda-cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae), in onion fields in New York. *Journal of Economic Entomology* 96: 1843-1848.

SPURLING, A.T. & SPURLING, D. (1972) Macadamias in Malawi. In: Proceedings of the Macadamia and Pecan Nut Symposium, Umtali, 9 - 10 November 1971, pp. 11-14.

STATISTICS SOUTH AFRICA (2011) Provincial Profile: Mpumalanga Census 2011. www.statssa.gov.za/publications/Report-03-01-77/Report-03-01-772011.pdf Accessed 29 July 2015.

STEPHENSON, R.A. & GALLAGHER, E.C. (1983) A preliminary evaluation of the timing of nitrogen applications to macadamias. In: Stephenson, R.A. and Gallagher, E.C. (Eds.) Proceedings of the First Australian Macadamia Research Workshop, Marcoola, Queensland, Australia, 12 - 16 September, 1983, pp. 331.

STEPHENSON, R.A. & TROCHOULIAS, T. (1994) *Macadamia*. In: Schaffer, B. & Anderson, P.C. (Eds.) Macadamia. *Environmental Physiology of Fruit Crops – Volume II: Sub-tropical and Tropical Crops*. CRC Press, Boca Raton, FL, pp. 147-163.

STEPHENSON, R.A., CULL, B.W., STOCK, J. (1986) Vegetative flushing patterns of macadamia trees in south east Queensland. *Scientia Horticulturae* 30: 53-62.

STEYN, W.P. (1991) Blaaspootjies by avokados. *Citrus and Subtropical Fruit Research Institute, Subtropica* 12(4): 10-13. [In Afrikaans].

STEYN, W.P. (2001a) Thysanoptera – Family Thripidae. *Heliothrips haemorrhoidalis* (Bouchè), greenhouse thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 228-231.

STEYN, W.P. (2001b) Thysanoptera – Family Thripidae. *Selenothrips rubrocinctus* (Giard), red-banded thrips. In: van den Berg, M.A., de Villiers, E.A., Joubert, P.H. (Eds.) *Pests* *and Beneficial Arthropods of Tropical and Non-citrus Subtropical Crops in South Africa*. Dynamic Ad, Nelspruit, pp. 239-240.

STOREY, W.B. & FROLICH, E.F. (1964) Report on the graft compatibility of macadamia. *California Macadamia Society Yearbook* 10: 54-58.

STROHSCHEN, B. (1986) Contributions to the biology of useful plants. 4. Anatomical studies of fruit development and fruit classification of the macadamia nut (*Macadamia integrifolia* Maiden and Betche). *Angewandte Botanik* 60: 239-247.

SUBTROP (2012) Avocado, Litchi, Mango and Macadamia Plantings in South Africa. *South African Subtropical Growers' Association, Tzaneen, Verified Census Data 31 May 2012*, p. 1.

SUBTROP (2013) Overview of the South African Macadamia Industry. http://www.subtrop.co.za. Accessed 19 April 2014.

SUPAMATEE, S., ITO, P.J., JALICHAN, D. (1992) Early performance of Australian and Hawaiian macadamia cultivars in Thailand. In Proceedings of the 1st International Macadamia Research Conference, 28 - 30 July 1992, Kailau-Kona, Hawaii, pp. 107-111.

TAVARES, J.M. (2013) Contribution of insect pollination to *Macadamia integrifolia*, *Coffea arabica* and *Dimocarpus longan* in Hawaii. Masters Thesis, University of Hawaii (Mānoa) p. 111.

TERRY, I. (1997) Host selection, communication and reproductive behaviour. In: Lewis, T. (Ed.) *Thrips as Crop Pests*, CAB International, Wallingford, United Kingdom, pp. 65-118.

TIMM, A.E., STILLER, M., FREY, J.E. (2008) A molecular identification key for economically important thrips species (Thysanoptera: Thripidae) in southern Africa. *African Entomology* 16(1): 68-75.

TRIPLEHORN, C.A. & JOHNSON, N.F. (2005) (Eds.) *Borror and DeLong's Introduction to the Study of Insects*. Thomson Brooks/Cole, Belmont.

TROCHOULIAS, T. & BURNSIDE, A. (1987) Close spaced macadamia. In: Proceedings of the 2nd Australian Macadamia Research Workshop, 15 - 19 September 1987, Bangalow, Australia, p. 221.

TRUEMAN, S.J. (2013) The reproductive biology of macadamia. Review Article. *Scientia Horticulturae* 150: 354-359.

TRUEMAN S.J., McCONCHIE, C.A., TURNBULL, C.G.N. (2002) Ethephon promotion of crop abscission for unshaken and mechanically shaken macadamia. *Australian Journal of Experimental Agriculture* 42: 1001-1008.

ULLMAN, D.E., SHERWOOD, J.L., GERMAN, T.L. (1997) Thrips as vectors of plant pathogens. In: Lewis, T. (Ed.) *Thrips as Crop Pests*. CAB International, Wallingford, United Kingdom, pp. 539-565.

ULLMAN, D.E., MEIDEROS, R., CAMPBELL, L.R., WHITFIELD, A.E., SHERWOOD, J.L., GERMAN, T.L. (2002) Thrips as vectors of tospoviruses. *Advances in Botanical Research* 36: 113-140.

URATA, U. (1954) Pollination requirements of *Macadamia*. *Hawaii Agricultural Experimental Station Technical Bulletin* 22: 40 pp.

VITHANAGE, V., O'CONNOR, K., PEACE, C., MEYERS, N., FORRESTER, R.I., McCONCHIE, C.A. (2003) Use of molecular markers in macadamia: managing pollination in orchards. In: Proceedings of the Second International Macadamia Symposium, Tweed Heads, Australia, 29 September - 4 October 2003, pp. 73-76.

WARREN, V. (2003) World round-up - New Zealand. In Proceedings of the 2nd International Macadamia Symposium, 29 September – 4 October 2003, Tweed Heads, Australia, pp. 13-14.

WAY, M.J. (2006) Incidence of *Fulmekiola serrata* (Thysanoptera: Thripidae) in South African sugarcane. In: *Proceedings of the South African Sugar Technologists' Association* 80: 199-201.

WENTZEL, P.C. (1971) Thrips discovered on Macadamia trees. *Farming in South Africa* 47(6) 57.

WENTZEL, P.C. (1973) Banana thrips. In: Milne D.L. (Ed.) *Insect Pests of Subtropical Fruit Crops*. Department of Agricultural Technical Services, South Africa, Entomology Memoir 33: 44.

WENTZEL, P.C., GEORGALA, M.B., BEDFORD, E.C.G. (1978) Citrus thrips, *Scirtothrips aurantii* Fauré. In: Bedford, E.C.G. (Ed.) *Citrus Pests in the Republic of South Africa*. South African Department of Agriculture, Technical Services, Science Bulletin 391: 137-141.

WESTON, P.H. (2007) *Proteaceae*: Protea family. In: Heywood, V.H., Brummitt, R.K., Culham, A. & Seberg, O. (Eds.) *Flowering Plant Families of the World*, pp. 268-269.

WHITFIELD, A.E., ULLMAN, D.E., GERMAN, T.L. (2005) Tospovirus-thrips interactions. *Annual Review of Phytopathology* 43: 459-489.

WIESENBORN, W.D. & MORSE, J.G. (1988) The mandible and maxillary stylets of *Scirtothrips citri* (Moulton) (Thysanoptera: Thripidae). *Pan-Pacific Entomologist* 64: 39-42.

WIID-HOBSON, E.M. (2003a) Botanical aspects. In: de Villiers, E.A. & Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 8-13.

WIID-HOBSON, E.M. (2003b) Cultivars. In: de Villiers, E.A. & Joubert, P.H. (Eds.) *The Cultivation of Macadamia*. ARC-Institute for Tropical and Subtropical Crops, Nelspruit, pp. 24-38.

WIID, M. & HOBSON, L. (1996) Why macadamia cultivar Beaumont produces high yields under ultra high density conditions in South Africa. In: Stephenson, R.A., & Winks, C.W. (Eds.) *Challenges for Horticulture in the Tropics*. Proceedings of the 3rd Australian Society of Horticultural Science Conference 18 - 22 August 1996, Broadbeach, Australia, pp. 220-223.

WILKIE, J.D., SEDGLEY, M., MORRIS, S., MULDOON, S., OLESEN, T. (2009) Characteristics of flowering stems and raceme position in macadamia. *Journal Horticultural Science & Biotechnology* 84: 387-392.

WINKS, C.W., GALLAGHER, E.C., LANHAM, T.E. (1987) Regional macadamia varietal trials. In: Proceedings of the 2nd Australian Macadamia Research Workshop, 15 - 19 September 1987, Bangalow, Australia, pp. 30-36.

WORNER, S.P. (2002) Predicting the invasion potential of exotic insects. In: Hallman, G.J. & Schwable, C.P. (Eds.) *Invasive Arthropods in Agriculture: Problems and Solutions*. Science Publishers Inc., Enfield, pp. 119-137.

ZUR STRASSEN, R. (1960) Catalogue of the known species of South African Thysanoptera. *Journal of the Entomological Society of Southern Africa* 23(2): 321-367.

ZUR STRASSEN, R. (2006) Checklist of the Thysanoptera (Insecta) of southern Africa. *African Entomology* 14(1): 63-68.

ANNEXURE I

Historical Background of Macadamia (Proteaceae)

In 1828, Allan Cunningham (1791-1839) (Fig. AI.1), an English botanist and explorer in the employ of Kew Gardens, was the first European to collect macadamias in Australia (Gregory 1987). He took part in many botanical explorations including numerous trips to Australia. Cunningham's collections of botanical specimens were housed at Kew Gardens and later at the British Museum. Unfortunately, he did not formally describe and name *Macadamia* (Gregory 1987, Hardner *et al.* 2009).

Baron Sir Ferdinand von Mueller KCMG (1825-1896) (Fig. AI.2), a German-Australian physician, geographer and renowned botanist, was appointed as Royal Botanist, Melbourne, Australia in 1853. He explored and collected the flora of Australia and established the National Herbarium of Victoria. In 1857, he and Walter Hill, the Director of the Botanic Gardens, Brisbane, conducted a botanical exploration of the forests along the Pine River in Moreton Bay, southern Queensland, during which specimens of macadamia nuts were collected. Thus, in 1857 von Mueller formally described *Macadamia*, naming it in honour of his colleague, John Macadam, Secretary of the Philosophical Institute of Victoria, as a new genus in the plant family Proteaceae, and the species, *Macadamia ternifolia* F. Muell. (Gregory 1987, Hardner *et al.* 2009).

Figure AI.1 Allan Cunningham (1791-1983) English botanist and explorer (Photo Source: http://www.historyservices.com.au)

Figure AI.2 Presidential portrait of Baron Ferdinand von Mueller, Royal Society of Victoria, Australia (Photo Source: Encyclopaedia of Australian Science)

According to Smith (1956 in Hardner *et al.* 2009), von Meuller's type specimen included material from both *M. ternifolia* and what was subsequently classified in 1897 as *Macadamia integrifolia* (Maiden and Betche 1897), which led to confusion for a number of years. This uncertainty regarding the species was compounded by the inclusion of *Macadamia tetraphylla* L.A.S. Johnson which, until 1954, was grouped with either *M. integrifolia* or *M. ternifolia* based on its spinose leaf margins, the major characteristic for identifying *Macadamia* species at that time (Smith 1956 in Hardner *et al.* 2009). In 1954 *M. tetraphylla* was recognised as a separate species, and by 1956 *Macadamia* species were resolved into three of the taxa cultivated today (Hardner *et al.* 2009). *Macadamia jansenii* C.L. Gross et P.H. Weston, an uncultivated species closely related to *M. integrifolia*, *M. tetraphylla* and *M. ternifolia* was more recently discovered by Ray Jansen (Gross and Weston 1992 in Hardner *et al.* 2009).

Genetic sequencing of germplasm shows *M. integrifolia* and *M. tetraphylla* to be sister species, with *M. ternifolia* more closely related to these two species than to *M. jansenii*, the genetic outlier of the four species (Peace *et al.* 2002 in Hardner et al. 2009, Waldron *et al.* 2002 in Hardner *et al.* 2009, Peace 2005 in Hardner *et al.* 2009).

1. Early Cultivation of Macadamias

First grown commercially in Hawaii (McConachie 1980, Gregory 1987, Moncur 1988, Wagner-Wright 1995 in Hardner *et al.* 2009), macadamias are currently produced in tropical and subtropical regions in Asia (China and Thailand), Australiasia (Australia and New Zealand), Africa (Kenya, Malawi and South Africa), North America (USA), and South America (Brazil, Guatemala and Costa Rica) (Piza *et al.* 2006 in Hardner *et al.* 2009, Trueman 2013). The research and improvement of germplasm in Hawaii, and the development of Hawaiian cultivars, has been vital in the worldwide commercialisation of macadamias (Hamilton and Storey 1956 in Hardner *et al.* 2009, Shigeura and Ooka 1984 in Hardner *et al.* 2009, Hamilton and Ito 1986, Nagao and Hirae 1992 in Trueman 2013, Wagner-Wright 1995 in Hardner *et al.* 2009). It is on this foundation, established by the Hawaiian pioneers, that much of the current world production is based (Hamilton and Fukunaga 1970 in Wiid-Hobson 2003, Allan 1989 in Hardner *et al.* 2009, Ito and Hamilton 1989 in Hardner *et al.* 2009, Stephenson 1990 in Hardner *et al.* 2009, Peace *et al.* 2005 in Hardner *et al.* 2009, Tay 2006 in Hardner *et al.* 2009).

The historical sequence by which countries imported macadamia seed and/or first established orchards is shown in chronological order below. This was compiled using historical literature available to the author, and is by no means an all-inclusive review of every country producing macadamias.

1.1 Hawaii, United States of America

There is some ambiguity as to exactly when macadamias were introduced to Hawaii and where the first plantings took place. In a recent publication by Hardner (2015) some of these queries have been addressed, and after an extensive historical literature and review, the author has been able to clarify some of these questions. The remaining uncertainties will probably remain a mystery as Hardner's review was extremely thorough and extensive.

Macadamia was first introduced to Hawaii between 1881 and 1885 from Australia by William Herbert Purvis (Hamilton and Storey 1956 in Hardner *et al.* 2009, Hamilton and Fukunaga 1959 in Hardner *et al.* 2009, Shigeura and Ooka 1984 in Hardner *et al.* 2009, Wagner-Wright 1995 in Hardner *et al.* 2009), a plant collector and investor in a sugar plantation, Pacific Sugar Mill, in Kapulena. For many years these trees were only used as windbreaks and ornamental plants (Gregory 1987). A further introduction in 1892 was made by a group of botanists who had returned from studying native plants in Australia (McConachie 1980, Gregory 1987). These *M. tetraphylla* seeds were included in reforestation plantings on the slopes of Mt. Tantalus above Honolulu, on land which later formed part of the Hawaii Agricultural Experiment Station (HAES) established in 1900. It is thought that most of the early experimental work was conducted on these trees and their progeny (McConachie 1980). Other notable introductions include that by Captain R.A. Jordan in 1892, First Mate of a sailing vessel which berthed in Brisbane. He visited friends at Pimpama, south of Brisbane, and was given "half a sugar bag" of nuts, which he took back to Hawaii; these nuts were from *M. integrifolia* trees (McConachie 1980) and produced six trees (Wagner-Wright 1995 in Hardner *et al.* 2009), which are considered to be the principal source from which the first Hawaiian commercial cultivars derive (Storey 1965 in Hardner *et al.* 2009).

The potential of macadamias as a crop was first considered in 1910, and by 1912 HAES began distributing seedlings for commercial plantings (Wagner-Wright 1995 in Hardner *et al.* 2009). In 1916 the first really significant plantings were made by the Honokaa Sugar Company on the island of Hawaii as part of a reforestation programme. As the potential of macadamias was realised, the trees received more attention and were eventually established as an orchard. More land was acquired and plantings made, and the Honokaa Sugar Company became a major grower in Hawaii (McConachie 1980) until 1940, when a processing factory was established and Honokaa Sugar Company became the largest grower in the world for the next thirty years (McConachie 1980).

In 1918-1919 the coffee industry was assisted in a diversification programme and macadamia trees were distributed by the HAES. By 1932, 432 acres of macadamias had been planted, but still very little known was known about best practice, yields were poor and production low (McConachie 1980).

One of the primary problems was that vegetative propagation of macadamia did not appear possible, they were considered “ungraftable”. In 1927 HAES employed two high school pupils for vacation work; William B. Storey and Ralph H. Moltzau, both of whom would later make major contributions to the development of the macadamia industry. Dr Willis T. Pope brought in a branch that wind had broken on a tree three weeks prior, but the branch had still remained attached to the tree. Ralph Moltzau was asked to take scions from this branch and graft these onto seedlings in pots, which he only did two days later. Some weeks afterwards, he went to check on the seedlings and found that two of the grafts had taken and started to grow. This was a breakthrough in the vegetative propagation of macadamias, but unfortunately the significance of the broken branch was lost, and in the years following only very few grafts were successful.

The Scion Selection Program was initiated by HAES between 1934 and 1936. The grafting technique was modified in 1936; scion wood was cinctured (girdled) and thus grafting became a reliable means of vegetative propagation (McConachie 1980). With this development, the variability in seedling material was reduced and preferential traits within the genetic composition could be specifically bred (Jones and Beaumont 1937 in Hardner *et al.* 2009, Shigeura and Ooka 1984 in Hardner *et al.* 2009). This was a major breakthrough in the history of cultivating macadamia (Hamilton and Fukunaga 1973 in Hardner *et al.* 2009, McConachie 1980, Shigeura and Ooka 1984 in Hardner *et al.* 2009, Wagner-Wright 1995 in Hardner *et al.* 2009).

In 1848 HAES established a 400 ha. orchard near Hilo, using the newly developed superior cultivars, from which time a major expansion of macadamia cultivation occurred (Gregory 1987). Importation of nuts from Australia to Hawaii continued until around 1936, and selections of scion wood for grafting trials were made in 1954 (McConachie 1980). Most countries growing macadamia commercially today have planted Hawaiian cultivars (Hardner *et al.* 2009).

The selection of suitable trees was made for commercial propagation and, between 1937 and 1939, 60 000 seedling trees were assessed. As a result 62 selections were made and scions were grafted on seedling trees and planted in four test orchards. During the 1940s Dr Storey began evaluating these and other trees, and in 1947 he awarded varietal status to the cultivars that produced large quantities of high quality nuts (Allan 1972, McConachie 1980). The first five Hawaiian cultivars were released in 1948 from the selection program. Similar programs have been conducted subsequently, with many new cultivars recommended and some previously selected cultivars rejected due to unfavourable traits (Hardner *et al.* 2009). These early Hawaiian cultivars are commonly referred to by their HAES numbers followed by their name in brackets, (e.g. 246 (Keauhou)) (McConachie 1980, Wiid-Hobson 2003b).

The first successful importation of Australian germplasm in 1949 was by the University of Hawaii. Although the material was from a highly productive clone, it was *M. tetraphylla* and not productive under Hawaiian conditions. Further introductions were made in the 1940s and 1950s (Hamilton and Fukunaga 1962 in Hardner *et al.* 2009).

Between the 1930s and 1940s major advances were made in processing macadamias. John C. Ripperton, chief chemist, and his colleagues at HAES were instrumental in determining the conditions required to process macadamias and worked out the specifications to design and construct processing equipment. Mr Frank Anderson together with Ripperton later devised and built processing equipment which incorporated an automatic packing line (McConachie 1980).

Hawaii was placed fourth in the estimated 2014/2015 world macadamia production and export of both nut-in-shell (NIS) and on a kernel production basis (Tables 2.1 and 2.2) (Anon. 2014, Henning 2014).

1.2 Australia

Even though macadamia is indigenous to Australia, it was not until 1882 that the first orchard was planted on three acres at Rous Mill near Lismore in New South Wales by Charles Staff (McConachie 1980, Gregory 1987). He planted seeds collected from wild *M. tetraphylla*. By 1900 five small *M. tetraphylla* orchards had been established in New South Wales; the first orchard in Queensland was only established in 1910 and consisted of thirty *M. tetraphylla* trees (McConachie 1980). During the 1920s and 1930s significant orchards were planted both in New South Wales and Queensland. However, during the 1940s and 1950s the cultivation of macadamia went through a major decline; of the approximately 900 acres planted over sixty years, only about 100 acres remained. This was in part due to the lack of knowledge of tree requirements and culture, the variability of seedlings, bush fires, damage by insect pests and difficulties in cracking and processing the nuts (McConachie

1980). Unable to crack the shells cleanly, without damaging the kernel, had the effect of restricting marketing and future plantings. Over the next couple of decades several experimental crackers (of local and international design), were tested without much success, and only in about 1950 was it established that by drying the nuts in the shells to full dehydration, a higher kernel recovery rate was achieved (McConachie 1980).

In 1962 the Colonial Sugar Refining Company Limited (later CSR Limited), one of Australia's oldest and largest public companies, conducted a feasibility survey to investigate developing the macadamia industry on a large scale in Australia. In 1963 the CSR-driven macadamia pilot project of 220 hectares was established at Maleny, Baffle Creek and Mt. Bauple. CSR Limited was also a driving force in developing research techniques used for subsequent commercial plantings, building new processing factories and developing manufacturing techniques (McConachie 1980).

Attempts at clonal grafting were unsuccessful until the mid-1950s (Leigh 1968, Leverington 1971 in Hardner *et al.* 2009, McConachie 1980). Australian orchards were established using seedling material until the mid-1960s (Wills 1961 in Hardner *et al.* 2009, Leverington 1962, 1971 in Hardner *et al.* 2009). Prior to the 1980s there were no reliable data for cultivar utilization specifically for Australian conditions; the Australian industry was therefore primarily based on Hawaiian cultivars (Hardner *et al.* 2009). In 1984-1985 a series of cultivar trials were established to gather data on cultivar performance under Australian conditions (Winks *et al.* 1987, Stephenson *et al.* 1995 in Hardner *et al.* 2009, Stephenson *et al.* 1999 in Hardner *et al.* 2009, Stephenson and Gallagher 2000 in Trueman 2013, Hardner *et al.* 2009, Mayer *et al.* 2006 in Hardner *et al.* 2009). Further trials were conducted in 1992, 1995 and 1996 (Stephenson 2001 in Hardner *et al.* 2009). Several reports of Hawaiian cultivars not performing as well as expected regarding yield and kernel quality were published (Cull 1978 in Hardner *et al.* 2009, Winks 1983 in Hardner *et al.* 2009, Hamilton and Ito 1986, Trochoulias and Burnside 1987, Stephenson 1990 in Hardner *et al.* 2009).

The cultivation and production of macadamia has steadily increased since the 1960s and Australia was the world's leading macadamia producing country for many years. Australia was ranked second in the estimated 2014/2015 world macadamia production and export of both nut-in-shell (NIS) and on a kernel production basis (Tables 2.1 and 2.2) (Anon. 2014, Henning 2014).

1.3 California, United States of America

The origins of the cultivars grown in California are relatively obscure. Amongst the first macadamias to be planted were those at the University of California, Berkeley, in the 1870s (McConachie, 1980). *Macadamia integrifolia* was introduced in about 1879, followed by further introductions and the arrival of *M. tetraphylla* in the 1880s or 1890s (Storey 1957, 1965 in Hardner *et al.* 2009, Ferguson and Arpaia 1990 in Hardner *et al.* 2009) and some early Australian selections in the 1960s (Storey and Frolich 1964).

California was looking in to new "replacement" horticultural crops as *Persea cinnamon* fungus and avocado root rot had decimated the avocado groves (Hobson 1972, Cooper 1980, McConachie 1980). The University of California conducted a study to see whether it would be feasible to cultivate macadamia as a replacement tree crop to avocados. The existing macadamia seedling trees were used to gather information on growth and cropping, and the first commercial orchard was established in 1946, when just over two hundred *M. tetraphylla* seedlings were planted (McConachie 1980). Yet it was only after the end of World War II that an awareness of macadamia nuts spread as many United States servicemen had passed through or been based in Hawaii and were introduced to the taste of macadamias. This brought about a response by farmers to look at growing macadamia as a commercial crop; *Macadamia tetraphylla* cultivars are the preferred choice of the Hawaiian varieties in California as they performed better in cooler climes (Cavaletto 1983 in Hardner *et al.* 2009). A number of cultivars have been developed in California. Although it will probably not become one of the major crops grown in California, macadamias have allowed growers to diversify their operations.

1.4 New Zealand

Introduction of macadamia was made in the 1890s and since then more cultivars were introduced in the 1970s (Richardson and Dawson 1991 in Hardner *et al.* 2009). Several varietal selections have been developed in New Zealand (Hardner *et al.* 2009). Cultivars are mainly derived from hybrid selections from Australia, and to a lesser extent from Hawaii (Gordon 1987, Richardson and Dawson 1991 in Hardner *et al.* 2009, Warren 2003).

1.5 Malawi

The first introduction of *M. integrifolia* nuts to Malawi was in 1930 from Queensland, Australia, by a private gardener. From these nuts, twenty-four trees were planted out at Bvumbwe Research Station and seedlings were distributed to three regions in Malawi. These plantings were neglected and no proper records were kept (Spurling and Spurling

1972). A second importation was made from South Africa in 1954, this time of *M. tetraphylla* seed. Again seedlings were raised and distributed but no data were recorded (Spurling and Spurling 1972).

In 1967, the director of a leading Convent Garden fruit and vegetable importing company in London saw the remaining *M. integrifolia* trees at Bvumbwe Research Station and initiated the commercial cultivation of macadamias in Malawi for export to the United Kingdom (Spurling and Spurling 1972). In 1968 plantings of approximately 650 *M. tetraphylla* seedlings were made at government plots and estates in numerous regions. *Macadamia integrifolia* seedlings derived from the original Australian maternal trees were planted out, mainly on tea estates, in 1968 and 1969 (Spurling and Spurling 1972).

1.6 South Africa

The historical background to the cultivation of macadamia in South Africa is presented in Chapter 2.4.

1.7 Brazil

Macadamias were introduced to Brazil in 1935 but the first commercial orchard was only established in the late 1970s. A series of selections have been developed in Brazil (Ojima *et al.* 1976 in Hardner *et al.* 2009, Barbosa *et al.* 1991 in Hardner *et al.* 2009), but no details are reported with regards to parentage (Hardner *et al.* 2009). In the 1990s Hawaiian cultivars dominated Brazilian macadamia plantings (Sacramento *et al.* 1995 in Hardner *et al.* 2009).

1.8 Kenya

In 1946 *M. tetraphylla* seeds were imported from Australia and planted in the Thika District, central Kenya. Further introductions of seeds were made in 1964 from Australia, California and Hawaii (Harries 2004 in Gitonga 2010). Prior to 1973 all plantings were made using seedling material (Gathungu and Likimani 1975 in Hardner *et al.* 2009). In 1971 the Kenyans initiated their own selection breeding program using superior performing trees for grafting material (Hardner *et al.* 2009, Gitonga 2010); *M. tetraphylla* and hybrid selections were grown (Gathungu and Likimani 1975 in Hardner *et al.* 2009). Several cultivars have been developed in Kenya since the late 1980s (Gitonga 2010).

Kenya was placed third in the estimated 2014/2015 world macadamia production and export of both nut-in-shell (NIS) and on a kernel production basis (Tables 2.1 and 2.2) (Anon. 2014, Henning 2014).

1.9 Thailand

Macadamia integrifolia seeds were first introduced to Thailand in 1953. In 1955 seedlings were planted at Fang, and in 1957 at Doi Muser. The Horticultural Experiment Station situated at Fang grafted several Hawaiian cultivars in 1968 (Supamatee *et al.* 1992). Several selections have been recorded from Thailand (Steiger *et al.* 2003 in Trueman 2013).

1.10 China

A range of Hawaiian and Australian cultivars were introduced to China in the 1970s (Xiao *et al.* 2002a in Hardner *et al.* 2009), and in the 1980s orchards were established in the coastal Provinces of Guanxi, Ueng Nang, Sichuan, Hainan and Fujien, however these were affected by severe cyclone damage (Lu *et al.* 1998, Xiao *et al.* 2002a, 2002b in Hardner *et al.* 2009). Since 1997 new plantings were established in Ueng Nang and Sichuan Provinces, although these regions have cool temperatures and high rainfall which may affect macadamia productivity (Xiao *et al.* 2002b in Hardner *et al.* 2009).

A breeding project has been established in the Panxi region, Sichuan Province, with particular attention to using *M. tetraphylla* germplasm for cold resistance (Xiao *et al.* 2002b in Hardner *et al.* 2009). Three cultivars, Hinde, Own Choice and Beaumont, are reported to be tolerant of the cooler temperatures and wind in the Panxi region, producing good yields (Xiao *et al.* 2002a, 2002b in Hardner *et al.* 2009, Zheng and Zhang 2002 in Hardner *et al.* 2009).

1.11 Israel

It is not clear as to when macadamias were first cultivated in Israel, but seeds were introduced from Hawaii in 1996 (Kadman and Slor 1982 in Hardner *et al.* 2009), and later from California (Aradhya *et al.* 1998 in Hardner *et al.* 2009). Israel has produced a number of cultivars from their selection program.

2. The Pioneers

The history of macadamia cultivation, its origin and subsequent distribution, has been quite fascinating. There were, and still are, those pioneers in the industry, who dedicated themselves to promoting, improving and developing which is now a much sought-after, profitable commodity. Most of the initial progress, development and research was not government-driven, but initiated by the private sector. Over the decades governments have become more involved with research being undertaken at agricultural research stations and Universities. A number of countries based their initial plantings on Hawaiian and Australian cultivars, but have now established their own breeding programmes, developing their own cultivars and varieties better suited to the growing conditions in their areas. With the advancement in technology and collaborations between countries, research on macadamias has escalated, facing new challenges and obstacles, but with the demand for this commodity far outweighing supply, the new pioneers will have to lead the way forward in making tomorrows history.

ANNEXURE II

Testing Kernel Maturity

Histograms Depicting Mature Kernel of Husks With and Without Thrips Damage and the 20-Nut Picked Sample as a Percentage for Each Study Site Over Both Growing Seasons.

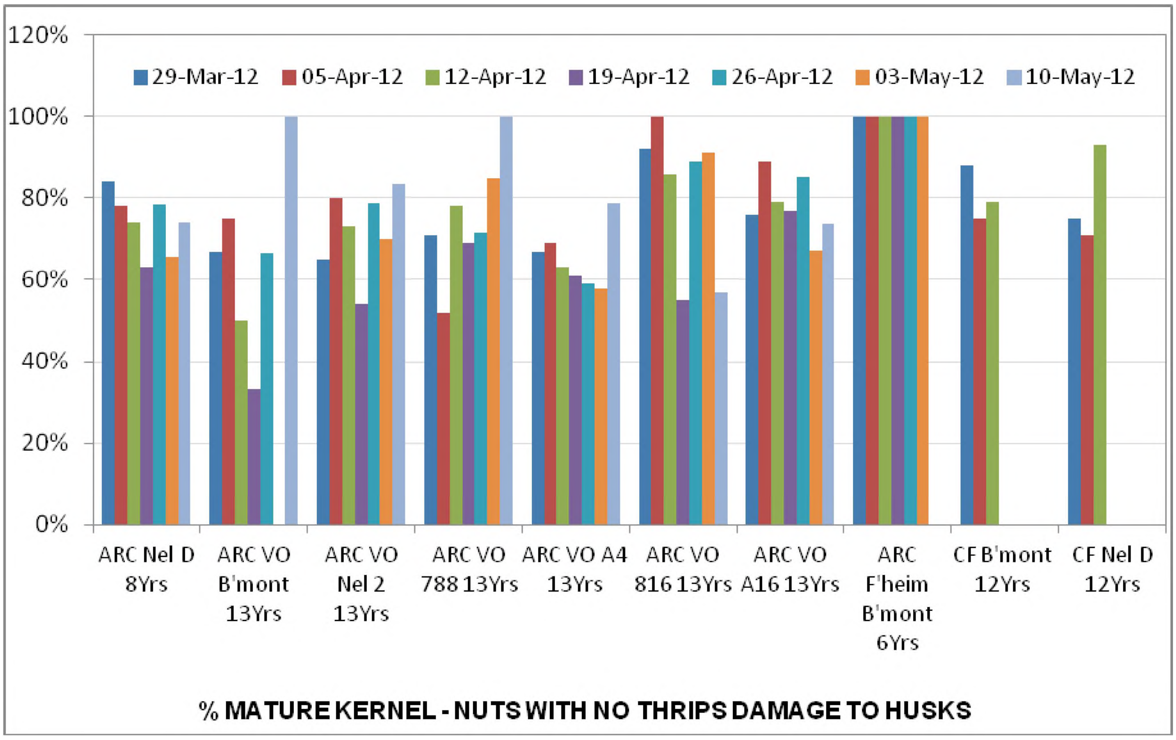


Figure AII (i) 2011/2012 Percentage of mature, abscised nuts with no thrips damage to the husks over a period of seven weeks prior to harvest.

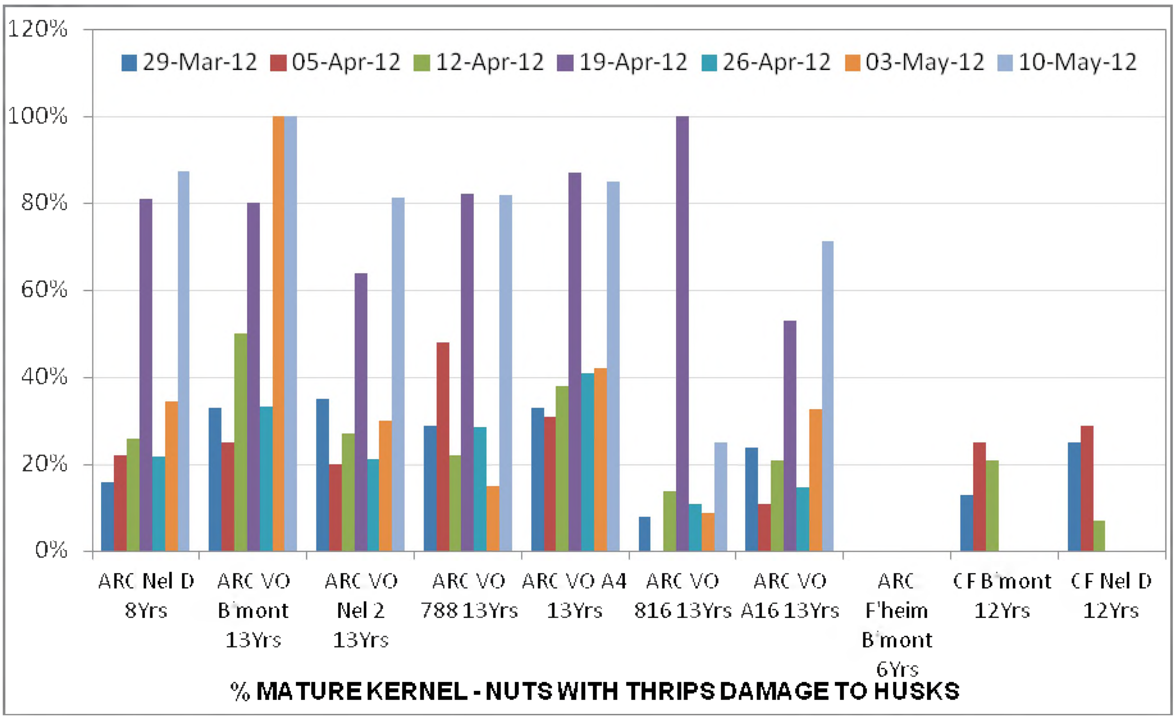


Figure AII (ii) 2011/2012 Percentage of mature, abscised nuts with thrips damage to the husks over a period of seven weeks prior to harvest.

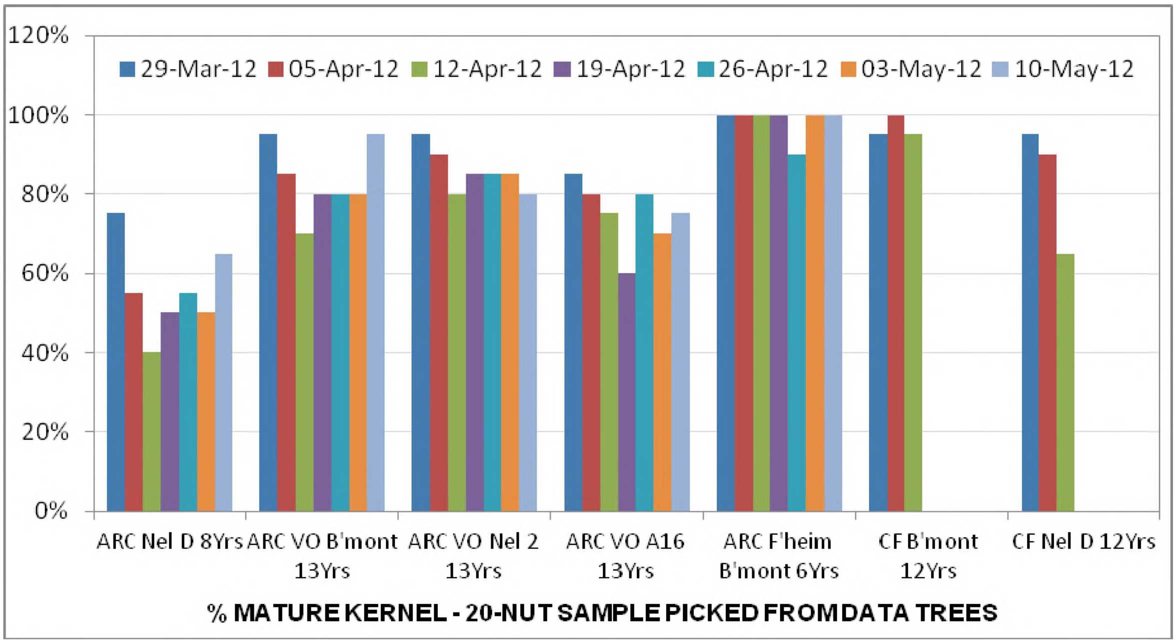


Figure AII (iii) 2011/2012 Percentage of mature nuts from the 20-nut sample picked from the data trees over a period of seven weeks prior to harvest.

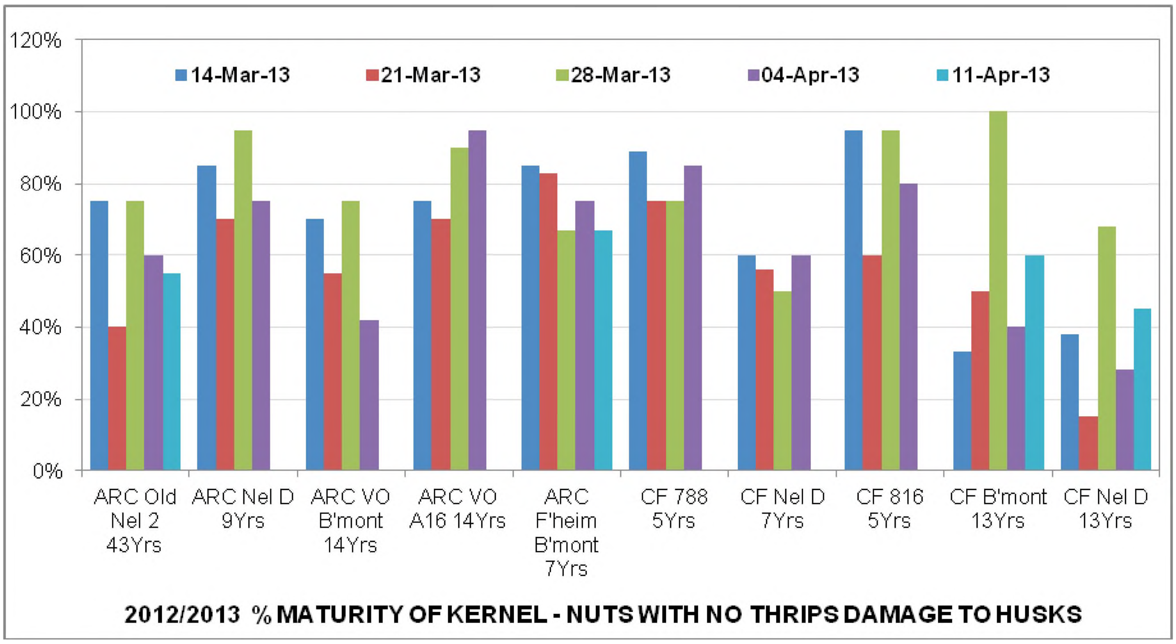


Figure AII (iv) 2012/2013 Percentage of mature, abscised nuts with no thrips damage to the husks trees over a period of five weeks prior to harvest.

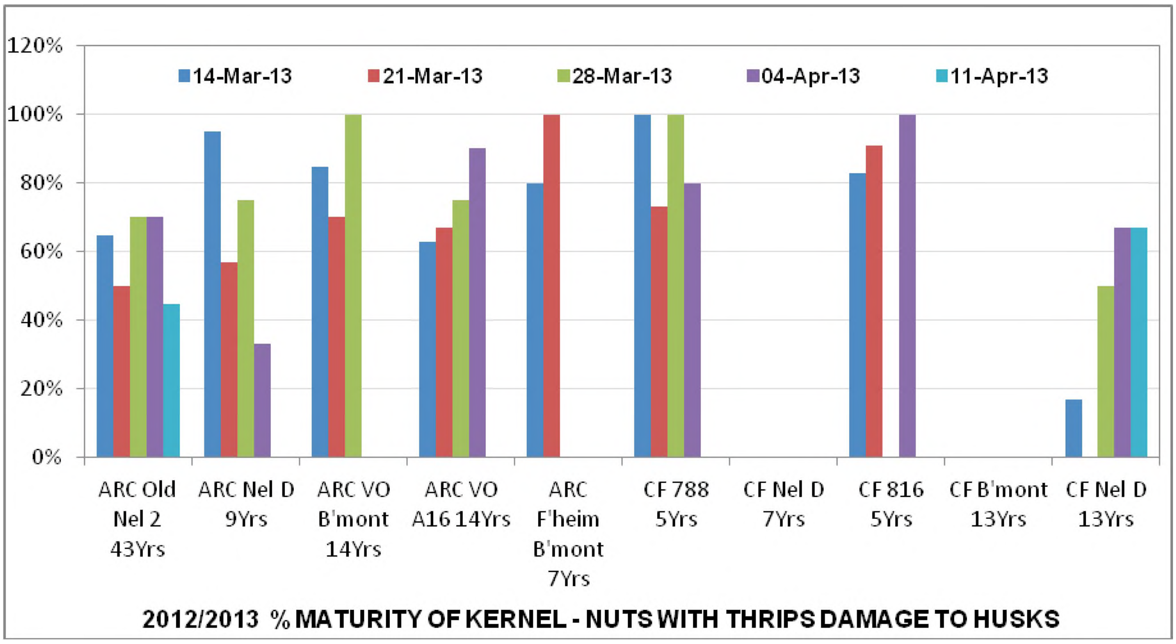


Figure AII (v) 2012/2013 Percentage of mature, abscised nuts with thrips damage to the husks trees over a period of five weeks prior to harvest.

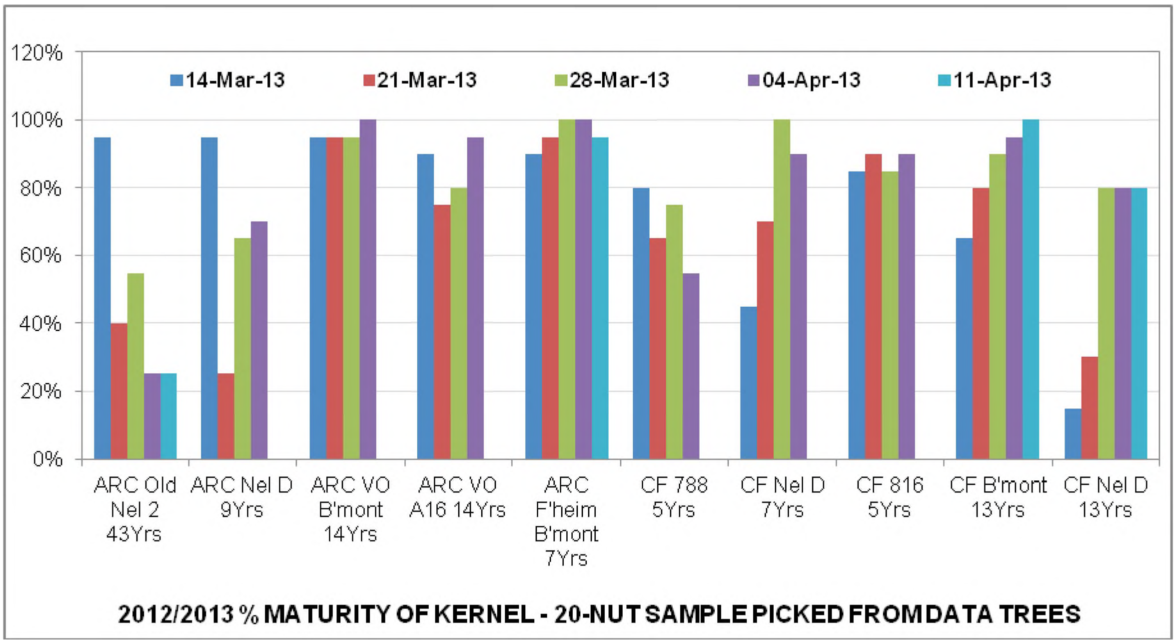


Figure AII (vi) 2012/2013 Percentage of mature nuts from the 20-nut sample picked from the data trees over a period of five weeks prior to harvest.