

**Faculty of Science and Engineering
School of Molecular and Life Sciences**

**Management of the broad-acre pest mite *Balaustium medicagoense* in
the high rainfall areas of southern Western Australia**

Svetlana Micic

**This thesis is presented for the Degree of
Master of Philosophy (Environment and Agriculture)
of
Curtin University**

July 2019

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: _____

Date: _____

Abstract

Balaustium medicagoense is an invertebrate pest that causes damage to cereals, canola and lupin crops – particularly at, or shortly after, germination. This study provides an improved understanding of the conditions under which this mite causes crop damage. The study has demonstrated that *B. medicagoense* was not found in paddocks without green plant material being present and the main precursor for high numbers of *B. medicagoense* was the presence of plant hosts between cropping seasons. Other factors that influenced abundance of the mite in germinating crops include the previous year's crop.

There have been suggestions from the farming community that the chemical control of other pest species such as *Halotydeus destructor* and *Penthaleus* spp. (collectively known as earth mites) has led to increases in *B. medicagoense* populations. However, *B. medicagoense* populations did not increase in the absence of earth mites, and the insecticides registered for the control of earth mites were shown to be non-efficacious against *B. medicagoense*.

Economic crop damage, assessed as seedling losses during crop establishment, was not found in any trials conducted. However, if economic crop damage was to occur, reliance on pesticides to control this mite is not sustainable with current available agricultural chemicals. There is only one chemical group, the synthetic pyrethroids, that is registered in broad-acre cropping that has efficacy against *B. medicagoense*. Long and sustained use of a single chemical group for the control of this mite is likely to lead to it developing pesticide resistance.

Integrated strategies for the management of *B. medicagoense* need to recommend insecticides are used judiciously. These strategies need to encompass the control of plant hosts prior to planting and planting crops such as canola that are susceptible to damage after a weed-free crop.

Contents

Declaration	ii
List of Figures	vii
List of Tables	ix
List of Appendices	x
Acknowledgements	xi
1 General introduction	1
1.1 Thesis aims	3
2 Review of literature on <i>Balaustium medicagoense</i> (Meyer and Ryke) (Acari: Erythraeidae)	4
2.1 Overview of the phylogenetic relationships of the Superfamily Erythraeoidea and the genus <i>Balaustium</i>	4
2.1.1 Phylogenetic relationships within the Acari	4
2.1.2 Phylogeny of Erythraeoidea	5
2.2 Phylogeny and adaptations of Parasitengona to xeric environments	6
2.3 Confused taxonomic history of the genus <i>Balaustium</i>	6
2.4 Distribution of the genus <i>Balaustium</i> in Australia.....	7
2.5 Feeding behaviour of mites in the genus <i>Balaustium</i>	7
2.5.1 Feeding damage in crops	9
2.6 Life history of mites in the genus <i>Balaustium</i>	9
2.6.1 Mode of reproduction	9
2.6.2 Life-cycle.....	9
2.6.3 Diapause	10
2.7 Possible management of <i>Balaustium medicagoense</i>	10
2.8 Conclusion	13
3 Host plants of and crop damage by <i>Balaustium medicagoense</i>	16
3.1 Introduction	16
3.1.1 Aims	18
3.2 Materials and methods.....	18
3.2.1 Compilations of Pestfax reports.....	18
3.2.2 Field plant host surveys	19
3.2.2.1 Sampling crops	19
3.2.2.2 Sampling middle storey and lower storey.....	19
3.2.2.3 Sampling of ground covers.....	20
3.2.2.4 Data analysis.....	20
3.3 Results	20
3.3.1.1 Distribution and frequency of <i>Balaustium medicagoense</i> crop damage from ‘Pestfax’	20
3.3.1.2 Crop damage and moisture stress	22
3.3.1.3 Mite numbers per plant requiring control	23
3.3.1.4 Correlation between ‘Pestfax’ and occurrences in the field	23
3.3.2 Plant host survey.....	23
3.3.2.1 Field survey of abundance of <i>Balaustium medicagoense</i> and earth mites in crops	24
3.3.2.2 Abundance of <i>Balaustium medicagoense</i> and earth mites in relation to sampling distance from the crop edge	24
3.3.2.3 Abundance of <i>Balaustium medicagoense</i> in remnant native vegetation	25
3.4 Discussion.....	26
3.4.1 Crop damage.....	26
3.4.1.1 Crop damage and moisture stress	26
3.4.1.2 Environmental conditions and <i>Balaustium</i> life stage	27

3.4.2	Potential thresholds.....	27
3.4.2.1	Differences in feeding damage between <i>Balaustium medicagoense</i> and earth mites..	28
3.4.3	Plant hosts.....	28
3.4.3.1	Crop hosts and distribution in the paddock ..	28
3.4.3.2	Native hosts	29
3.4.3.3	Introduced plant species	29
3.5	Conclusion.....	30
4	The effect of plant-host associations and competition on <i>Balaustium medicagoense</i> numbers.....	31
4.1	Introduction	31
4.1.1	Pest status of <i>Balaustium medicagoense</i>	31
4.1.2	The need for alternative control measures to pesticides	31
4.1.3	Effect of competition on <i>Balaustium medicagoense</i> populations.....	33
4.1.4	Aims	33
4.2	Materials and methods.....	34
4.2.1	Experiment set up	34
4.2.1.1	First year.....	34
4.2.1.2	Years 2 and 3	36
4.2.2	Scoring plant damage	36
4.2.3	Assessment of pasture composition.....	37
4.2.4	Assessment of abundance of non-crop plants.....	37
4.2.5	Harvest.....	37
4.2.6	Mite sampling	37
4.2.7	Data analysis.....	37
4.3	Results	38
4.3.1	Seasonal abundance patterns	38
4.3.2	Reproductive output of <i>Balaustium medicagoense</i> on different crop types	42
4.3.3	Crop damage.....	42
4.3.4	Competition effects on <i>Balaustium medicagoense</i>	43
4.3.4.1	Reproductive output of <i>Balaustium medicagoense</i> regressed against numbers of adult <i>Balaustium medicagoense</i>	44
4.3.4.2	Reproductive output of <i>Balaustium medicagoense</i> regressed against numbers of adult earth mites.....	47
4.4	Discussion.....	48
4.4.1	Green-bridge and abundance of <i>Balaustium medicagoense</i>	48
4.4.1.1	Potential diapause	48
4.4.1.2	Effect of controlling a green-bridge	48
4.4.2	Effect of plant hosts on persistence and reproduction of <i>Balaustium medicagoense</i> ..	49
4.4.3	Potential thresholds for <i>Balaustium medicagoense</i>	49
4.4.4	Competition niche theory	50
4.4.4.1	Inter-specific competition.....	50
4.4.4.2	Intra-specific competition.....	52
4.5	Conclusion.....	52
5	Chemical efficacy and effects of cropping rotations for control of <i>Balaustium medicagoense</i>	53
5.1	Introduction	53
5.1.1	Aims	55
5.2	Materials and methods.....	55
5.2.1	Field efficacy experiments.....	56
5.2.1.1	Chemical efficacy experiment 1	56
5.2.1.2	Chemical efficacy experiment 2	57
5.2.2	Farming systems experiments.....	58
5.2.2.1	Experiment 1: Effect of prophylactic sprays and stubble retention on <i>Balaustium medicagoense</i>	58
5.2.2.1.1	First year.....	58

5.2.2.1.1.1	Experiment design.....	58
5.2.2.1.1.2	Crop establishment and harvest details	59
5.2.2.1.1.3	Mite sampling technique	59
5.2.2.1.2	Second year.....	59
5.2.2.1.2.1	Experiment design.....	59
5.2.2.1.2.2	Crop establishment and harvest details	60
5.2.2.1.2.3	Pitfall trap sampling	60
5.2.2.1.2.4	Plant counts and mite feeding damage assessments.....	61
5.2.2.1.3	Data analysis.....	61
5.2.2.2	Experiment 2: Timing of herbicide and prophylactic insecticide applications.....	61
5.2.2.2.1	Experiment design	61
5.2.2.2.2	Suction sampling	62
5.2.2.2.3	Plant counts.....	62
5.2.2.2.4	Data analysis.....	62
5.2.2.3	Experiment 3: Effects of cropping rotations on <i>Balaustium medicagoense</i> numbers .	62
5.2.2.3.1	Experiment design	62
5.2.2.3.2	Suction sampling	63
5.2.2.3.3	Plant counts and mite feeding damage assessments	63
5.2.2.3.4	Data analysis.....	64
5.3	Results	64
5.3.1	Field efficacy experiments.....	64
5.3.1.1	Chemical efficacy experiment 1	64
5.3.1.2	Chemical efficacy experiment 2	64
5.3.2	Farming systems experiments.....	65
5.3.2.1	Experiment 1: Effect of prophylactic sprays versus stubble retention on <i>Balaustium medicagoense</i>	65
5.3.2.1.1	Efficacy of pitfall trap catches versus suction sampling methods	65
5.3.2.1.2	Effect of treatments on numbers of <i>Balaustium medicagoense</i>	66
5.3.2.1.3	Mite feeding damage on canola seedlings	67
5.3.2.2	Experiment 2: Effect of weed control and insecticide spray applications	68
5.3.2.2.1	Weed control.....	68
5.3.2.2.2	Prophylactic insecticide applications.....	69
5.3.2.2.3	Interactions of prophylactic insecticide applications and weed control	69
5.3.2.2.4	Pitfall trap catches versus suction sampling	70
5.3.2.3	Experiment 3: Effect of different cropping rotations on <i>Balaustium medicagoense</i> numbers	70
5.3.2.3.1	Crops and <i>Balaustium medicagoense</i> numbers	70
5.3.2.3.2	Mite damage to crops	71
5.3.2.3.3	Plant densities.....	72
5.4	Discussion.....	73
5.4.1	Effect of insecticide applications on <i>Balaustium medicagoense</i> populations	73
5.4.1.1	Insecticide efficacy	73
5.4.1.2	Efficacy of insecticides in the presence of stubble retention.....	76
5.4.1.3	Efficacy of insecticidal seed dressings	77
5.4.2	Effect of weed control on <i>Balaustium medicagoense</i> populations	77
5.4.3	Impact of cropping rotations on <i>Balaustium medicagoense</i> populations	78
5.4.4	Damage thresholds for <i>Balaustium medicagoense</i>	79
5.5	Conclusions	79
6	Recommendations for an integrated approach for the control of <i>Balaustium medicagoense</i>	81
6.1	Introduction	81
6.2	Concluding remarks.....	89
7	References	91

List of Figures

Figure 1:	<i>Balaustium medicagoense</i> (scale bar 1 mm).	1
Figure 2:	<i>Halotydeus destructor</i> (left) and <i>Penthaleus</i> spp. (right) (scale bar 1 mm).	1
Figure 3:	Hypothesized relationships of higher mite taxa based on morphology.	4
Figure 4:	Hypothesized relationships of cohorts in the assemblage (suborder) Trombidiformes.	5
Figure 5:	Damage to lupin cotyledon by <i>Balaustium medicagoense</i>	16
Figure 6:	Damage to canola by <i>Balaustium medicagoense</i> . Note cupped cotyledons.	16
Figure 7:	Mite feeding damage to cereals.	17
Figure 8:	Distribution of <i>Balaustium medicagoense</i> (1996 to 2010) in Western Australia, showing mean rainfall isohyets. Individual data points represent observations (n = 135) of <i>Balaustium medicagoense</i> reported via ‘Pestfax’	21
Figure 9:	Time of year of Pestfax reports from 2006-2010 in relation to actual numbers of mites observed in surveys in 2010.	23
Figure 10:	Mean number (+SED) of <i>Balaustium medicagoense</i> and earth mites on different crops over all sample times.	24
Figure 11:	Mean number of <i>Balaustium medicagoense</i> and earth mites at set distances (metres) from the crop edge on different crop types.	25
Figure 12:	Experimental design of field enclosure experiment.	35
Figure 13:	Total monthly rainfall (mm) and mean soil temperature with maximum and minimum range for the month, from Esperance Downs Research Station during 2006 - 2008.	39
Figure 14:	Mean number (\pm SE) of <i>Balaustium medicagoense</i> found on irrigated pasture, irrigated summer weeds followed by barley and a conventional* barley crop. .	40
Figure 15:	Mean number of <i>Balaustium medicagoense</i> (\pm SE) on canola, lupins and barley. 40	
Figure 16:	Floristic composition of pasture in 2007 and 2008.	41
Figure 17:	Average number of plants per square metre within plots and percentage of weeds present in each plot.	41
Figure 18:	Reproductive output of <i>Balaustium medicagoense</i> (\pm SE) on different crops over 2007 and 2008.	42
Figure 19:	Average plant damage (\pm SE) caused by mite feeding at the seedling stage of crops in 2007 and 2008.	43
Figure 20:	Multiple linear regression for reproductive output (R_o) of <i>Balaustium</i> <i>medicagoense</i> for the 2007 and 2008 growing season versus number of adult <i>Balaustium medicagoense</i> at the start of the season (N_o) on four different crop types.	45
Figure 21:	Multiple linear regression for reproductive output (R_o) of <i>Balaustium</i> <i>medicagoense</i> through diapause versus number of <i>Balaustium medicagoense</i> at the end of the previous season (N_o) on four different crop types.	46
Figure 22:	Experimental design of ‘Chemical Efficacy Experiment 1’	56
Figure 23:	Experimental design of ‘Chemical Efficacy Experiment 2’	57
Figure 24:	Experimental design of ‘Farming Systems Experiment 1’ in Year 1.	59

Figure 25:	Experimental design of ‘Farming Systems Experiment 1’ in Year 2.....	60
Figure 26:	Experimental design of ‘Farming Systems Experiment 2’.....	61
Figure 27:	Experimental design of ‘Farming Systems Experiment 3’.....	63
Figure 28:	Mean number of <i>Balaustium medicagoense</i> 3 days after insecticide applications and percentage of control achieved by spray applications compared to untreated plots.....	64
Figure 29:	Mean number of <i>Balaustium medicagoense</i> before spray and 2 days after spray application.....	65
Figure 30:	Number of <i>Balaustium medicagoense</i> (+SE) in pitfall trap catches versus suction sampling in Year 1 in wheat, lupins or pasture. Data are means (n = 20)	66
Figure 31:	Average number of <i>Balaustium medicagoense</i> (\pm SE) on canola planted after different crops in Year 2.....	67
Figure 32:	Canola density over time.....	69
Figure 33:	Mean number of <i>Balaustium medicagoense</i> from all sample dates in different crops in year 1 and year 2.....	70
Figure 34:	Number of <i>Balaustium medicagoense</i> in canola planted after pasture, barley, canola, lupins or wheat in Years 2 and 3.....	71

List of Tables

Table 1:	Registered rates, trial rates and approximate cost of insecticides that control common pests of broad-acre crops.	13
Table 2:	Mode of action of insecticides listed in Table 1	15
Table 3:	Frequency of reports of <i>Balaustium medicagoense</i> on crops (1996 to 2010) in broad-acre growing areas of Western Australia. Data are field observations (n=117) reported by industry via the ‘Pestfax’ database.....	21
Table 4:	Number of ‘Pestfax’ reports stating crop type and crop stage for which control for <i>Balaustium medicagoense</i> was required.	22
Table 5:	Frequency of <i>Balaustium medicagoense</i> causing crop damage in relation to moisture stress from ‘Pestfax’	22
Table 6:	Number of <i>Balaustium medicagoense</i> per plant noted in ‘Pestfax’ as causing damage to crops.....	23
Table 7:	Frequency of <i>Balaustium medicagoense</i> on all plant types sampled.	26
Table 8:	Average mite numbers per square metre present at the time of scoring crop seedlings for mite feeding damage in 2007 and 2008.	43
Table 9:	Percentage difference of earth mite numbers between mixed and pure sub-treatments	44
Table 10:	Co-efficients ($b \pm SE$) and constant ($\pm SE$) from multiple regressions testing if the number of adult (N_o) <i>Balaustium medicagoense</i> or earth mites influenced the reproductive output (R_o) of <i>Balaustium medicagoense</i> under different crop treatments.	47
Table 11:	Crop type, planting rate, planting date and harvest date.	63
Table 12:	Mean number of <i>Balaustium medicagoense</i> per square metre in plots \pm stubble and \pm prophylactic spray applications over all times.	67
Table 13:	Average score of mite feeding damage on canola seedlings in treatments \pm different crop residues and \pm spray applications.	67
Table 14:	The effect of early versus late weed control before planting on earth mite numbers, canola plant densities and yields.....	68
Table 15:	The effect of prophylactic sprays on earth mite numbers (post planting), canola plant densities and yields.....	69
Table 16:	Mean number of <i>Balaustium medicagoense</i> per square metre from all sample dates in various crops in Year 2 after various crops in Year 1.....	71
Table 17:	Mean mite damage score on seedling crops in Year 2 (2009).	72
Table 18:	The effect of the previous year’s crop type on mite feeding damage and canola density.	72
Table 19:	Average prices for crops grown in 325-750 mm rainfall in Western Australia	84

List of Appendices

Appendix 1:	Feedback from Western Australian canola growers survey on the use of insecticides	107
-------------	---	-----

Acknowledgements

The research was funded by the Grains Research and Development Corporation and the Department of Agriculture and Food, Western Australia.

Technical assistance from Mr Tony Dore, Mr Bill Sharpe, Mr Colin Boyd, Mr Chris Matthews and Mr David Mills, valuable feedback and support from Dr Daniel White, Dr Ross Brennan and especially Mr Stewart Learmonth is gratefully acknowledged.

A special thanks to my supervisors Jonathan Majer and Mark Gibberd for ongoing support and above all to Mr John Moore whose undying enthusiasm and encouragement has led to the completion of the thesis.

My appreciation to my husband and family, without their patience this study would never have been completed.

1 General introduction

Balaustium medicagoense Meyer and Ryke (Acari: Erythraeidae) is a relatively recent pest of agricultural significance in Australia. It has only been since the late 1990's that this mite has been officially documented as causing damage to the seedlings of grain crops in the southern cropping area of Western Australia (Agriculture Western Australia 2000). *Balaustium medicagoense* tends to be found in sympatry with *Halotydeus destructor* Tucker (redlegged earth mite) (Acari: Penthaleidae), members of the *Penthaleus* species complex (blue oat mites) (Acari: Penthaleidae), and *Bryobia praetiosa* Koch (clover mite) (Acari: Tetranychidae) (Micic *et al.* 2008). Consequently, farmers initially had difficulty in recognising *B. medicagoense* as causing damage to crops (Mangano and Severtson 2007). However, the distinctive morphology of *B. medicagoense* compared to other mite species, enables it to be easily recognised (Emery *et al.* 2005). It is reddish in colour and twice as large as *H. destructor* or *Penthaleus* spp., making it highly unlikely for adult *B. medicagoense* to be mistaken for other mite species (Figure 1, Figure 2).



Figure 1: *Balaustium medicagoense* (scale bar 1 mm).



Figure 2: *Halotydeus destructor* (left) and *Penthaleus* spp. (right) (scale bar 1 mm).

Grain crops susceptible to damage by *B. medicagoense* are grown in southern Western Australia which has a Mediterranean climatic region characterized by medium to high winter dominant rainfall and no summer rainfall. In this region typical rainfall is between 450 – 800 mm per year

(Poole *et al.* 2002) and rainfed crops are planted between April and June each year (Cramb 2000).

Pests from Mediterranean climate regions frequently have mechanisms to survive the dry summers and understanding these mechanisms in *B. medicagoense* will provide insight into options for control. For instance, some pests undergo summer diapause and hatch or emerge when conditions are favourable. For instance, *H. destructor* hatch from over-summering (aestivating) eggs when there has been rainfall and the weekly maximum temperature has been below 21.5 °C for a period of 7 days (Jeppson *et al.* 1975; Ridsdill-Smith and Annells 1997; Wallace 1970). If crops are planted during periods when temperatures remain above 21.5 °C, control of *H. destructor* is unnecessary.

Other pest species survive on alternative hosts over summer. Cereal aphids that include the species *Rhopalosiphum padi* L. (Oat aphid) (Hemiptera: Aphididae) survive during the summer months on perennial grasses, summer weeds and volunteer crops. Plant hosts are more prevalent if there has been a summer rainfall event and subsequently aphid numbers also increase (Thackray *et al.* 2004; Knight and Thackray 2007). Therefore, it is possible to predict aphid population development on summer hosts by modelling regional temperatures and rainfall data (Thackray *et al.* 2004, 2008; Knight and Thackray 2007).

By comparative standards *B. medicagoense* is a minor crop pest. Earth mites are considered to be damaging pests of crops causing \$AUS 75 million dollars of damage (Murray *et al.* 2012) if uncontrolled. By comparison, *B. medicagoense* is estimated to cause \$AUS 0.92 million dollars of damage if uncontrolled (Murray *et al.* 2012). Murray *et al.* (2012) also rank earth mites as the most damaging with a score of 1 (out of 10 – with 1 being the most damaging and 10 the least), whereas *B. medicagoense* are ranked as 9 out of 10.

The minor significance of this pest should not be taken as a given. Since the first report of crop damage by *B. medicagoense* the number of reports of this mite causing crop damage has increased (Hoffmann *et al.* 2008). In southern Western Australia the increase in reports has coincided with changes to farming systems (Hoffmann *et al.* 2008). Over the last 20 years, areas planted to crops, especially canola, have increased (ABARE 2010, 2017), sowing times have changed in response to climate (Glen 2000) and there has been an increase in the uptake of minimum or no tillage systems (Ugalde *et al.* 2007). The tillage system change has led to an increase in invertebrate biodiversity (Stinner and House 1990) and to potentially more pest species present and at different densities (Hoffmann *et al.* 2008). Hence, there has been an increase in the use of insecticides, which are now routinely applied prophylactically for the control of pests in minimum tillage systems (Gu *et al.* 2007; Mangano and Micic 2008; McDonald *et al.* 1999; Micic *et al.* 2008; Umina 2007). Umina and Hoffmann (2003) reported that some farmers may apply up to four pesticide sprays on a canola crop in a single season.

This increase in chemical use is related to the low cost of chemicals and significant damage that occurs in some seasons when they are not used. For example alpha-cypermethrin, a commonly used broad-spectrum synthetic pyrethroid registered for the control of a number of invertebrate pests costs only \$(AUS) 0.60 per ha (Moore and Moore 2017). The increased use of prophylactic sprays has provided effective control of *H. destructor* and *Penthaleus* spp. These mites are collectively referred to as earth mites and are known to cause extensive economic damage in broad-acre crops especially canola and legumes (McDonald *et al.* 1999; Newman 1936; Umina and Hoffmann 2004). Earth mites are susceptible to many agricultural pesticides (Robinson and Hoffman 2000), whereas *B. medicagoense* is more tolerant (Arthur *et al.* 2008). Growers have postulated that the increases in *B. medicagoense* populations are due to decreased competition with other mite species.

Repeated spraying with products from the same mode of action group also increases the risk of resistance occurring. Populations of *H. destructor* have been detected with resistance to commonly applied synthetic pyrethroids (Umina 2007). Analysis of paddock spray applications showed that the sprays were not necessarily targeted against *H. destructor* but rather against pests such as aphids (Edwards *et al.* 2008). It is highly likely *H. destructor* were present in the paddocks and exposed to the insecticide applications. As *B. medicagoense* occurs in sympatry with *H. destructor* (Micic *et al.* 2008), it is probable that spray applications that have led to *H. destructor* developing resistance are likely to constitute a selection pressure for the development of resistance in *B. medicagoense*.

In order to decrease spray applications a better understanding of the actual crop losses that occur from *B. medicagoense* feeding damage is required. To date much of the work on *B. medicagoense* has been conducted under laboratory conditions (see Arthur *et al.* 2008; 2010). Thresholds and damage scores under laboratory conditions caused by pests are difficult to extrapolate into realistic field recommendations due to many abiotic and biotic factors that occur in the field.

1.1 Thesis aims

The aims of this thesis were to investigate the following:

1. The effect of host plants on persistence and reproduction on *B. medicagoense*;
2. Field thresholds for spraying of crops at crop emergence for *B. medicagoense*;
3. Chemical control options for *B. medicagoense*; and
4. If the control of earth mites has led to increased numbers of *B. medicagoense*.

2 Review of literature on *Balaustium medicagoense* (Meyer and Ryke) (Acari: Erythraeidae)

2.1 Overview of the phylogenetic relationships of the Superfamily Erythraeoidea and the genus *Balaustium*

2.1.1 Phylogenetic relationships within the Acari

The Acari have existed since the Devonian period, about 6 million years ago (Norton *et al.* 1993). Generally three superorders are recognised: Parasitiformes, Opilioacriiformes and Acariformes (Figure 3). The Parasitiformes and Opilioacriiformes (=Anactinotrichida) are considered to be sister groups (Norton *et al.* 1993), as they do not possess actinochitin setae (a layer of optically active chitin) which are present in Acariformes (=Actinotrichida) (Walter *et al.* 1996).

There is debate as to whether or not the Acari as a group are monophyletic with an identifiable sister group with other arachnids or diphylectic consisting of two arachnid lineages that converged (Norton *et al.* 1993). The arguments for diphyly rely on the two lineages of Achinotrichida and Anactinotrichida being distinctly different. However, the main difference cited is that the Achinotrichida possess holokinetic chromosomes (chromosomes with centromeres) whereas monokinetic chromosomes (chromosomes without centromeres) are found in Anactinotrichida (Helle *et al.* 1984; Oliver 1977). As holokinetic and monokinetic chromosomes are found in the Arachnida, it is unlikely that this trait is not evolutionarily conservative (Helle *et al.* 1984), and the Achinotrichida and Anactinotrichida should be considered monophyletic. The assumed relationships of higher mite taxa are shown in Figure 3.

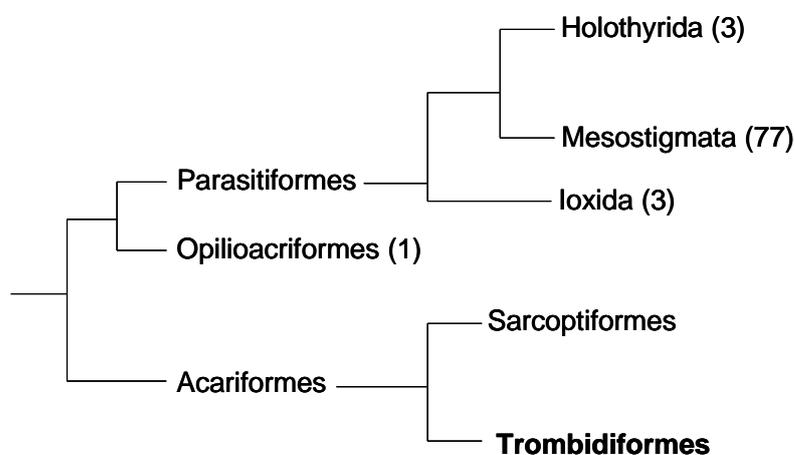


Figure 3: Hypothesized relationships of higher mite taxa based on morphology.

Number of families in parentheses. Adapted from Norton *et al.* (1993) p 10. Bold indicates assemblage Family Erythraeidae belongs to.

The Acariformes are divided into two assemblages, the Trombidiformes and the Sarcoptiformes, (Figure 3) which together contain over 340 families (Norton *et al.* 1993; Proctor 1998). The majority of Trombidiformes are characterised by possessing chelicerae with a hook or stylet-like movable digit and a pad-like or rayed median empodium (an unpaired structure arising between the tarsal claws). By contrast, the Sarcoptiformes possess a claw like or disc-shaped empodium (Linquist 1996). Further defining characters for these two groups rely on the placement of setae as described by O'Connor (1984).

2.1.2 Phylogeny of Erythraeoidea

The Trombidiformes consist of the Sphaerolichida and Prostigmata, of which the prostigmatans are characterised by possessing stigmatal openings to the tracheal system located anteriorly (Linquist 1996). The super-family Erythraeoidea is placed within the Trombidiformes. The proposed cladistic relationship is shown in

Figure 4.

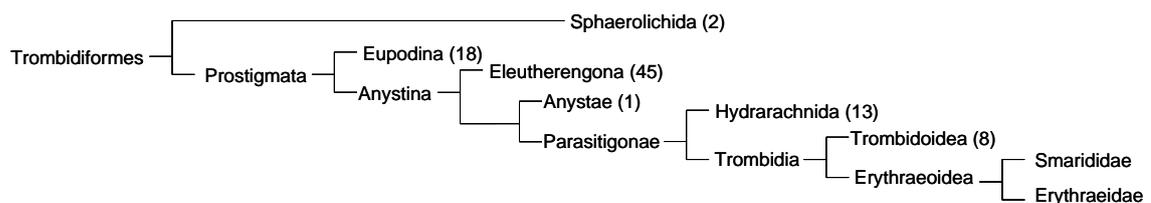


Figure 4: Hypothesized relationships of cohorts in the assemblage (suborder) Trombidiformes.

Number of families in parentheses. Adapted from Lindquist (1996), Welbourn (2005) and Wohltmann *et al.* (2001).

The super-family Erythraeoidea contains two families: Erythraeidae and Smarididae (Southcott 1961; 1997). The two families are readily distinguished from each other in both the adult and nymphal stages. Nymphal and adult Smarididae have a flattened fish-shaped body (idiosoma), and nymphs possess pedal trichobothria (Southcott 1961) i.e. elaborate seta set in a cup-like base (Walter 2005); whereas species in the Erythraeidae have globular bodies and nymphs lack pedal trichobothria (Southcott 1961). There are 823 species comprising of 60 genera in the family Erythraeidae, to which *Balaustium* belong (Hallan 2005; Munoz-Cardenas *et al.* 2015). It is difficult to determine how many species are in this family. There are morphological and feeding behavioural differences between larva and post larval stages and without experimental rearing it has led to misidentifications or double classifications- when a larva and post-larva form of the same species are classified separately (Munoz-Cardenas *et al.* 2015).

2.2 Phylogeny and adaptations of Parasitengona to xeric environments

The cohort Parasitengona is characterised by species with complex life cycles. The larval stages are usually parasitic, whilst the adult stages are free-living and predatory and have calyptostatic proto- and tritonymphs (i.e. nymphs with non-functional mouthparts or legs) (Southcott 1961; Proctor 1998; Wohltmann *et al.* 2001). Mites within the Parasitogona have one or more generations per year, synchronized by a hibernating or aestivating egg or pre-larva (Southcott 1961, Wohltmann *et al.* 2001). Wohltmann *et al.* (2001) suggest that mites within this cohort are well adapted to survival in arid (xeric) environments as they possess glands in the region of the body orifices that secrete lipids to protect against water loss, and possess red pigment to protect against UV radiation (Wohltmann *et al.* 2001; Yoder *et al.* 2008).

Within the Parasitogones, species in the Erythraeoidea are well adapted to survive xeric conditions. Species in this superfamily are able to tolerate fluctuating humidity, through the following adaptations: (1) eggs are laid ensheathed with lipidaceous and proteinaceous secretions protecting the egg from desiccation, which enables eggs to tolerate relative humidities down to 76%; (2) pre-larval development within the egg is arrested at relative humidities below 98% and continues when eggs are exposed to 98% relative humidity or above for a 24 hour period, and; (3) calyptostatic instar development continues at relative humidities above 76% (Wohltmann *et al.* 2001). Yoder *et al.* (2008) have found that within the Erythraeidae, species of the genus *Balaustium* (von Heyden) are able to tolerate high temperatures of 50 °C due to secretions of fluids that assist in water-proofing the mites' body thereby decreasing fluid loss.

2.3 Confused taxonomic history of the genus *Balaustium*

Of all of the genera in the Erythraeidae, the number of species in the genus *Balaustium* is the most difficult to determine. According to Makol (2012, 2013), (cited in Fuentes-Quentero *et al.* 2014) there are 36 described species of *Balaustium* from the Americas (North, South, and Central), Europe, Asia, South Africa and Australia, of these 5 are described from larval forms. However, the exact number of species in this genus is difficult to determine due to its confused taxonomic history, caused in part by the description of a species based on the morphology of larval and post-larval stages which has led to morphological similarity of *Balaustium* to the genus *Abrolophus* Berlese (Gabrys 2016; Halliday 1998, 2001; Southcott 1961; Mayoral and Barranco 2009). Cladistic analysis conducted by Wohltmann *et al.* (2001) suggests that *Balaustium* and *Abrolophus* are closely related, being on a shared branch of the phylogenetic tree (Halliday 2001; Wohltmann *et al.* 2001).

The genus *Abrolophus* is distinguished from the genus *Balaustium* by the absence of urnulae, which are present in all species of the genus *Balaustium* (Halliday 2001). Urnulae are tubercles present behind the anterolateral eyes and which are considered to be sensory structures (Halliday 2001). However, Yoder *et al.* (2006) found that these urnulae have a secretory function releasing an alarm pheromone when the mite is disturbed which leads to predators such as ants avoiding the mite. This is likely due to the pheromone blocking or over-stimulating chemosensory receptors on the ant's antennae causing the ants to ignore the mite (Yoder *et al.* 2006).

Before 2001, there were eight species of *Balaustium* described in Australia. However, Halliday (2001) found that six species had been misidentified and belonged to the genus *Abrolophus* and that *B. medicagoense* had been misidentified as *B. murorum* Hermann. Consequently, *Balaustium medicagoense* is the only species from the genus *Balaustium* to occur in Australia.

2.4 Distribution of the genus *Balaustium* in Australia

Balaustium medicagoense is endemic to South Africa as is *H. destructor* (Halliday 2001). Halliday (2001) surmised that it is likely that *B. medicagoense* was introduced into Australia at the same time as *H. destructor* and this introduction was likely to have been with shipments of hay.

The earliest record of *B. medicagoense* in Australia is from 1935 on pastures at Werribee, Victoria (Halliday 2001). It is possible there was more than one introduction of this mite; however, *B. medicagoense* has a predicted distribution extending throughout the Mediterranean climate areas of southern Australia (Halliday 2001; Arthur *et al.* 2011).

2.5 Feeding behaviour of mites in the genus *Balaustium*

Balaustium is considered an unusual member of the Parasitiformes as the larvae have only a weak tendency toward parasitism and generally are either predators or casual parasites of insects (Southcott 1961). Furthermore, the adults tend to exhibit generalised feeding habits. They are considered to be predaceous: active instars of *Balaustium* have been recorded feeding on eggs and early instars of Lepidoptera, Coleoptera, Diptera, psyllids, Homoptera and acari such as Tetranychidae (Cadogan and Laing 1977, 1981; Childers and Rock 1981; Hayes 1985; Munoz-Cardenas *et al.* 2014; Newell 1963; Putman 1970; Welbourn and Jennings 1991) as well as on plant material, including pollen grains (Newell 1963; Southcott 1961; Halliday 2001). Many larval stages have been collected from plants (Southcott 1961; Halliday 2001; Mayoral and Barranco 2009) making feeding behaviour difficult to determine. Larval instars of *B. putmani* have been shown to consume pollen grains but were not able to survive solely on this diet (Cadogan and Laing 1977). However, larval instars were able to survive on a diet of eriophyid

mites (Cadogan and Laing 1977; Putman 1970). Munoz-Cardenas *et al.* (2014) found that female *B. leanderi* Heitlinger (Fuentes-Quintero *et al.* 2014) had increased fecundity and larvae had a increased survival when fed a mixed diet rather than when single diet of either two spotted mites eggs, whitefly eggs or first instar thrips. Similarly, larvae fed on a single diet showed higher mortality than larvae fed a mixed diet.

Larvae of *B. medicagoense* are not able to complete their life cycle by feeding on plant material alone (Arthur *et al.* 2010) and require an additional food source in order to complete their life cycle. Larval stages of other *Balaustium* species were also not able to survive on plants alone, requiring a protein food source to survive (Cadogan and Laing 1977). Other studies have shown that the microflora present on the soil surface (MacLennan *et al.* 1998) assists mites such as *H. destructor* to reproduce and it has been suggested that *B. medicagoense* larval stages may also require microfloral fungi to complete their life cycle (Arthur *et al.* 2010). Studies conducted by Yoder *et al.* (2009) found no evidence of fungal spores within the body of *Balaustium* spp. suggesting that the mites are not fungivorous. It is more likely that *B. medicagoense* larvae are predatory.

Based on its predatory habits, it has been surmised that species in the genus *Balaustium* could be possible biocontrol agents (Cadogan and Laing 1981; Munoz-Cardenas *et al.* 2014; Munoz-Cardenas *et al.* 2015). Species of *Balaustium* are natural enemies of agricultural pests but there is no record of these mites being mass reared to be used as biological control agents (Munoz-Cardenas *et al.* 2015), this is likely to be due to the difficulty in rearing *B. medicagoense* species under laboratory conditions. *Balaustium* spp. have been recorded as predating on *Panonychus ulmi* Koch (European red mite) (Acari: Tetranychidae) in Canada but due to their slow increase in numbers are not considered to be effective biological control agents (Jeppson *et al.* 1975). Similarly, *B. medicagoense* was originally considered to be a beneficial predator (James 1995; James *et al.* 1995) and a potential biological control agent for *H. destructor* (Halliday 2000). Even though this species is known to feed on *P. major* it is not considered of importance in reducing pest populations (Jeppson *et al.* 1975). However, once it was found that *B. medicagoense* caused feeding damage to crops it was not considered to be a potential candidate for biological control in Australia.

2.5.1 Feeding damage in crops

In its country of origin, South Africa, *B. medicagoense* is not considered to be a pest of crops (Halliday 2001; Hoy 2011). It is likely that the generalist feeding behaviour (i.e. feeding on plant and invertebrates) of *B. medicagoense* was not recognised in Australia and therefore damage to emerging crops prior to 1997 was overlooked (Agriculture Western Australia 2000; Hoffmann et al. 2008; Micic et al. 2008; Arthur et al. 2010).

The damage *B. medicagoense* causes to crops depends on the crop type. Damage in canola, for example, can be characterised by distorted and cupped cotyledons, which may have a leathery appearance (Micic 2005) or canola leaves may be silvered. Similarly in pulses and cereals (wheat and barley), *B. medicagoense* causes silvering of the leaves, especially on the leaf tips (Arthur et al. 2010; Micic and Mangano 2006). Plant feeding experiments in greenhouses have demonstrated that *B. medicagoense* causes more feeding damage to wheat and lupins than it does to canola and oats (Arthur et al. 2010).

2.6 Life history of mites in the genus *Balaustium*

2.6.1 Mode of reproduction

Based on the absence or rarity of males, species within the genus *Balaustium* reproduce by thelytokous parthenogenesis (Norton et al. 1993) as is the case in *B. near putmani* (Hedges et al. 2012) *B. murorum* (Makol 2010) and *B. leanderi* (Munoz-Cardenas et al. 2014; Fuentes-Quentero et al. 2014). Studies on the genotyping of allozyme and DNA data from multiple field populations of *B. medicagoense* by the University of Melbourne suggest that *B. medicagoense* reproduces parthenogenetically as well (Micic et al. 2008).

2.6.2 Life-cycle

The exact length of time from egg to adult in *B. medicagoense* is not known. The life-cycles of three *Balaustium* species have been studied in detail *B. putmani* Smiley (Cadogan and Laing 1977, 1981), *B. hernandezii* von Heyden (Munoz-Cardenas et al. 2015) and *B. leanderi* (Munoz-Cardenas et al. 2014). These have been observed to have 7 developmental stages: egg, pre-larva, protonymph, deutonymph, tritonymph and adult (Cadogan and Laing 1977; Munoz-Cardenas et al. 2014). *Balaustium putmani*, eggs only hatch if kept moist. If these conditions are met, the length of time from egg laying to hatching depended on temperature. Eggs kept at 17.5 to 22.5 °C hatched 16 to 9 days after laying, whereas eggs kept at 12 °C took on average 35 days to hatch. The optimum development of larval stages was at 20 °C and on average larvae kept at this temperature only took 20 days to reach adulthood whereas larvae kept at 25 °C took on average 35 days (Cadogan and Laing 1977). Whereas Munoz-Cardenas et al. (2014) found that

life span of *B. leanderi* (Munoz-Cardenas *et al.* 2014; Fuentes-Quentero *et al.* 2014) varied with diet, mites fed eggs of white flies and two-spotted mites had a life span of 50 days whereas those fed larvae of thrips had an average life span of 75 days.

In Australia, *Balaustium medicagoense* is active from March to December and there are at least two generations per year (Arthur *et al.* 2010). This is likely to vary with seasonal temperature and rainfall. Other species of *Balaustium* species have been recorded as being bivoltine (Cadogan and Laing 1981; Welbourne 1985) or univoltine (Hedges *et al.* 2012; Makol 2009), with adults laying eggs prior to a northern hemisphere winter, whereby eggs do not hatch until spring (Cadogan and Laing 1981; Yoder *et al.* 2017).

2.6.3 Diapause

Mites from the genus *Balaustium*, such as *B. putmani*, enter diapause at the egg and hexapod larval stages, if climatic conditions are unfavourable or when prey is not available (Cadogan and Laing 1977). According to Wohltmann *et al.* (2001), eggs of erythraeids undergo reversible cessation of development depending on relative humidity. This suggests that *B. medicagoense* eggs can undergo diapause when conditions are not favourable. Studies by Arthur *et al.* (2011) also suggest that there is a potential diapause stage in *B. medicagoense*.

2.7 Possible management of *Balaustium medicagoense*

Insecticides registered for use on *H. destructor* are not effective against *B. medicagoense* (Arthur *et al.* 2008; 2010; Micic *et al.* 2008). Laboratory bioassays have shown that *B. medicagoense* has a high tolerance to a range of pesticides registered to control *H. destructor* and *Penthaleus* spp. (collectively known as earth mites) in Australia. For example, *B. medicagoense* has a 16-fold higher tolerance for alpha-cypermethrin and a 26-fold higher tolerance for bifenthrin than *H. destructor* (Arthur *et al.* 2008). Robinson and Hoffmann (2000) and Umina and Hoffmann (1999) have shown that mites exhibiting high tolerance of insecticides under laboratory conditions require higher rates of chemical applications for their control in the field.

Changes in spray practices likely contributed to *B. medicagoense* being recognised as a crop pest. From 1942 to 1985, DDT was commonly applied for the control of pests in crops such as *H. destructor* (Michael 1987; Jenkins 1945) at rates that would also control *B. medicagoense* (Michael pers. comm.). Post DDT usage, organophosphates, the organochlorine endosulfan, and synthetic pyrethroids were used extensively for invertebrate control (Michael 1987). Of these endosulfan that was commonly applied for the control of *H. destructor* (Michael 1987) and also provided control of *B. medicagoense*, however, organophosphates and synthetic pyrethroids

applied for the control of *H. destructor* would not also provide control of *B. medicagoense* (see Table 1).

There have been few studies on the toxicity of insecticides on other *Balaustium* species. Orchards sprayed with DDT, parathion, permethrin or azinphosmethyl were found to have reduced numbers of *B. putmani* (Hagley and Simpson 1983; Herne and Putman 1966), whereas *B. murorum* was found to be controlled by pirimiphos-methyl (Wilkin and Warner 1985). Only permethrin is registered for use in broadacre crops of wheat, oat, barley and field pea, the rest are either not registered for use in Australia or do not have a registration for use in agricultural crops (APVMA 2017; Moore and Moore 2017).

Moore and Moore (2017) summarised the registered and trial rates of chemical application for the control of common pests in broad-acre crops (Tables 1 and 2) and suggested that controls applied for earthmites, *Bryobia praetiosa*, Aphididae, *Sminthuris viridis* L. (Lucerne flea) (Collembola: Sminthuridae), would not provide effective control of *B. medicagoense*. Higher rates are required for the control of *B. medicagoense*. Whereas, applications for the control of *Listroderes difficilis* Germain (Vegetable weevil) (Coleoptera: Curculionidae) with alpha-cypermethrin or cypermethrin would also control *B. medicagoense*.

Worldwide, this dependence on pesticides for the control of invertebrate pests has led to over 300 agricultural pest species now becoming resistant to insecticides (Whalon *et al.* 2008). In Australia, for broad-acre crop mite pests, resistance to insecticides has only been identified in *H. destructor* to synthetic pyrethroids (Umina 2007) and tolerances to organophosphates (Micic and Lord 2015; Umina *et al.* 2017).

Current management options for *B. medicagoense* rely on applying pesticides to seedling crops when damage is first seen (A Heinrich pers. comm. 2010). This dependence on pesticides for insect control is not a new phenomenon. In 1959, Stern *et al.* (cited in Stern 1973) highlighted that insecticides were being applied without any understanding of the density at which pests caused economic injury to crops. It was Stern (1973) who defined this concept to mean the density at which control measures should be applied to prevent the lowest population density causing economic damage to a crop. Currently, crop protection thresholds, adapted from Ellis *et al.* (2009), can be defined as:

1. Action threshold – The pest density that warrants initiation of the control strategy.
2. Economic damage – The amount of damage that justifies the cost of artificial control.
3. Economic injury levels (EIL) – The lowest population density that will cause economic damage.
4. Economic threshold (ET) – The level at which control measures should be implemented to prevent pest populations reaching the EIL.

There are currently no thresholds for *B. medicagoense*.

Another way in which to reduce pesticide applications is to suppress pest populations through the use of predators. For instance *Mononychellus progresivus* Doreste (Cassava green mite) (Acari: Tetranychidae) originally introduced from South America to Africa (Mutisya *et al.* 2016), was a very important pest of cassava in Africa (Hoy *et al.* 2011; Mutisya *et al.* 2016) but has been controlled through the introduction of the predatory mite *Typhlodromalus aripo* DeLeon (Acari: Phytoseiidae) which has led to cassava yields increasing by 30% (Hoy 2011; Yaninek 2007). According to Hoy (2011) *T. aripo* has been a successful predator as it has a preference for *M. progresivus* but is able to predate on other insect hosts when numbers of *M. progresivus* are low. It is uncommon for a predator to suppress pest populations without having to use other control measures alone (Hoy 2011). In Australian pastures, the mite *Anystis wallacei* Otto (Acari: Anystidae) was introduced as a biological control agent for *H. destructor*. This mite caused up to a 30% reduction in *H. destructor* numbers but was found to only persist in high numbers in pasture environments that had moderate grazing pressures and were not mechanically manipulated (Michael 1995). Further studies to identify potential specialist predators identified 55 species that were suitable candidates and of these 11 species were considered to be potential biological control agents however, these were not specific in their feeding behaviour to be effective predators of *H. destructor* and it was concluded that there were no predatory mites in South Africa that would be suitable biological control agents for *H. destructor* (Halliday 2005; Halliday and Paull 2004). Like *H. destructor*, *B. medicagoense* is an introduced pest to Australia; it is not known to have any specialist predators here. It is possible potential biological control agents may be identified in its country of origin. However, until this occurs, other control methods need to be considered for this pest.

Control measures other than the use of pesticides and biological control agents are needed for *B. medicagoense*. Alternative control measures are known as cultural controls and include modifications to agronomic practices to reduce pest damage and include changing: time of sowing or harvest operations, cultivation, crop rotation to minimise pest damage (Flint and Gouveia 2001; Hoy 2011). It is unlikely that solutions for the control of *B. medicagoense* will be able to be extrapolated from successful case studies of integrated pest management from other countries, as integrated management solutions differ across localities and commodities and for management practices to be adopted they need to fit into current farming practices (Hoy 2011; Walter 2005).

Even though in other grain growing regions of the world, where barley, wheat or canola are grown, mites are considered to be minor pests of these crops (see Hill 1987; Hoy 2011; Lamb 1989; Nawaz *et al.* 2016; Ochoa *et al.* 1994; Weiss *et al.* 2006) some cultural practices may be useful for consideration. For instance, in the United States the main mite pests of wheat are *Petrobia latens* Muller (Brown wheat mite) (Acari: Tetranychidae), *Oligonychus pratensis*

(Banks grass mite) (Acari: Tetranychidae) and *P. major*. These pests are more likely to be found in fields where wheat is grown continuously and are more likely to be found on stressed crops (Godfrey *et al.* 2006; McCornack *et al.* 2017; Tuck *et al.* 2009). Recommended control measures to growers is to minimise damage to wheat from mite pests and to not plant wheat more than two years in succession by growing broad-leaf crops or controlling host plants in or adjacent to the cropped field (McCornack *et al.* 2017; Tuck *et al.* 2009). However, *P. latens* especially is considered a sporadic pest of moisture stressed wheat and management recommendations centre on irrigating fields (Godfrey *et al.* 2006; Hu *et al.* 1987). In Western Australia crops are grown under production systems that are rainfed without any form of irrigation, so the use of irrigation as a management tool to minimise crop damage from *B. medicagoense* is not possible (Anderson *et al.* 2016). But management practices that consider cropping rotations to suppress *B. medicagoense* or weed control do fit into currently applied cropping systems (Anderson *et al.* 2016) and may be suitable for *B. medicagoense*.

The application of insecticides with a threshold, combined with cultural controls and use of predators is termed integrated pest management (Dent 1995; Flint and Gouveia 2001). The aim of which is to manage pests by preventing their populations increasing by changing components of the cropping system (Hoy 2011; Walter 2005). However, a robust alternative to chemical control according to Walter (2005) is difficult to achieve as chemical control can be applied with little delay, act quickly to reduce pest populations and can be more economical than other management options.

2.8 Conclusion

There is only one species of *Balaustium* in Australia: *Balaustium medicagoense*. This mite is likely to have been introduced to Australia from South Africa in the early part of the 20th century but it is only since the 1990's that this mite has been identified as causing damage to crops here. It is likely that changes in common spray control practices from organochlorine to synthetic pyrethroid products have led to crop damage by *B. medicagoense* being more readily observed. Higher rates of insecticides than those registered for *H. destructor* are generally required for its control and these are applied without knowing how many mites it takes for economic crop damage to occur. Alternative controls to insecticides such as biological and cultural controls require further investigations for the management of *B. medicagoense*.

Table 1: Registered rates, trial rates and approximate cost of insecticides that control common pests of broad-acre crops.

Application rates are mL/ha; registered rates are in bold and costs is AU\$ per ha (2017). Adapted from Moore and Moore 2017. BM is *Balaustium medicagoense*.

Insecticides	BM	Bryobia Spp.	Penthaleus major	Halotydeus destructor	Aphididae spp.	Sminthurus viridis	Listroderes difficilis
Alpha-cypermethrin 100 g/L	400 (\$2.58)		50 (\$0.32)	50 -100 (\$0.32-0.64)	125 -300 (\$0.81-1.93)		400 (\$2.58)
Beta-cyfluthrin 25 g/L			200 (\$3.63)	200 (\$3.63)	1000 (\$18.14)		
Bifenthrin 100 g/L		200 (\$1.92)	100 (\$0.96)	50 -100 (\$0.48-0.96)			200 (\$1.92)
Carbaryl 500 g/L				500 (\$7.89)		500 (\$7.89)	2000-2200 (\$31.56-34.72)
Carbaryl 800 g/kg				300 (\$7.38)		350 (\$8.61)	
Chlorpyrifos 500 g/L			70 -300 (\$0.50-2.15)	140-300 (\$1.00-2.15)	200-300 (\$1.43-2.15)	70 (\$0.50)	700-800 (\$5.00-5.72)
Cypermethrin 200-260 g/L	400 (\$3.39)		50-75 (\$0.42-0.64)	50 -75 (\$0.42-0.64)	500 (\$4.24)		400 (\$3.39)
Lambda-cyhalothrin 250 g/L			18 (\$2.77)	9 (\$1.39)			
Diazinon 800 g/L or kg					700-850 (\$17.32-21.04)		
Dicofol 480 g/L		1000 (\$28.85)					
Dimethoate 400 g/L		600 (\$3.86)	90 (\$0.58)	40-50 (\$0.26-4.82)	340-750 (\$2.19-4.82)	55-85 (\$0.35-0.55)	
Endosulfan 350 g/L	500 (\$6.10)	800 (\$9.76)	500-1000 (\$6.10-12.20)	500-1000 (\$6.10-12.20)	2000 (\$24.40)		
Fipronil 500 g/L	20 (\$16.28)			20 (\$16.28)			
Gamma-cyhalothrin 150 g/L				8 (\$1.45)			
Imidacloprid 200 g/L					250 (\$13.20)		
Maldison 500-1180 g/L		1200-2000 (\$14.18-23.64)		300 (\$3.55)	1000-2000 (\$11.82-23.64)	140 -300 (\$1.65-3.55)	1000 (\$11.82)
Methidathion 400 g/L			90-200 (\$1.68-3.74)	90-200 (\$1.68-3.74)	1200 (\$22.44)	90-200 (\$1.68-3.74)	
Methomyl 225 g/L					1000 (\$11.55)		
Omethoate 290 g/L		120 (\$2.24)	100 (\$1.87)	100-120 (\$1.87-2.24)		100 (\$1.87)	
Omethoate 800 g/L			100 (\$4.48)	40 (\$1.79)	250 (\$11.21)	35 (\$1.57)	
Pirimicarb 500 g/kg					100-1000 (\$1.93-19.25)		
Sulfoxaflo 240 g/L					50-100 (\$14.08-28.16)		

Table 2: Mode of action of insecticides listed in Table 1

Adapted from IRAC (2012).

Main Group	Mode of action	Chemical sub-group and active ingredient	Active constituent	Trade name example
1	<i>Acetylcholine esterase inhibitors</i> Nerve action	1A Carbamates	Methomyl Carbaryl	Lannate Carbaryl
		1B Organophosphates	Chlorpyrifos Diazinon Dimethoate Maldison Methidathion Omethoate Pirimicarb	Lorsban Diazol Rogor Hymal Suprathion Le-mat Pirimor
2	GABA-gated chloride channel antagonists Nerve action	2A Cyclodiene organochlorides	Endosulfan	Thiodan
		2B Phenylpyrazoles	Fipronil	Regent
3	<i>Sodium channel modulators</i> Nerve action	3A Pyrethroids	Alpha-cypermethrin Beta-cyfluthrin Bifenthrin Cyfluthrin Cypermethrin Deltamethrin Esfenvalerate Fenvalerate Gamma-cyhalothrin Lambda-cyhalothrin	Fastac Bulldock Talstar Tugon Scud Decis Hallmark Sumifly Trojan Karate
			3B DDT	DDT
4	Nicotinic acetylcholine receptor (nAChR) agonists Nerve action	4A Neonicotinoids	Imidacloprid	Gaucho
23	Inhibitors of acetyl CoA carboxylase. Lipid synthesis, growth regulation	Tetronic and Tetramic acid derivatives	Spirotetramat	Movento
UN	Compounds of unknown or uncertain MoA2	Dicofol	Dicofol	Kelthane

3 Host plants of and crop damage by *Balaustium medicagoense*

3.1 Introduction

It is only since the 1990's that *B. medicagoense* has been reported as causing damage to crops at emergence (Agriculture Western Australia 2000). Consequently, *B. medicagoense* is considered to be an emerging mite pest of broad-acre crops in southern Western Australia (Arthur *et al.* 2010; Hoffmann *et al.* 2008). Previously, this mite was considered to be a beneficial predator of earth mites such as *Halotydeus destructor* and the *Penthaleus* spp. complex (James 1995; James *et al.* 1995), even though it also fed on plant matter (James 1995).

Feeding damage by *B. medicagoense* is characterised by chlorotic bleaching of leaf plant tissue but this characteristic can vary with plant type. Light feeding damage by *B. medicagoense* in canola is characterised by distorted and cupped cotyledons, which may have a leathery appearance (Figure 5), though heavy infestations can cause silvering (Micic 2005). In pulses and cereals, *B. medicagoense* causes bleaching of the leaves, especially on the leaf tips (Micic and Mangano 2006). This damage is similar to that caused by moderate numbers of earth mites, that also can cause bleaching in cereals, and silvering on cotyledons of canola and lupins, (Ridsdill-Smith *et al.* 2008; Umina and Hoffmann 2004; Micic 2005; Micic and Mangano 2006). Currently there are no thresholds for *B. medicagoense* in crops.



Figure 5: Damage to lupin cotyledon by *Balaustium medicagoense*.



Figure 6: Damage to canola by *Balaustium medicagoense*. Note cupped cotyledons.



Figure 7: Mite feeding damage to cereals¹.

Balustium medicagoense is a pest that feeds on a number of crops including canola, cereals and pulses as well as pasture and weed grasses (Arthur *et al.* 2010). The extent and distribution of this mite in Western Australia is poorly recorded. Arthur *et al.* (2010) have conducted some surveys and predicted its distribution nationally. Another method to determine how wide spread this mite is in Western Australia and how much damage it actually does to crops is to review ‘Pestfax’ reports. ‘Pestfax’ is a weekly updated news report produced by the Department of Agriculture and Food, WA that aims to provide broad-acre agribusinesses with information on crop pests and diseases during the broad-acre growing season (Mangano and Severtson 2007). Even though samples from sightings used within these reports were not formally identified, a high level of confidence is assumed as the reports are from trained and experienced agronomists (Mangano and Severtson 2007). Also *B. medicagoense* has a very distinctive morphology, being reddish in colour and twice as large as *H. destructor* or *Penthaleus* spp., therefore it is highly unlikely for adult *B. medicagoense* to be mistaken for other mite species (Micic 2008) (See Chapter 1: Figure 1, Figure 2).

Even though *B. medicagoense* is considered to be polyphagous, understanding its exact plant hosts will assist in determining control strategies that do not solely rely on insecticides. For instance, seedling crops vary in their risk of sustaining damage from *H. destructor* depending on the paddock planting histories. Clover-dominant pastures, for example, sustained high numbers of *H. destructor* (Umina and Hoffmann 2004), whereas lentils and chickpeas sustained lower numbers of this mite species (Merton *et al.* 2005; Umina and Hoffmann 2004). Therefore planting crops such as canola after pasture is likely to lead to increased damage whereas planting canola after lentils or chickpeas lowers the likelihood of crop damage. Weeds, especially broadleaved weeds (Gauil and Ridsdill-Smith 1996; Umina and Hoffmann 2004; Weeks and Hoffmann 1999), harbour high mite numbers, so controlling weeds also leads to

¹ Photograph by A. Heinrich

decreased pest pressure (Berlandier and Baker 2007; Hopkins and MacDonald 2007; Miles *et al.* 2007; Pavri 2007).

Control of *B. medicagoense* using paddock management, requires an in-depth understanding of the plant-host dynamics. The ability for a mite species to persist in a paddock across seasons is directly related to its relationship with the available host plant species. For example, plant-host associations have been studied in earth mites and differences in the ability of species within the earth mite complex to persist and reproduce on different crops and weeds have been reported. For instance, *H. destructor* is able to persist on canola, wheat and oats (Merton *et al.* 1995; Umina and Hoffmann 2004), *Penthaleus major* persists on oats and wheat, and *Penthaleus falcatus* persists on canola (Umina and Hoffmann 2004).

Non-crop hosts of *B. medicagoense* also need to be determined. Biota adjacent to fence-lines in cropped paddocks may possibly be a host for this mite. Non-crop hosts would allow *B. medicagoense* to survive in the absence of crop-host plants and then disperse into paddocks once cropped. For instance, Weeks *et al.* (2000) found that border sprays were required to prevent *H. destructor* dispersal from plant hosts along fencelines.

3.1.1 Aims

The aim of this chapter is to:

- Determine the severity of crop damage caused by *B. medicagoense* and subsequent thresholds for control
- Determine plant hosts of *B. medicagoense* in southern agricultural areas of Western Australia.

3.2 Materials and methods

3.2.1 Compilations of Pestfax reports

Reports from ‘Pestfax’ from 1996-2010 were analysed in order to understand the effects of feeding damage by *B. medicagoense*, as well as the environmental precursors that may contribute to increased crop damage. Interrogation of reports was done using the ‘Pestfax’ database, developed by the Department of Agriculture and Food, Western Australia and each report was individually assessed. The locations of *B. medicagoense* in the reports were mapped against rainfall isohyets, (obtained with permission from the Department of Agriculture and Food, 2010), the frequency of *B. medicagoense* on different crops, incidence of damage, control requirements, crop moisture stress and numbers of *B. medicagoense* per plant in the reports were also tabulated. Chi-square statistical analysis and/or ANOVA were completed using the computer software package GenStat version 10.1.0.7.1.

3.2.2 Field plant host surveys

To better understand the abundance and distribution of *B. medicagoense* in the field, surveys of *B. medicagoense* and earth mites were conducted in both crop and native vegetation. This survey was conducted in conjunction with two other field surveys: A) Pest suppressive landscapes: Linking IPM and natural resource management, lead by Dr Nancy Schellhorn (CSIRO) and B) Developing IPM guidelines for the WA grain belt and strategies to manage the wheat curl mites' spread of wheat streak mosaic virus lead by Dr Darryl Hardie (Department of Agriculture and Food, WA).

Seasonal distribution of *B. medicagoense* in paddocks of wheat, barley, canola and pasture was monitored from February to October 2010. Six paddocks of each crop type from the South Stirling region of Western Australia were monitored monthly for the abundance of *B. medicagoense* adults and earth mites. The seasonal distribution of *B. medicagoense* was also monitored in remnant vegetation adjacent to these paddocks. Remnant vegetation was divided into middle storey, lower storey and ground covers. Middle and lower storeys of vegetation were sampled because other species of *Balaustium* have been found to be present on trees (see Cadogan and Laing 1981; Childers and Rock 1981; Newell 1963).

3.2.2.1 Sampling crops

Pastures did not have any pesticides applied, cereals had only imidacloprid seed dressings and canola had imidacloprid seed dressing plus a bare-earth spray of bifenthrin (100 g.a.i./L) at 200 mL/ha applied after planting and before crop emergence.

Mites in crops and pastures were sampled using a modified posthole digger with collection aperture of 0.03 m². The design of the suction sampler was based on Wallace (1972). Each suction sample lasted 5 seconds (as per Umina and Hoffmann 2005) and were taken at 10 m intervals along two straight lines spaced 30 m apart starting at 5 m from the crop edge and extending 45 m into the crop. Three suction samples were pooled at each sampling point. The numbers of *B. medicagoense* and earth mites were counted and if numbers of either mite were greater than 50, then the number of mites was estimated by counting groups of 10 mites.

3.2.2.2 Sampling middle storey and lower storey

Beating was used to sample vegetation more than 55 cm tall. This was performed by holding a totebox in one hand under a branch or sapling and using a 1 m x 20 mm piece of dowel to tap the vegetation three times over the totebox (dimensions of 120 mm by 350 mm by 450 mm). If the vegetation was large this was repeated a further two times on the same plant on different sections. If the vegetation was small, two more plants were sampled. The three samples were pooled and the number of earth mites and *B. medicagoense* were counted visually. This was repeated three times for each family of plants. Native plants from the following families were

sampled: Mimosaceae, Proteaceae, Myrtaceae, Fabaceae; the following weed species were sampled when present: *Conyza* spp. (fleabane), *Solanum* spp. (nightshade), *Carduus* spp. (thistle), *Asparagus asparagoides* (bridal creeper), *Raphanus raphanistrum* (wild radish) and *Dysphania pumilo* (small crumbweed).

3.2.2.3 *Sampling of ground covers*

Grasses and plants that could not be effectively sampled by beating over a totebox due to their prostrate form, were sampled by suction using the modified post-hole digger (see 3.2.2.1). For each plant species or family, as described below, three suction samples were taken. The samples were then emptied into a totebox and a visual count of the number of earth mites and *B. medicagoense* was made. This was repeated three times for each plant type.

Weed species sampled included *Arctotheca calendula* (capeweed), *Citrullus lanatus* (camel melon) and *Ornithopus* spp. (serradella). Due to the difficulty in sampling a single grass species, exotic grasses, synonymously known as weed grasses, were pooled and included *Bromus* spp. (brome grass), *Eragrostis curvula* (African lovegrass) *Lolium rigidum* (annual ryegrass) and *Hordeum* spp. (barley grass). Native plants with sedge like leaves were also pooled and classified as sedges. These plants were from the families Dasypogonaceae e.g. *Lomandra* spp and Haemodoraceae e.g. *Conostylus* spp.

3.2.2.4 *Data analysis*

GenStat version 10.1.0.71 was used for all analyses.

3.3 Results

3.3.1.1 *Distribution and frequency of *Balaustium medicagoense* crop damage from 'Pestfax'*

PestFax reports only cover the grain growing regions of the Western Australia. Reports in PestFax of *B. medicagoense* on crops have come from as far north as Northampton, south to Albany and east to Esperance (Figure 8) and the majority of reports of *B. medicagoense* are in areas that have an average annual rainfall between 350 and 600 mm.

There were a total of 135 Pestfax reports from 1996 to 2010 mentioning *B. medicagoense*. Of these only 117 specified the crop type on which *B. medicagoense* was found. *Balaustium medicagoense* was reported feeding on barley, wheat, oats, canola, pasture, mustard and pulses (Table 3). Similar frequencies of damage for cereals, pulses and canola were recorded at 62%, 69% and 72% respectively. Only 36% of reports specifically stated that control for *B. medicagoense* was warranted and this was similar for cereals, pulses and canola at 36%, 38% and 42% respectively (Table 3). For pastures low levels of damage, with some silvering of grasses, were reported and at no time were controls recommended.

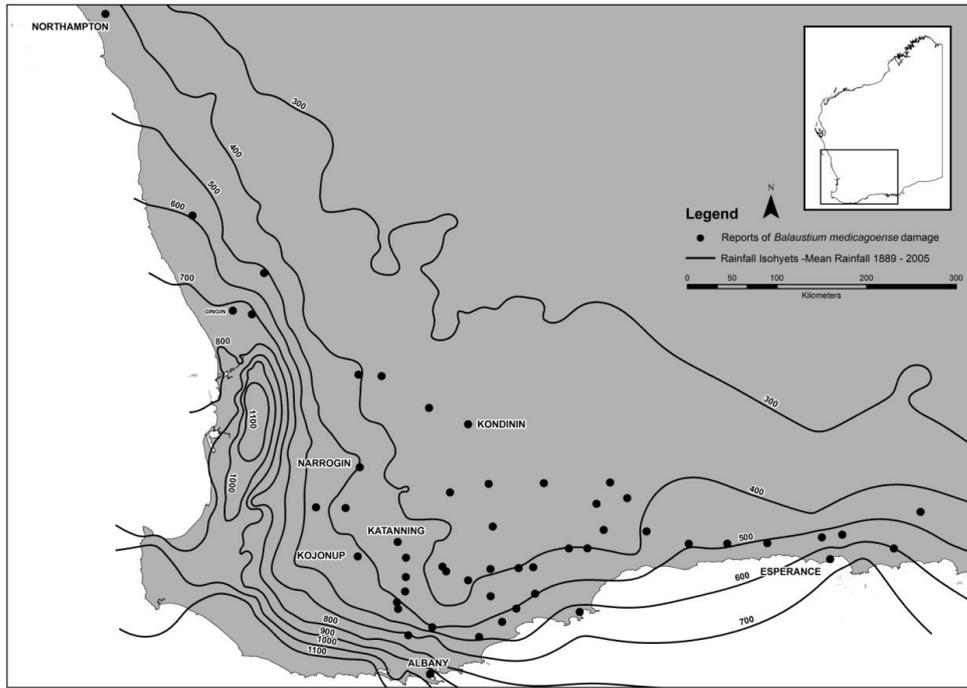


Figure 8: Distribution of *Balaustium medicagoense* (1996 to 2010) in Western Australia, showing mean rainfall isohyets. Individual data points represent observations (n = 135) of *Balaustium medicagoense* reported via ‘Pestfax’.

Table 3: Frequency of reports of *Balaustium medicagoense* on crops (1996 to 2010) in broad-acre growing areas of Western Australia. Data are field observations (n=117) reported by industry via the ‘Pestfax’ database.

‘?’ indicates that the report did not specify an answer to the posed question.

Crop type	No. of reports	Were crops moisture stressed?			Did <i>B. medicagoense</i> cause crop damage?			Was control for <i>B. medicagoense</i> required?		
		No	Yes	?	No	Yes	?	No	Yes	?
Barley	27	11%	48%	41%	0%	74%	26%	15%	44%	41%
Cereal unspecified	9	0%	33%	67%	0%	44%	56%	0%	22%	78%
Oats	4	25%	25%	50%	0%	50%	50%	25%	25%	50%
Wheat	10	10%	40%	50%	10%	50%	40%	20%	30%	50%
Total cereals	50	10%	42%	48%	2%	62%	36%	14%	36%	50%
Field pea	2	0%	0%	100%	0%	50%	50%	0%	0%	100%
Lupins	14	7%	36%	57%	0%	71%	29%	0%	43%	57%
Total pulses	16	6%	31%	63%	0%	69%	31%	0%	38%	62%
Canola	43	5%	35%	60%	2%	72%	26%	7%	42%	51%
Total other	8	38%	0%	62%	25%	13%	62%	38%	0%	62%
Total	117	9%	35%	56%	3%	64%	33%	11%	36%	53%

3.3.1.2 Crop damage and moisture stress

There was only sufficient data for lupins, canola and combined cereals to give an estimation of crop growth stage and whether growers reported control as warranted. Young crops were more susceptible to *B. medicagoense* damage than established crops (χ^2 $p < 0.001$) and no controls were advised for established crops. Insecticide applications were recommended by agronomists for seedling crops and mainly for cereals and canola (Table 4). A Pearson chi squared test on the total number of reports as measured by the agronomists opinion as to whether control was warranted (Table 4) had a value of 1.1 indicating that there was no significant difference between the susceptibility of cereals, canola and lupins to *B. medicagoense* damage.

Of the PestFax reports that recorded both crop stress and requirement for control, 29/42 (69%) of respondents reported that control was warranted on stressed plants but only one recommended control on unstressed plants (Table 5). Ignoring the “not specified” responses in Table 5, the chi square was highly significant at 24.27 ($p < 0.001$).

Table 4: Number of ‘Pestfax’ reports stating crop type and crop stage for which control for *Balaustium medicagoense* was required.

* growth stage not specified, generic term for ‘young’ crop.

Crop damaged	Crop Stage	Control warranted		
		No	Yes	Not specified
Cereals	Seedling*	0	8	4
	1 leaf	0	3	4
	2 leaf	2	3	3
	3 leaf	1	0	1
Cereals Total		3	14	12
Canola	Cotyledon	2	7	6
	Seedling*	1	6	1
	1 leaf	0	2	1
Canola Total		3	15	9
Lupins	Seedling*	0	4	2
	3 leaf	0	0	1
	4 leaf	0	1	0
Lupins Total		0	5	3
Grand Total		6	34	24

Table 5: Frequency of *Balaustium medicagoense* causing crop damage in relation to moisture stress from ‘Pestfax’.

Were crops moisture stressed?	Control warranted			Total number of reports
	No	Yes	Unsure	
No	9	1	1	11
Yes	3	29	9	41
Unsure	1	11	68	80
<i>Total number of reports</i>	13	41	78	132

3.3.1.3 Mite numbers per plant requiring control

The actual number of *B. medicagoense* stated as causing damage on seedling crops varied for each crop type. The highest frequencies of spray applications were to: cereals at the 1-2 leaf stage that had 10 mites per plant; canola at emergence with 2-4 mites per plant and lupins at the seedling stage with 15-30 mites per plant (Table 6). These constituted only 18% of reports.

Table 6: Number of *Balaustium medicagoense* per plant noted in ‘Pestfax’ as causing damage to crops.

Crop damaged	Crop Stage	Number of <i>B. medicagoense</i> /plant		
		1-4	5-10	>10
Cereal	1-3 leaf	3	9	1
Canola	Emergence-1 leaf	6	0	0
Lupins	3-4 leaf	0	0	2

While there was no difference in the apparent susceptibility of crops to *B. medicagoense* the number of mites observed to be causing this damage was significant. Lupins carried the largest number of mites followed by cereals, then canola ($\chi^2 = 23.69$, $p < 0.001$)

3.3.1.4 Correlation between ‘Pestfax’ and occurrences in the field

The reports received on Pestfax followed the abundance of pests as measured in the survey fairly closely early in the season. Late in the season there were few reports despite pest numbers being high in spring. This indicates that growers and advisers assume *B. medicagoense* is an early season pest and start looking and reporting before the numbers build-up in late autumn and ignore the spring (October) flush (Figure 9).

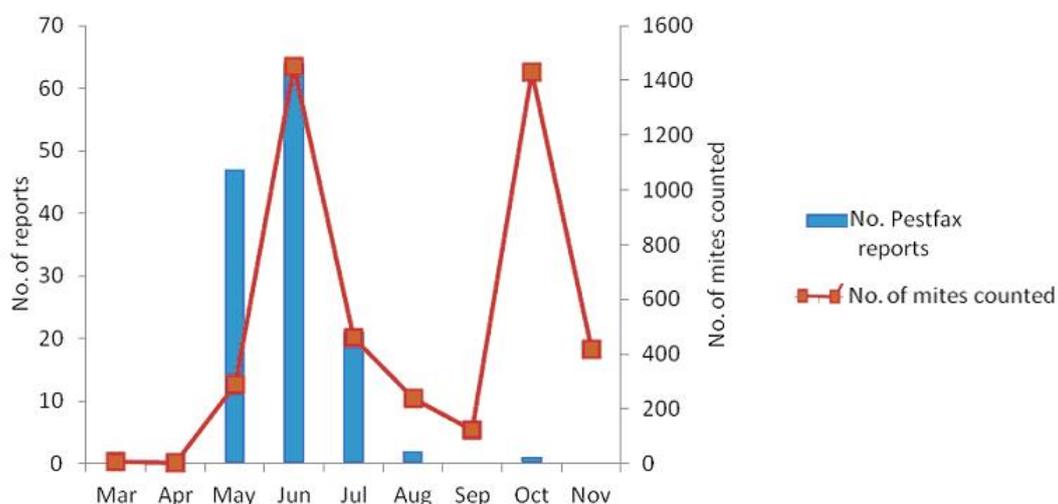


Figure 9: Time of year of Pestfax reports from 2006-2010 in relation to actual numbers of mites observed in surveys in 2010.

* Numbers are based on plant host surveys conducted on 6 of each pasture, canola and cereal paddocks in 2010

3.3.2 Plant host survey

3.3.2.1 Field survey of abundance of *Balaustium medicagoense* and earth mites in crops

Pasture sustained higher numbers of mites than cereal or canola crops. On average, pasture had significantly higher ($p < 0.001$) numbers of *B. medicagoense* and earth mites than crops (Figure 10), whereas cereals had higher numbers ($p < 0.001$) of *B. medicagoense* than canola (Figure 10). These differences could be due to different in-season spray regimes.

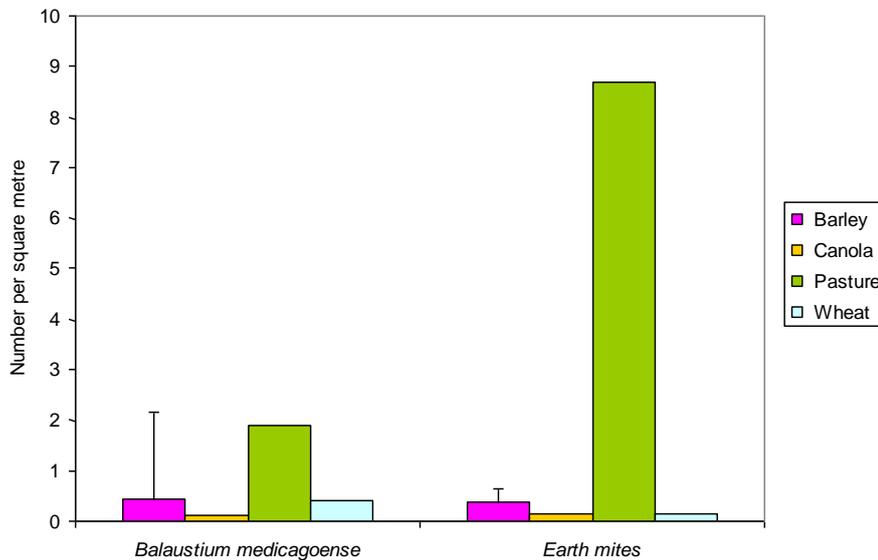


Figure 10: Mean number (+SED) of *Balaustium medicagoense* and earth mites on different crops over all sample times.

Agronomists have reported *B. medicagoense* as causing damage to seedling and moisture stressed crops. Agronomists suggested canola having a threshold of four mites per seedling; lupins with 15 mites per seedling; and cereals had 10 mites per seedling.

3.3.2.2 Abundance of *Balaustium medicagoense* and earth mites in relation to sampling distance from the crop edge

There was no change in *B. medicagoense* population density from the field edge to 45 m from the edge in wheat, barley, canola or pasture fields. Earth mites however did show decreasing abundance with increasing distance from the field edge in canola and barley fields but not in wheat (Figure 11) or pasture.

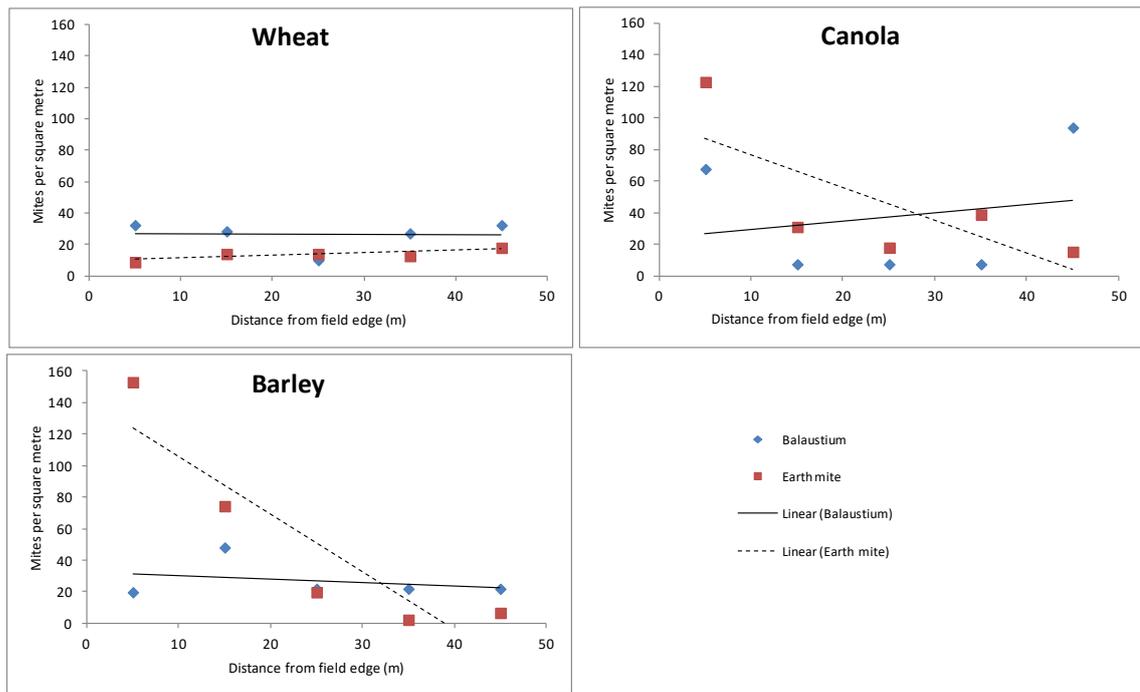


Figure 11: Mean number of *Balaustium medicagoense* and earth mites at set distances (metres) from the crop edge on different crop types.

3.3.2.3 Abundance of *Balaustium medicagoense* in remnant native vegetation

Balaustium medicagoense was found on a wide range of plants. Low numbers of this mite were found on species from the Papilionaceae and Proteaceae families (Table 7), which had on average less than one mite per three totebox samples, suggesting plants within these families are not suitable hosts. There were no mites found in beat samples from plants in the Mimosaceae and Myrtaceae families. Suction sampling did find *B. medicagoense* on native sedges, weed grasses and wild melon (Table 7). No mites were found on fleabane, mintweed, nightshade, tagasaste, thistles, capeweed or bridle creeper. Though suction sampling found *B. medicagoense* on native sedges from the Dasyopogonaceae and Haemodoraceae families, weed grasses may also have been inadvertently sampled. At some sites it was observed that stands of native sedges had weed grasses in proximity. Even though the number of samples taken of native sedges and weed grasses were the same, weed grasses had on average 2.48 times more *B. medicagoense* than native sedges (Table 7). It is likely that native sedges are less suitable host plants when compared to weed grasses.

Even though the abundance of *B. medicagoense* cannot be directly compared between the two different sampling methodologies used in the surveys, namely suction sampling and beating, comparisons can be made between plants sampled using the same technique. Thus, weed grasses are likely to be more suitable hosts than sedges as they supported higher densities of *B. medicagoense* than native vegetation (Table 7). Wild melon plants were not prolific in native

vegetation and very low numbers of mites were found on them (two mites were found on twelve plants). This suggests that wild melons are unlikely to be a suitable host for *B. medicagoense*.

Table 7: Frequency of *Balaustium medicagoense* on all plant types sampled.

Sampling method	Plant type	Frequency	Total mites	Number of samples
Beat sampling	Proteaceae	0.4%	2	503
	Papilionaceae	0.8%	5	503
Suction sampling	Melon weed	16.7%	2	12
	Weed grass	18.2%	151	506
	Native sedge	7.3%	37	506
	Pasture	38.7%	3804	180
	Barley	16.3%	189	180
	Canola	3.6%	140	180
	Wheat	15.7%	253	180

3.4 Discussion

3.4.1 Crop damage

Balaustium medicagoense is considered to be a pest of seedling canola (Berlandier and Baker 2007; Gu *et al.* 2007; Micic 2005) and lupins (Mangano *et al.* 2008), though not of cereals (Hopkins and McDonald 2007). The lack of pest status of *B. medicagoense* in cereals is probably due to the morphological structure of cereal plants which allows the plants to out-grow mite feeding damage. Cereals have the shoot apex protected within the sheath of older leaves (Kirby and Appleyard 1987) and this enables these crops to produce new leaves even if older leaves have been extensively damaged (Setter and Carlton 2000b). By contrast, canola and lupin plants have an exposed shoot apex and if it is damaged, this can lead to plant death (Dracup and Kirby 1996; Hadley and Pearson 1999). Consequently, cereals can withstand more feeding damage. However, field agronomists do recognise that damage is occurring and regularly recommend control measures. Agronomists believe cereals, lupin and canola are equally susceptible to economic damage at the seedling stage and that *B. medicagoense* causes little damage to older crops (Table 4).

3.4.1.1 Crop damage and moisture stress

Balaustium medicagoense is more likely to cause damage to stressed plants than to those experiencing good growing conditions. This may be because seedlings that are moisture stressed show a reduced capacity to compensate for mite feeding damage because moisture stress retards crop growth (Anderson *et al.* 2000; Duff *et al.* 2006; French and White 2008). Seed size of affected plants may also play a part. Chapman *et al.* (2000) concluded that under water stress pasture varieties with small seed had less ability to compensate for mite feeding damage than those with larger seed sizes.

However, moisture stress and feeding damage by *B. medicagoense* could be confused. The Pestfax survey recorded the opinions of agronomists assessing fields and under poor growing conditions it is difficult to apportion the observed lack of growth between pest and seasonal effects. This survey showed that agronomists believe the effects of *B. medicagoense* are worse in stressed conditions and this is a hypothesis that could be tested in well designed experiments.

3.4.1.2 Environmental conditions and *Balaustium* life stage

Usually moisture stress in crops in broad-acre situations coincides with warmer environmental conditions. Species in the genus *Balaustium* are able to tolerate arid environments (Wohltmann *et al.* 2001; Yoder *et al.* 2006, 2008). According to Cadogan and Laing (1977), *Balaustium putmani* developed at faster rates at temperatures of 22.5 °C, though moisture was essential for egg development. But if egg eclosion has already occurred, development of the prelarva to deutonymph is possible under low humidities (76%) (Wohltmann *et al.* 2001). Under warmer conditions *B. medicagoense* nymphs will develop into adults at a faster rate. This means higher numbers of *B. medicagoense* adults will be found on moisture stressed crops. This could be tested under laboratory conditions. Preliminary experiments, not reported in this thesis, were not successful in rearing *B. medicagoense* from egg to adult.

3.4.2 Potential thresholds

Agronomists assessed numbers of *B. medicagoense* per plant rather than numbers per square metre. This is because assessment of mite numbers per square metre is nearly impossible to ascertain without the use of a suction sampler (PJ Michael pers. comm. 2004). Even so, *B. medicagoense* is not just found on the plants but can also be located on the soil surface. Thresholds for other mites take this into account, for instance the current threshold for earth mites is one mite per 10 cm².

It is the established crop density at the beginning of the season that determines whether or not there is going to be sufficient yield if abiotic conditions are not limiting. Crop density is mainly determined by the seeding rate but soil conditions, stubble retention, seed size and many other factors also impact on crop establishment.

The Pestfax survey showed agronomists believed thresholds of 5-15 mites per seedling were damaging and this was modified by the stress the crop was currently experiencing and the stage of growth. Further work is required to unravel the relationship between pest abundance, plant species, growth stage, and the effects of seasonal conditions such as temperature, soil moisture and frost on both the pest and the host. The survey had shown that experienced agronomists are adjusting their advice depending on these factors and the presence of other pests.

3.4.2.1 *Differences in feeding damage between *Balaustium medicagoense* and earth mites*

Balaustium medicagoense causes less feeding damage to crops than earth mites (Murray *et al.* 2012). This difference in feeding damage is possibly due to the morphological differences in the chelicerae. Earth mites possess long styliform moveable cheliceral digits that are well adapted to sucking out the contents of a single cell (Krantz and Lindquist 1979; Lindquist 1996; Ridsdill-Smith 1997). The depth to which a mite can penetrate the leaf on which it is feeding depends on the length of the digits that are attached to the chelicerae (Ridsdill-Smith 1997). *Halotydeus destructor* possess moveable digits approximately 20 µm in length and plant cell damage by is limited to the top 50 µm of the leaf. Whereas in *P. major* the moveable digits are approximately 70 µm long, causing greater feeding injury to plants than *H. destructor* (Ridsdill-Smith 1997). In contrast, the Erythraeidae undergo radical ontogenetic change from the non-retractable hook-like chelicerae of the larvae to the retractable stylet-like (dagger-like) chelicerae of adults (Krantz and Lindquist 1979; Lindquist 1996; Makol 2010; Soller *et al.* 2001; Southcott 1961; Wohltmann *et al.* 2001), both of which lack a cheliceral digit (Krantz and Lindquist 1979; Wohltmann *et al.* 2001). Even though, both adult and larval forms of *Balaustium* have been observed feeding on plant material (Arthur *et al.* 2010; Krantz and Lindquist 1979; Newell 1963), their chelicerae may not be as well adapted to phytophagy as mites with cheliceral digits (Ridsdill-Smith 1997).

3.4.3 **Plant hosts**

3.4.3.1 *Crop hosts and distribution in the paddock*

Balaustium medicagoense was found to feed on all major crops and pastures grown in southern Western Australia. This supports findings from Arthur *et al.* (2008, 2010, 2011). Higher numbers of *B. medicagoense* were found in pasture than on other crop types, so crops grown after pasture will have higher numbers of *B. medicagoense*. Similar findings for earth mites have found that the crops: canola, wheat, barley are considered to be host plants of earth mites and crops grown after pastures have higher numbers of these pests (see Gaull and Ridsdill-Smith 1996; Umina and Hoffmann 2004; Weeks and Hoffmann 1999).

However, unlike earth mites, *B. medicagoense* does not have a gradient in its distribution in tilled paddocks. This could be because:

(1) insecticides applied in paddocks only had efficacy on earth mites. This is why earth mites were found in higher numbers on crop edges (where exposure to insecticides would be limited) whereas there was no gradient in their distribution in pasture paddocks.

(2) the act of tillage affects the distribution of earth mites, but not *B. medicagoense*. Tillage decreases plant densities and earthmite move into paddocks on weeds (Weeks and Hoffman 1999). Whereas the distribution of *B. medicagoense* 45 m into crops from

which there was limited plant material from the crop edge suggests that the mites probably hatch or survive in situ rather than invade from the edge of cropped paddocks.

3.4.3.2 Native hosts

This mite was only ever found on ground covers. It is unlikely to have a climbing habit like other species in the genus *Balaustium*. The endemic flora surveyed is unlikely to be plant hosts of *B. medicagoense*. Even though very low numbers were collected from native sedges, these mites are more likely to have come from associated grasses adjacent to the sedges rather than the sedges themselves. This indicates that native sedges are potentially poor plant hosts for *B. medicagoense*, though these surveys need to be repeated to ensure pure plant stands are sampled.

Halotydeus destructor, one of the main component species of earth mites, and *B. medicagoense* are both endemic to South Africa and are known to feed on the same broad-acre and pasture species (Arthur *et al.* 2010; Gu *et al.* 2007; Micic 2005; Micic *et al.* 2008; Umina and Hoffmann 2003). So it is likely that *B. medicagoense* will feed on similar endemic plant species to *H. destructor*, however, according to Qin and Halliday (1996), *H. destructor* has never been collected from native vegetation in Australia. Hence, it is plausible that the plant host range of *B. medicagoense* does not extend to native species that were surveyed. Nevertheless it cannot be discounted that *B. medicagoense* may use other endemic plant species as hosts. For instance, this mite has a preference for grasses (Arthur *et al.* 2010), so endemic Poaceae may be a suitable host. However, these were not included in the plant host survey as pure stands could not be found to sample. Further surveys are required to determine the native vegetation host range of *B. medicagoense*.

3.4.3.3 Introduced plant species

Within the Western Australian vegetation, it is the exotic flora that is more likely to sustain higher numbers of *B. medicagoense*. Plant host surveys found that exotic grasses had the highest abundance of *B. medicagoense*. Similarly, plant host surveys conducted by Qin and Halliday (1996) on *H. destructor* found this mite in association with introduced grasses rather than native grasses. It is highly probable that it is exotic grasses, especially those originating from South Africa, that are likely to be the preferred hosts for *B. medicagoense*.

Exotic grasses are either perennial or annual and are able to persist between cropping seasons especially if there has been adequate summer rainfall (Whalley *et al.* 2005; Wheeler *et al.* 2002). It is probable that this mite is able to persist on exotic grasses in native vegetation between cropping seasons.

Native vegetation that has a high proportion of weeds may be a potential source for *B. medicagoense* incursions into crops. According to Weeks *et al.* (2000), dispersal of *H.*

destructor and *Penthaleus major* into crops starts from the crop edge, but these mites are able to disperse up to 15 m in one week from the point of entry into a crop. This movement was aided by the presence of green plant material.

3.5 Conclusion

The distribution of *B. medicagoense* is recorded from areas of Western Australia that have an average rainfall of 350 to 600 mm. Crops grown in this area are most at risk of damage from this pest. However, the capability of *B. medicagoense* to cause economic feeding damage on crops depends on two factors. Firstly, adult *B. medicagoense* need to be present in sufficient numbers when crops are at emergence and secondly, crops must not be able to outgrow mite feeding damage. This inability to outgrow damage is usually due to sub-optimal abiotic conditions for crop growth e.g. limited soil moisture.

Balaustium medicagoense is polyphagous. However, native plants are not significant hosts and infestations in native vegetation are probably on exotic species. The non-crop plant hosts are primarily exotic grasses.

Despite the use of imidacloprid seed dressing or/and a bare earth spray application of bifenthrin, there was no gradient in the distribution of *B. medicagoense* in cropped paddocks. This indicates a lack of mid-paddock control for this mite; whereas there is a defined edge in the distribution of earth mites suggesting current farming practices are restricting the movement of this mite.

Further research is required on actual numbers of *B. medicagoense* on plants that require control. However, pasture sustains higher numbers of this mite than other crops, thus crops planted after pastures are more likely to have higher populations of *B. medicagoense* than continuously cropped paddocks.

4 The effect of plant-host associations and competition on *Balaustium medicagoense* numbers

4.1 Introduction

4.1.1 Pest status of *Balaustium medicagoense*

Since the 1990's, the amount of canola grown in southern Western Australia has increased (ABARE 2010, 2017; Duff *et al.* 2006), and the number of reports of feeding damage by *B. medicagoense* on crops has also increased (Arthur *et al.* 2010; Hoffmann *et al.* 2008). Prior to 1990, *B. medicagoense* was not considered to be a crop pest (James 1995). The change to pest status of *B. medicagoense* was probably due to the shift from animal-based agricultural production to annual cropping systems based on rotations of wheat, barley and canola (ABARE 2010, 2017; Hoffmann *et al.* 2008). It is likely that feeding damage to plants by *B. medicagoense* remained unnoticed in grazing systems as pasture plants, such as clover and grasses, are better able to compensate for mite feeding damage than annual crops (Michael 1997; Thackray *et al.* 1997).

4.1.2 The need for alternative control measures to pesticides

Effective crop management often needs to focus on the period before planting to protect the crop seedlings from damaging numbers of pests. If this is not done then seed dressings, bare-earth or post-crop emergence applications need to be considered. The only option once the crop emerges is to apply control measures using pesticides with a rapid knock-down and high efficacy (see Chapter 2, Table 1; Table 2). Rapid knockdown and bare-earth sprays are preferred to foliar applications of systemic products and seed dressings because of the potential of crop loss if pests are present at high densities.

Consequently, the predominant control measure for pests in broad-acre crops is the application of prophylactic insecticides before planting. These are usually applied for the control of weevil and mite pests such as *B. medicagoense* (see Appendix 1). Pesticides applied after planting usually target earth mites (James 1991; Mangano and Micic 2008; Mangano and Severtson 2007) but the rates commonly used do not control *B. medicagoense* (Arthur *et al.* 2008; James *et al.* 1995).

Alternative controls to insecticide applications for *B. medicagoense* need to be developed. Firstly, there is increasing demand in international markets for agricultural commodities to be produced using sustainable farming practices, which includes decreasing pesticide residues (Kingwell and Pannell 2005; McMullen 2003; Williams and Il'ichev 2003). Secondly, there is a risk that *B. medicagoense* will develop resistance to commonly applied insecticides similar to

the resistance to synthetic pyrethroids already detected in populations of *H. destructor* (Umina 2007). This has been postulated to be due to the over reliance on synthetic pyrethroids for the control of invertebrate pests (Umina 2007). As *H. destructor* occurs in sympatry with *B. medicagoense* (Micic *et al.* 2008), these populations are being exposed to repeated applications of insecticides.

To date there are no known crop varieties with resistance to mite feeding damage (Liu and Ridsdill-Smith 2001; Moritz and McDonald 1995; Ridsdill-Smith *et al.* 2008). According to Gu *et al.* (2008) there are some cultivars of canola that are more tolerant of mite feeding damage than other cultivars. There have been clover cultivars developed with increased tolerance to *H. destructor* damage and there is some evidence to suggest these clover cultivars decrease the fecundity of *H. destructor* (Nichols *et al.* 2009; 2012). For broad-acre cropping the use of cultivars or varieties of crops such as canola that are resistant to feeding damage from mites are not currently available.

Another option is to look at whole paddock management. For instance, seedling crops vary in their risk of sustaining damage from *H. destructor*, depending on the paddock planting histories. Clover dominant pastures, for example, sustained high numbers of *H. destructor* (Umina and Hoffmann 2004), whereas lentil, chickpeas and cereals sustained lower numbers of this mite species (Merton *et al.* 2005; Umina and Hoffmann 2004). Therefore planting crops such as canola after pasture is likely to lead to increased damage to crops whereas planting canola after lentils or chickpeas or cereals lowers the likelihood of crop damage.

Control of *B. medicagoense* using paddock management, requires an in-depth understanding of the plant-host dynamics. The ability for a mite species to persist in a paddock across seasons is directly related to its relationship with the available host plant species. For example, plant-host associations have been studied in earth mites and differences in the ability of species within the earth mite complex to persist and reproduce on different crops and weeds have been reported. For instance, *H. destructor* is able to persist on canola, wheat and oats (Merton *et al.* 1995; Umina and Hoffmann 2004), *Penthaleus major* persists on oats and wheat, and *Penthaleus falcatus* persists on canola (Umina and Hoffmann 2004). Conversely, Arthur *et al.* (2010), whilst able to show that *B. medicagoense* will exhibit certain plant host preferences, with high numbers being found on wheat, lupins, oats and pasture, were not able to show consistent persistence on these crop types from one season to another.

It could be that the presence of a green-bridge may allow for the persistence of *B. medicagoense* populations between cropping seasons. The term 'green-bridge' describes the mass of vegetation consisting of weeds and crop volunteers growing in paddocks, headlands, roadsides and non-crop land between cropping seasons (Berlandier 2004; Leonard 2009; Micic 2005). In southern Western Australia, a green-bridge is the result of summer rainfall, which may provide

B. medicagoense with suitable habitat and food sources to survive over the summer and persist within the environment all year round. It is likely that development of *B. medicagoense* instars is similar to that of *B. putmani*, which undergo diapause if conditions are unfavourable, particularly the lack of suitable moisture (Cadogan and Laing 1977). The presence of a green-bridge signifies that there is moisture within the environment that may aid the survival of *B. medicagoense*.

4.1.3 Effect of competition on *Balaustium medicagoense* populations

Other factors such as the removal of competition may also affect populations of *B. medicagoense*. As *B. medicagoense* and earth mites have a sympatric distribution (Micic *et al.* 2008), there is likely to be niche overlap between these species. According to Pianka (1974), even if two organisms have extensive niche overlap, this does not necessitate competition if resources are plentiful, as these can be shared without detriment to either organism. However, Denno *et al.* (1995) suggest that even if resources are plentiful, inter-specific competition between phytophagous organisms can still occur if the same feeding niche is shared. So the control of earth mites in paddocks may leave a niche open for *B. medicagoense* to fill.

It is also possible that intra-specific competition may impact on the fecundity of *B. medicagoense*. Intra-specific competition occurs between individuals of the same species and there are two recognized forms: scramble and contest competition. Scramble competition occurs when all individuals are similarly affected by the availability of resources and if resources are limited all individuals are equally affected. Conversely, in contest competition some individuals have an adequate share of resources whereas others die as they are unable to obtain optimum resources for survival (Begon *et al.* 2006). Within *H. destructor* and *P. major*, intra-specific competition was found to occur as scramble competition. It was found to be variable, occurring in some years and not others (Umina and Hoffmann 2005; Weeks and Hoffmann 2000). Hence, intra-specific competition is a factor that needs to be considered.

4.1.4 Aims

In this chapter, the effects of different plant hosts on the persistence and reproduction of *B. medicagoense* are investigated and the subsequent crop damage and thresholds for economic damage are discussed. The abundance of *B. medicagoense* in the presence and absence of competing earth mites is also investigated. This information will provide the basis for developing sustainable practices, such as cropping rotations and weed management ultimately leading to integrated pest management guidelines for the control of this pest.

The aims of this chapter are to:

- Determine the effect of green-bridges on the abundance of *B. medicagoense*;

- Determine the effect of various potential host plants on the persistence and reproduction of *B. medicagoense* in the field;
- Determine the effect of inter and intra specific competition on *B. medicagoense* populations.

4.2 Materials and methods

A large field experiment was conducted at Esperance Downs Research Station, Gibson, Western Australia (33°36'01"S, 121°46'55"E).

This experiment was established to investigate:

- (a) The ability of *B. medicagoense* to persist on host plants;
- (b) The effect of inter-specific and intra-specific competition on abundance of *B. medicagoense*; and
- (c) The effect of a green-bridge on populations of *B. medicagoense*.

The site was chosen because of the abundance of *B. medicagoense* in surrounding pastures and its close proximity to a water source for irrigation to form a green-bridge over summer. This experiment was conducted over 3 years on five land-use patterns: pasture, barley, canola, lupins and barley planted after a green-bridge. Crops that were investigated were chosen because they are predominantly grown in southern Western Australia, namely canola, barley and lupins (ABARE 2010, 2017) as well as pasture. Wheat, though it is also a major crop in southern Western Australia (ABARE 2010, 2017), was excluded due to the size constraints of the trial area.

4.2.1 Experiment set up

4.2.1.1 First year

A randomized block design of crops in 15 m by 3 m strips was prepared by planting crops between pre-existing strips of pasture (Refer to Figure 12 for experimental lay out). In June 2006, barley, canola and lupins were planted using a 1.5 m plot seeder, with 25.4 cm row spacings.

Block 1					Block 2					Block 3					Block 4				
1	0	0	1	0	1	0	1	1	1	0	0	1	0	1	1	1	0	1	0
0	0	1	0	1	0	0	0	1	0	1	0	0	1	1	0	0	1	1	0
1	1	0	1	0	1	1	1	0	1	0	1	1	0	0	1	1	0	0	1
0	1	1	0	1	0	1	0	0	0	1	1	0	1	0	0	0	1	0	1

Treatments:

■	Barley
■	Canola
■	Lupins
■	Pasture
■	Barley + summer weeds

Sub-treatments: 1 = earth mites & *B. medicagoense*; 0 = *B. medicagoense*

Figure 12: Experimental design of field enclosure experiment.

Prior to planting, the entire experiment area received herbicide spray applications of 1 L/ha of glyphosate (510 g.a.i./L) and 0.1 L/ha of carfentrazone-ethyl (400 g.a.i./L) plus fertilizer applications of Allstar® (13.9% N, 14.1% P, 9.1% S, 01.3% Cu, 0.13% Zn, 0.05% Mn) at 105 kg/ha. At the same time lupin and canola crops also received herbicide applications of 0.55 kg/ha of simazine (900 g.a.i./kg) and 0.55 kg/ha of atrazine (900 g.a.i./kg). Crops were planted at the following rates: barley at 90 kg/ha, canola at 6 kg/ha and lupins at 120 kg/ha. Following planting, but before the emergence of the crop, the entire experiment area was sprayed with 50 mL/ha of bifenthrin (100 g.a.i./L) for control of earth mites. These rates of bifenthrin do not have efficacy on *B. medicagoense* (see Arthur *et al.* 2008).

In all plots, once they were planted, weeds were controlled by spraying with undiluted glyphosate (510 g.a.i./L) or were removed by hand if they could not be controlled chemically. Specifically for broadleaved weeds, mainly *Arctotheca calendula* (capeweed), in lupin and canola plots, and grasses, such as *Hordeum* spp., in the barley plots.

Four weeks after crop emergence, eighty individual circular plots, with a diameter of approximately 2 m were each constructed using sheet metal (6.29 m in length, 0.25 mm thick, 1 m high) that was dug 30 cm into the ground, based on similar experiments of Umina and Hoffmann (2004) and Michael (1995).

Earth mites consisting of *Halotydeus destructor* (redlegged earth mites) and *Penthaleus* spp. (blue oat mite) were collected together with *B. medicagoense* from adjacent paddocks (33°36'07"S, 121°47'04"E). *Balaustium medicagoense* was separated from the earth mites using a dissecting microscope and then 100 *B. medicagoense* and 200 earth mites were added to 40 plots as shown in Figure 12. This was done over a 10 day period in late July. In the remaining 40 plots, resident *B. medicagoense* were the only pest mite species present, as the bifenthrin spray application controlled the earth mites.

In order to prevent mite movement between plots, polybutene was spread on the upper inside edge of the sheet metal and reapplied monthly. Bimonthly, weeds on the outside of plots were

controlled 1 m from the outside edge of each plot using 2 L/ha of Sprayseed™ (active ingredients: 135 g/L paraquat (present as paraquat dichloride), 115 g/L diquat (present as diquat dibromide)) and invertebrates were controlled using 200 mL/ha of bifenthrin (100 g.a.i./L). The pastures were also cut every 8 weeks to approximately 10 cm in height using hand held hedge clippers.

Umina and Hoffmann (2004) found that in shade house experiments mite numbers decreased after introduction by as much as 50%. To reduce this effect, and allow surviving mite populations to reproduce, plots were not sampled until September 2006. Refer to 3.2.2.1 for mite sampling technique.

4.2.1.2 Years 2 and 3

In 2007 and 2008, each plot was planted with the same crop species as the year before, using the same herbicide applications and fertilizers. Each crop was hand planted at the following rates: barley at 90 kg/ha, canola at 6 kg/ha and lupins at 120 kg/ha. In addition, the fungicide carbendazim (500 g.a.i./kg) was applied to the lupin seed at a rate of 0.5 g/kg of seed to decrease the incidence of disease. Post planting, weed control was conducted as in year 1.

An automated watering system was set up in March 2007 and February 2008 in all pasture plots and barley + summer weeds plots (See Figure 12). This simulated summer rainfall to germinate weed seeds to form a green-bridge. Watering occurred for 3.5 hours daily from 00:00 hrs to 03:30 hrs. Each watered plot received on average 12.5 L of water per hour through drip irrigation to simulate summer rainfall. Plots were irrigated daily for 8 weeks to allow maximum germination of volunteer crop or weeds. In 2008, to reduce evaporation and assist in weed growth, 50% shade cloth was placed over the plots and was removed 4 weeks later once green plant material was established.

4.2.2 Scoring plant damage

In each plot, crops and pasture plants were scored for feeding damage by mites. In cropped plots, each seedling along 2 m of crop row was assessed for mite feeding damage, whereas in pasture plots an average assessment was made for plants in a square quadrat of 0.1 m² in area. This was done when canola and lupins were at the cotyledon stage and cereals were at the 2 leaf stage.

Damage was assessed as the amount of bleaching to cotyledons or to the first two cereal leaves and was rated on a visual scale. The scale indicators used for this study were: 0 = nil damage; 2.5 = 50% damage and 5 = all plants dead or dying. This scale was modified from methodology described by Chapman *et al.* (2000), Gillespie (1991) and Umina and Hoffmann (2004) who rated damage by earth mites to pasture and crops using a scale of 0-10.

4.2.3 Assessment of pasture composition

Composition of pasture was assessed by determining the relative percentage of each species in each pasture enclosure. This was done each year one day before crop harvest. The average was then taken as a representation of the composition of the pasture for that year.

4.2.4 Assessment of abundance of non-crop plants

In September 2006, weed abundance was visually assessed as a percentage of the total plant biomass in each plot. In 2007 and 2008 this was repeated at each sampling date. This was done as an estimate over the entire area of each enclosure.

4.2.5 Harvest

Each year, the entire crop in each plot was hand harvested along with any weed material. The dry weight of each was taken to provide the biomass of weeds relative to that of the crop as an indication of an alternative food for mites.

4.2.6 Mite sampling

Mites were suction sampled using a Stihl™ blowervac BG55. The nozzle of the blowervac had a sieve with fine mesh (holes at ~ 10 µm) placed 5 cm into the aperture of the blowervac. The nozzle of the blowervac was held 2 cm above the ground and 1.5 m of crop row or pasture by 12 cm width was suction sampled. Samples were placed into 150 mL sample jars containing 70% ethanol. All mite species collected were identified to genus and counted using a dissecting microscope. The experiment was first sampled in December 2006 and then monthly until November 2008.

4.2.7 Data analysis

Mite and plant numbers were converted to the number per square metre for analyses. Effects of plant hosts and green-bridge on *B. medicagoense* numbers were determined by using a square root transformation ($\sqrt{(x+0.5)}$) to achieve normal distributions of the data sets prior to analysis. Treatment effects were compared by analysis of variance (ANOVA) using the computer software package GenStat version 10.1.0.71.

Competition effects were determined by normalising mite numbers using a $\log_{10}(x+1)$ transformation. The reproductive output (R_0) was calculated for *B. medicagoense* in pure and mixed treatments and for earth mites in mixed treatments for each plant type. The normal reproductive output was calculated by dividing the number of adult mites in September by the number of adult mites in May (as per Weeks and Hoffmann 2000) in 2007 and 2008 as this is when both earth mites and *B. medicagoense* were present in the trial area. Diapause R_0 was calculated as the number of adult mites at the start of 2008 divided by the number of adult mites

at the end of 2007 (Umina and Hoffmann 2005; Weeks and Hoffmann 2000). To determine if inter-specific competition occurred, R_0 values from *B. medicagoense* were compared to mixed treatments on each plant type using ANOVA (Umina and Hoffmann 2005; Weeks and Hoffmann 2000). Multiple regressions were used to determine if R_0 in 2007 and in the diapause generation was dependant on N_0 number of earth mites or number of adult *B. medicagoense* at the end of the season (Weeks and Hoffmann 2000). This allowed inter-specific and intra-specific competition to be examined (as per Umina and Hoffmann 2005; Weeks and Hoffmann 2000). If there was a significant relationship between R_0 and N_0 in *B. medicagoense* this suggests intra-specific competition occurred. T-tests were used to determine if the slope of the regression (b) was significantly different from -1. Under contest competition b does not significantly differ from -1 and under scramble competition b should differ from -1 (Umina and Hoffmann 2005; Weeks and Hoffmann 2000).

The difference between crop types on the reproductive output was analysed as the difference between the constants, where the linear regression equation is: $R_0 = \text{constant} + bN_0$.

4.3 Results

4.3.1 Seasonal abundance patterns

Balaustium medicagoense was found only in the presence of a green-bridge over summer. Variable control of weeds in the summer of 2006/7 resulted in the majority of plots having a green-bridge. Consequently, the experiment was repeated in the summer of 2007/8. Unlike summer 2006/7, which had a rainfall event of 160 mm in January (Figure 13), the summer of 2007/8 was characterised by having low rainfall (Figure 13) and resulted in no plants germinating naturally in any of the plots. Subsequent sampling of all plots found no *B. medicagoense*, even though *B. medicagoense* were present in all plots in the previous season (Figure 14). After irrigation was applied, summer weeds germinated in all irrigated plots and subsequent samplings found *B. medicagoense* present only in these plots (Figure 14). Un-irrigated plots remained weed free over summer until rainfall in April 2007 (Figure 13). Summer weeds that germinated included grasses of the *Avena* spp. (wild oats), *Bromus* spp. (brome grass) and *Hordeum* spp. (barley grass) from the Poaceae family, *Romulea rosea* (onion grass) from the Iridaceae family and *Arctotheca calendula* (cape weed) from the Asteraceae family.

Balaustium medicagoense persisted over greater temperature ranges than earth mites. This mite was found in plots when mean temperatures ranged from 11 °C to 27 °C (refer to Figure 13, Figure 14 and Figure 15). Conversely, earth mites were only found in plots from May to September in 2007 and April to September 2008. Mean temperatures ranged from 11 °C to 15 °C

during these months in 2007 and 10 °C to 20 °C in 2008. There was no apparent correlation between rainfall *per se* and *B. medicagoense* numbers.

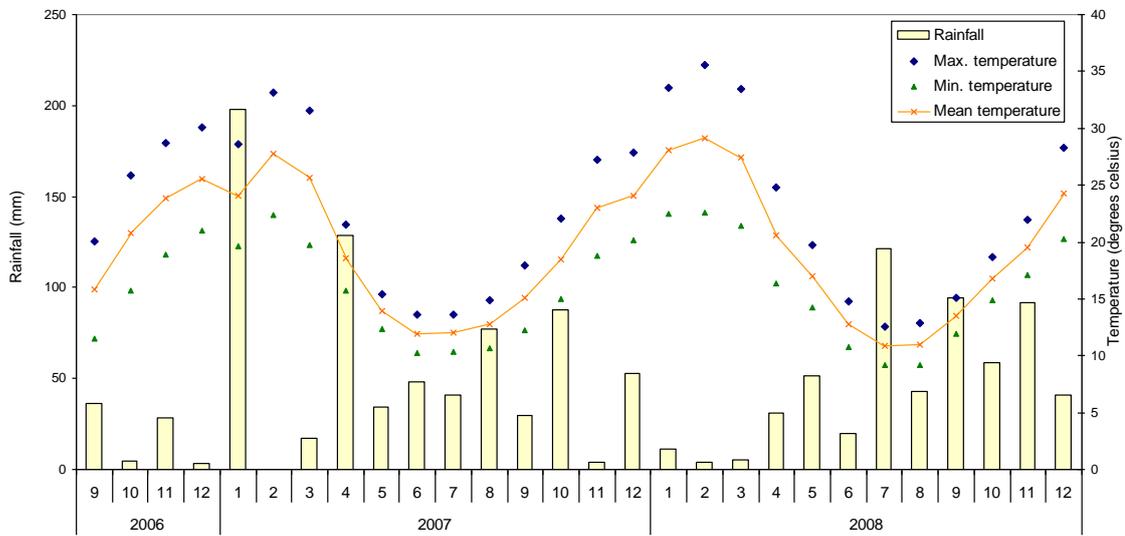


Figure 13: Total monthly rainfall (mm) and mean soil temperature with maximum and minimum range for the month, from Esperance Downs Research Station during 2006 - 2008.

Pastures sustained higher numbers of *B. medicagoense* than canola, barley or lupin crops. Significantly higher ($p < 0.001$) numbers of *B. medicagoense* were found in un-irrigated pasture than in crop plots at the last sampling in September 2006 (Figure 14, Figure 15) and this pattern was observed throughout 2007 (Figure 14). On average there were significantly ($p < 0.001$) more *B. medicagoense* present on pastures than on crops in both years (Figure 14, Figure 15). In 2008 and 2007 barley plots with summer weeds sustained more mites than un-irrigated plots (Figure 14; Figure 15). Even though pasture plots in 2008 were irrigated during summer, the numbers of mites on them decreased from 2006 to 2007 and from 2007 to 2008 (Figure 14). This may be due to changes in floristic composition as pasture plots in 2007 had significantly ($p = 0.004$) less cape weed and significantly more ($p < 0.001$) grasses than were found in the same plots in 2008 (Figure 16). There was no difference in *B. medicagoense* density attributable to crop types of canola, lupins or barley (Figure 15). However, the presence of a green-bridge in the barley plots increased *B. medicagoense* numbers in 2008 ($p < 0.001$) at early and mid-season sampling times (Figure 14).

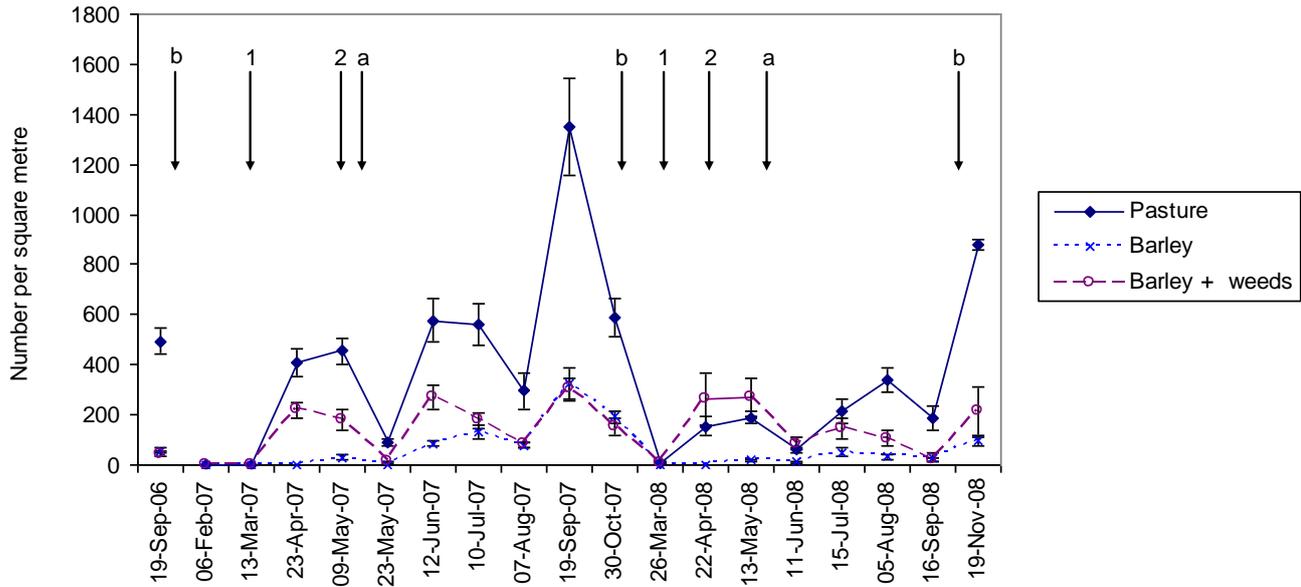


Figure 14: Mean number (\pm SE) of *Balaustium medicagoense* found on irrigated pasture, irrigated summer weeds followed by barley and a conventional* barley crop.

Arrows indicate dates of: irrigation starting (1), irrigation ceasing (2), planting of crops (a) and of harvest (b).
* barley sown in the absence of summer weeds

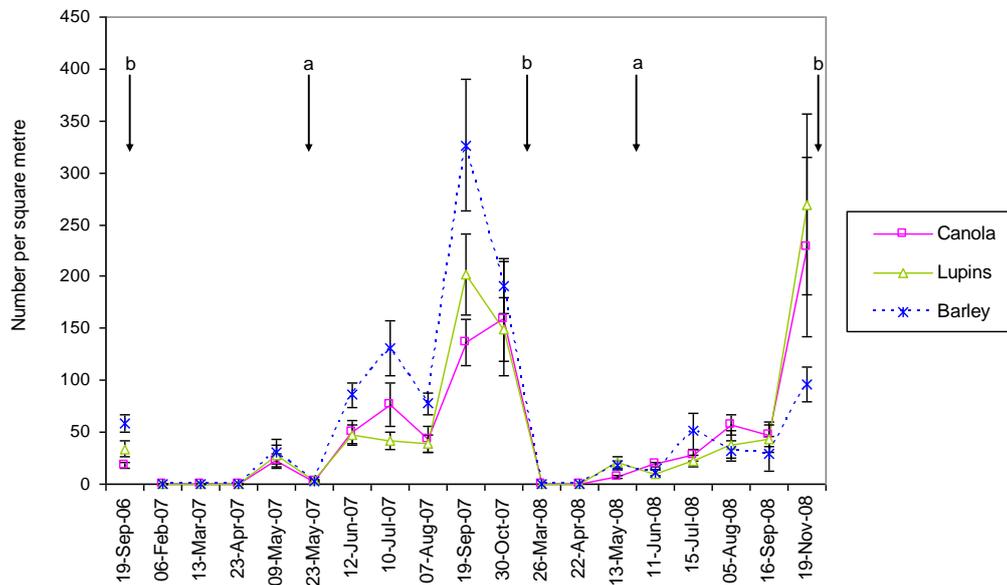


Figure 15: Mean number of *Balaustium medicagoense* (\pm SE) on canola, lupins and barley.

Arrows indicate dates of: planting of crops (a) and of harvest (b).

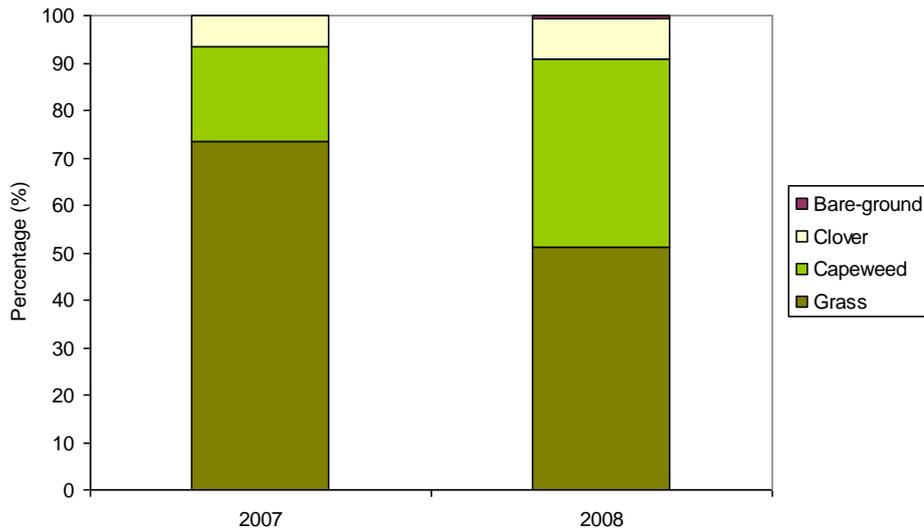


Figure 16: Floristic composition of pasture in 2007 and 2008.

Cropped plots were hand weeded but some weeds were still present during the growing season. Throughout the 2007 growing season, the average percentage of weeds in all crop plots was less than 10% (Figure 17). In 2008, plots with lupins and canola had 40% weed material. This increase in weed material in 2008 coincided with decreased plant densities across all plots (Figure 17). Weeds provided an alternative food source for mites; however, the effect on *B. medicagoense* numbers was insignificant compared to the effect of having continuous pasture versus the bare area associated with planting a crop (Figure 14).

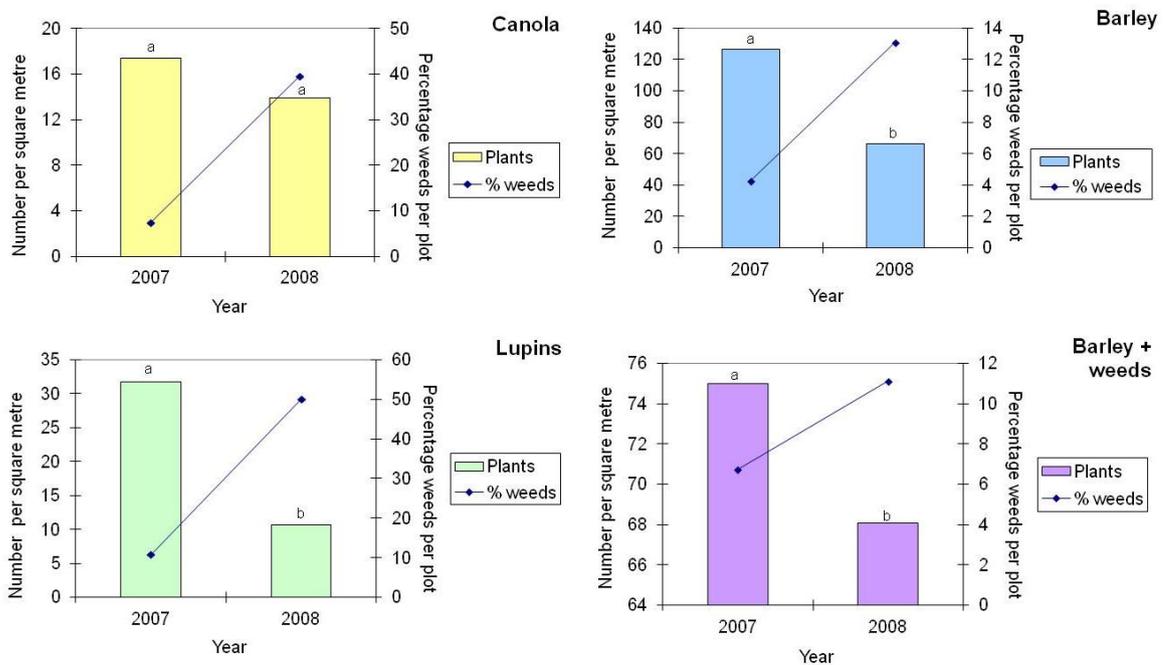


Figure 17: Average number of plants per square metre within plots and percentage of weeds present in each plot.

Note graphs have different scales. Different letters indicate significantly different means.

4.3.2 Reproductive output of *Balaustium medicagoense* on different crop types

Plant type had a significant effect on the reproductive output of *B. medicagoense*. Even though higher numbers of this mite were found in pasture and barley with summer weeds than on crops, with on average 32% more mites being found in pasture and 18% more being found in barley with summer weeds than were found on crops (Figure 14), *B. medicagoense* had higher reproductive outputs in crops. On average significantly higher ($p=0.001$) reproductive outputs were observed on canola, lupins and barley treatments than on pasture or barley with weeds, with this mite having an average 43% and 20% greater reproductive output on crops than on pasture or barley with weeds respectively (Figure 18). Even so, the reproductive outputs of *B. medicagoense* between crops decreased from 2007 to 2008, coinciding with a decrease in plant densities (Figure 18, Figure 17).

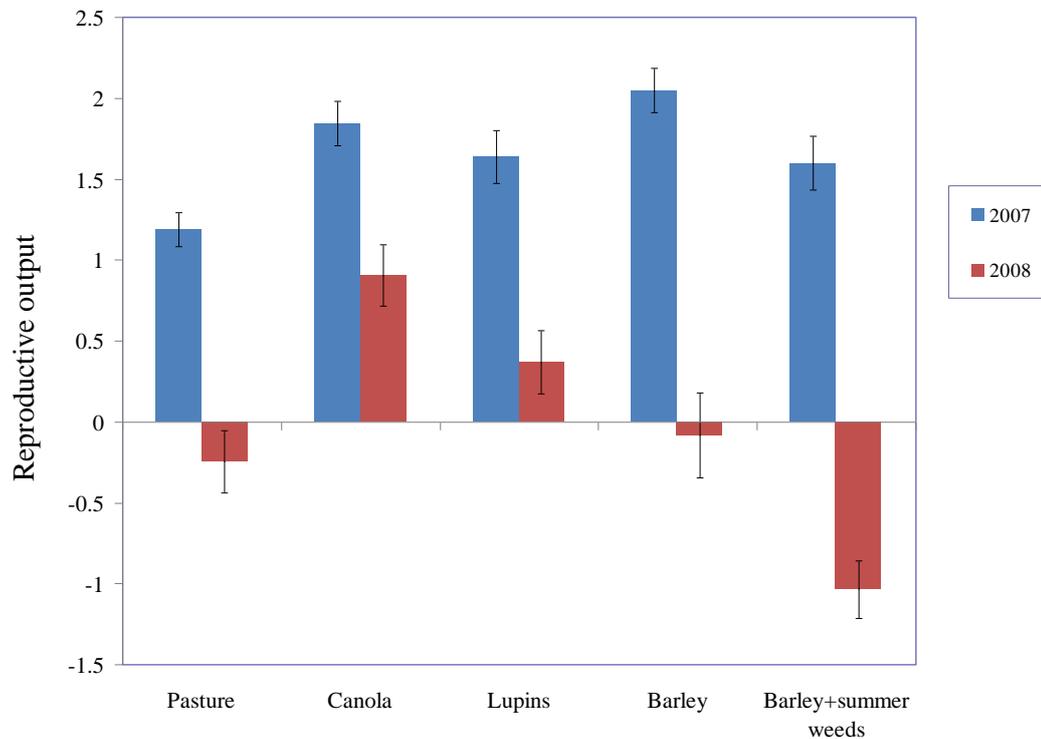


Figure 18: Reproductive output of *Balaustium medicagoense* (\pm SE) on different crops over 2007 and 2008.

4.3.3 Crop damage

The extent of mite feeding damage to crops was significantly different between the years of this study and the main treatments of crop type. There was no significant difference in the plant damage score due to the sub-treatments or interaction between treatment (crop type) and sub-treatment (\pm earth mites). In 2007, barley with summer weeds sustained significantly more

($p < 0.001$) feeding damage than barley, canola and lupin crops, with on average having a feeding score 1.7 times higher than the other crops. Whilst in 2008, there was no significant difference between barley \pm summer weeds, instead lupins and canola had significantly more ($p < 0.001$) damage with on average a feeding damage score twice as high as that of barley + weeds (Figure 19). This is likely due to differences in mite densities present in treatments between years. Canola and lupin plots had similar numbers of *B. medicagoense* in 2007 and 2008, whereas mite numbers decreased in barley plots (Table 8). The total mites present (i.e. *B. medicagoense*, *H. destructor* and *Penthaleus* spp.) in the plots did not cause sufficient feeding damage to seedlings to cause plant death (Figure 19). Also there was no significant difference in plant densities between sub-treatments i.e. \pm earth mites. This suggests that for mite feeding damage to cause seedling losses, total mite numbers i.e. *B. medicagoense* + earth mites need to exceed the mite numbers that were present at the time the plant damage assessments were made in 2007 and 2008 (Table 8).

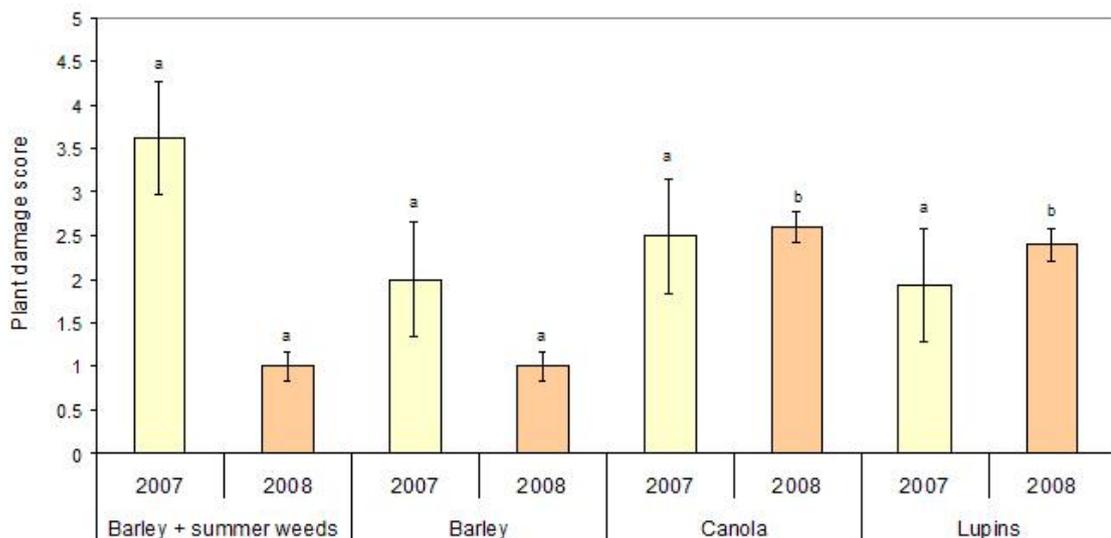


Figure 19: Average plant damage (\pm SE) caused by mite feeding at the seedling stage of crops in 2007 and 2008.

Letters indicate significantly different means within years, not between years.

Table 8: Average mite numbers per square metre present at the time of scoring crop seedlings for mite feeding damage in 2007 and 2008.

Note BM is *Balaustium medicagoense* and earth mites are *Penthaleus* spp and *Halotydeus destructor*.

Mite species	2007		2008					
	Canola	Lupins	Barley	Barley +weeds	Canola	Lupins	Barley	Barley +weeds
BM	40	41	77	249	50	26	34	77
Earth mites	72	100	281	76	24	15	5	52
Total mites	112	141	358	325	37	23	13	110

4.3.4 Competition effects on *Balaustium medicagoense*

The absolute exclusion of earth mites to create the “pure” *B. medicagoense* (or “nil earth mite”) sub-treatment was not achieved. The differences in numbers of earth mites between sub-treatments was significant ($p < 0.001$) with on average (over all years) ‘pure’ treatments having 47% fewer earth mites than mixed treatments. This percentage was significant in 2007 ($p = 0.003$) and 2008 ($p < 0.001$) (Table 9).

The reproductive output of *B. medicagoense* between mixed and pure sub-treatments over all crop types was not significantly different when analysed using a one-way ANOVA. This indicates that earth mites do not affect the reproductive output of *B. medicagoense*. The data from pure and mixed plots were considered as independent points and linear regression was used to determine the frequency and intensity of any competitive interactions.

As the reproductive output of *B. medicagoense* is strongly associated with plant hosts it is unlikely that this species of mite has a strong tendency towards obligatory predation. If the reproductive output of this species was correlated with prey, such as earth mites, then the regression analysis should have shown positive b parameters for the regression of R_0 against earth mite numbers (N_0). For all comparisons the b values were negative or not different to zero (Table 10).

Table 9: Percentage difference of earth mite numbers between mixed and pure sub-treatments

* over all years

Crop type	2007	2008	Average*
Pasture	40.12	53.49	45.77
Canola	37.66	87.27	47.15
Lupins	39.39	56.29	44.90
Barley	32.01	85.51	39.91
Barley+ weeds	58.85	65.38	61.68

4.3.4.1 Reproductive output of *Balaustium medicagoense* regressed against numbers of adult *Balaustium medicagoense*

During the 2007 and 2008 seasons, on all crops, there was a significant negative relationship between the reproductive output of *B. medicagoense* and the number of adult *B. medicagoense* at the beginning of the season (Figure 20, Table 10 b, c). Thus, plots with higher densities of *B. medicagoense* had lower reproductive outputs over the season indicating intra-specific competition.

Crop type also affected the reproductive output of *B. medicagoense*, during the 2007 and 2008 season. If the constant of the regression of $\log N_0$ on $\log R_0$ is significantly different from zero

then there is a treatment affect². For all crops with the exception of barley + weeds in 2008, the constant was significant indicating reproductive output is also dependent on crop type during the growing season (see Table 10 b, c).

Density (N_0) at the end of the season also negatively affected the reproductive output of *B. medicagoense* over the diapause period of 2007-08 (Figure 21). Linear regression indicated a significant negative relationship only in canola between reproductive output of *B. medicagoense* and numbers of *B. medicagoense* in the preceding season (Table 10 d). Similarly, the constant of canola significantly differed from zero (Table 10 d), indicating that the crop type also influenced the reproductive output of *B. medicagoense*. The slope of the regression line also was not significantly different from -1 suggesting contest competition had occurred.

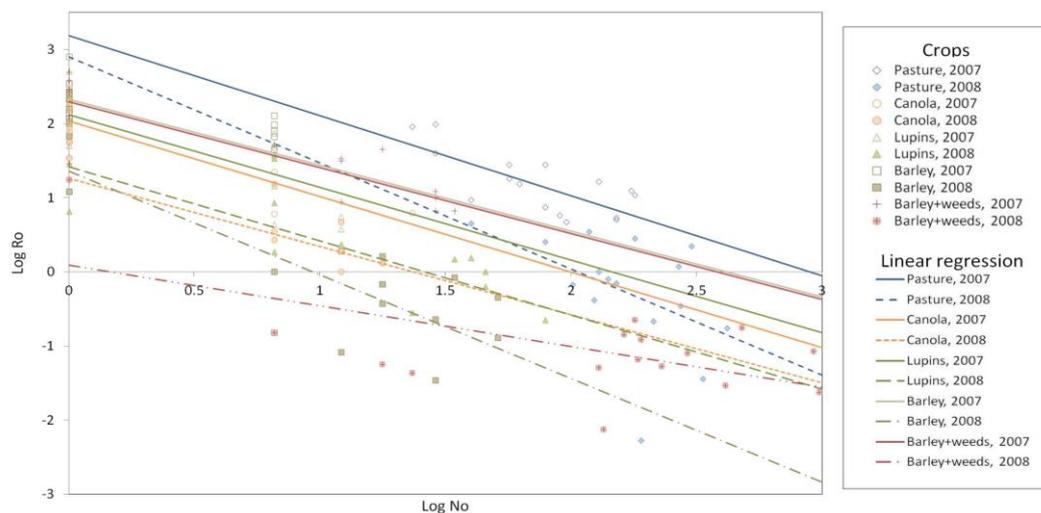


Figure 20: Multiple linear regression for reproductive output (R_o) of *Balaustium medicagoense* for the 2007 and 2008 growing season versus number of adult *Balaustium medicagoense* at the start of the season (N_o) on four different crop types.

² When the number of mites at the end of the period = the number at the beginning there is no effect of the treatment and $R_o = 1$ and $\text{Log } R_o = 0$.

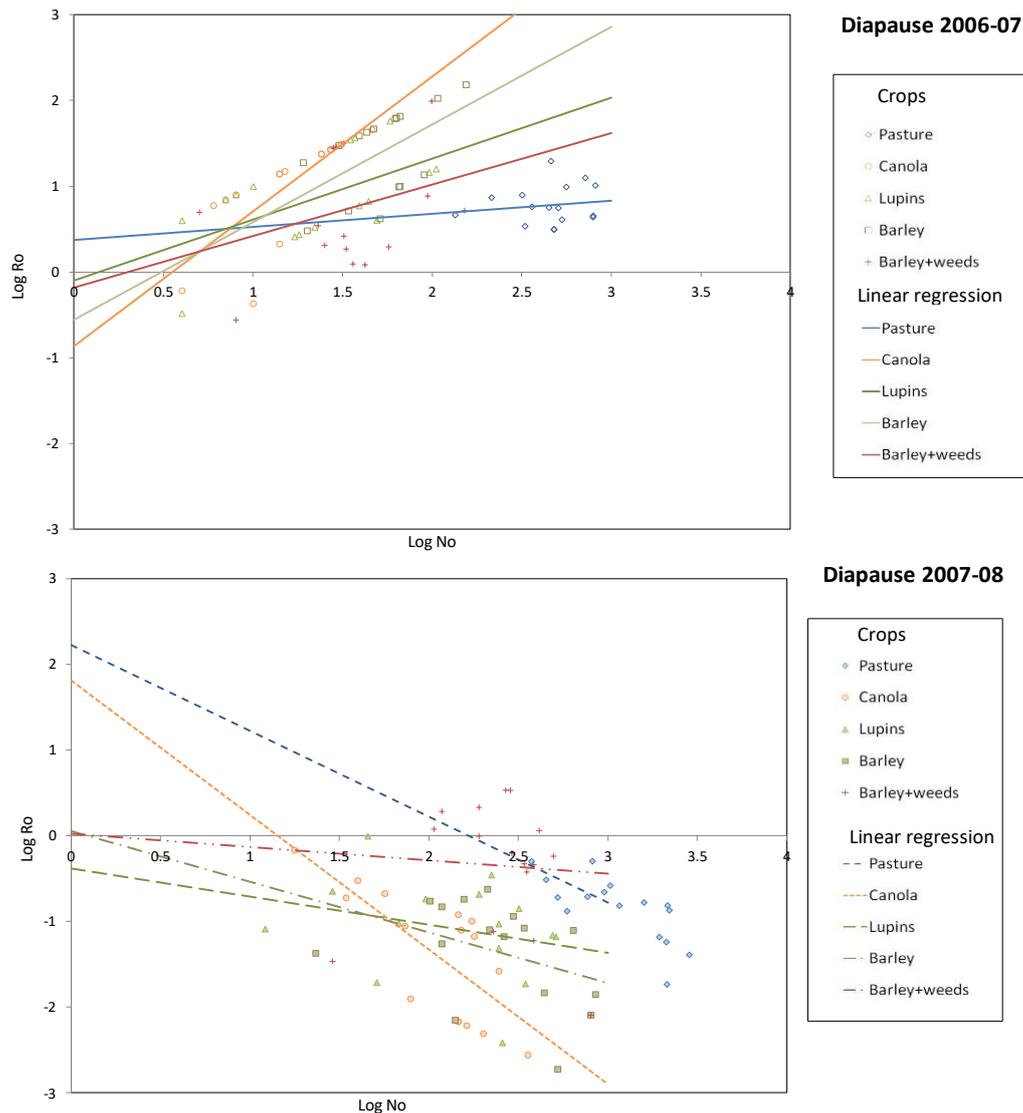


Figure 21: Multiple linear regression for reproductive output (R_0) of *Balaustium medicagoense* through diapause versus number of *Balaustium medicagoense* at the end of the previous season (N_0) on four different crop types.

However, there was a different pattern in the diapause period for 2006-07, with higher numbers of *B. medicagoense* adults in the previous season leading to a higher reproductive output (Figure 21). This suggests there was no intra-specific competition occurring. The relationship between reproductive output of *B. medicagoense* and numbers of *B. medicagoense* adults in the previous season was significant in the canola, lupins and barley monoculture crop treatments but not for the mixed species of pasture and barley + weeds (Table 10 a). There was also no significant difference between constants, suggesting crop type did not influence reproductive output over the 2006-07 diapause period (Table 10 a).

One of the main differences between the diapause periods of 2006-07 and 2007-08 was rainfall. In January 2007 a total of 198 mm was recorded as compared to only 11 mm in January 2008 (Figure 13). Rainfall in January 2007 was observed to have caused the germination of weeds in all plots and is possible to have led to *B. medicagoense* eggs to hatch. No samples were taken in

January to confirm this and no mites were found in sampling conducted in late February. Sampling in February occurred after a period of 4 weeks in which there had not been any rainfall (see Figure 13) and during which weeds were observed to have senesced.

Table 10: Co-efficients ($b \pm SE$) and constant ($\pm SE$) from multiple regressions testing if the number of adult (N_0) *Balaustium medicagoense* or earth mites influenced the reproductive output (R_0) of *Balaustium medicagoense* under different crop treatments.

(a) R_0 during the 2007 season regressed against the number of adult mites at the start of 2007);
 (b) R_0 through diapause (2006-07) regressed against the number of adult mites before diapause (end 2007);
 (c) R_0 during the 2008 season regressed against the number of adult mites at the start of 2008;
 (d) R_0 through diapause (2007-08) regressed against the number of adult mites before diapause (end 2007).
 Significance of the effect of N_0 on R_0 where $\sigma = P \leq 0.05$; $\eta = P \leq 0.01$; $\zeta = P \leq 0.001$;
 Degrees of freedom of the residual = 14 for all crop types.
 R_0 and N_0 were log10 transformed.

R_0	Crop type	Species (regressed against)			
		<i>Balaustium medicagoense</i>		Earth mites	
		<i>b</i>	Constant	<i>b</i>	Constant
(a) end 2006– start 2007					
	Pasture	0.15±0.28	0.37±0.76	0.13±0.05	0.67±0.07 ζ
	Canola	1.57±0.34 ζ	-0.87±0.42	-0.23±0.49	1.03±0.17 ζ
	Lupins	0.71±0.26 η	-0.10±0.37	-1.75±0.54 σ	0.95±0.11 ζ
	Barley	1.14±0.47 σ	-0.56±0.82	0.01±0.23	1.37±0.15 ζ
	Barley + weeds	0.60±0.47	-0.18±0.73	-0.19±0.28	0.82±0.22 ζ
(b) start 2007 – end 2007					
	Pasture	-1.08± 0.26 ζ	3.19±0.49 η	0.08±0.16	1.05±0.30 η
	Canola	-1.02±0.22 ζ	2.04±0.11 ζ	0.10±0.53	1.83±0.15 ζ
	Lupins	-0.98±0.27 ζ	2.12±0.18 ζ	-0.34±0.52	1.68±0.18 ζ
	Barley	-0.89±0.24 ζ	2.33±0.13 ζ	0.14±0.25	2.00±0.16 ζ
	Barley + weeds	-0.89± 0.13 ζ	2.30±0.13 ζ	0.41±0.33	1.48±0.19 ζ
(c) start 2008 – end 2008					
	Pasture	-1.43±0.69 η	2.93±1.55 σ	0.19±0.32	-0.61±0.66
	Canola	-0.92±0.09 ζ	1.26±0.15 ζ	-0.1±0.15	0.90±0.19 ζ
	Lupins	-1.00±0.20 ζ	1.42±0.24 ζ	-0.68±0.46	0.52±0.22 σ
	Barley	-1.4±0.31 ζ	1.36±0.36 ζ	-0.55±1.03	-0.05±0.28
	Barley + weeds	-0.55±0.19 η	0.09±0.41	-0.08±0.16	-0.93±0.27 η
(d) end 2007 – start 2008					
	Pasture	-1.00±0.25	2.22±0.76	0.19±0.13	-0.95±0.12 ζ
	Canola	-1.57±0.38 ζ	1.81±0.78 σ	-0.61±0.56	-1.33±0.19 ζ
	Lupins	-0.33±0.31	-0.38±0.67	0.45±0.73	-1.1±0.15 ζ
	Barley	-0.59±0.37	0.05±0.89	0.45±0.8	-1.35±0.16 ζ
	Barley + weeds	-0.15±0.44	0.02±1.06	0.08±0.19	0.14±0.68 σ

4.3.4.2 Reproductive output of *Balaustium medicagoense* regressed against numbers of adult earth mites

The relationship between reproductive output of *B. medicagoense* and numbers of earth mites was also investigated with multiple linear regressions. Linear regressions were not significant over any time period except for in lupins for R_0 over the 2006-2007 diapause period (Table 10) suggesting it is only in this crop that *H. destructor* numbers reduced *B. medicagoense* reproductive output. Of interest is that the constant for the regression of numbers of earth mites was significant for all crops except for barley in the 2008 season indicating crop type is more likely to affect the reproductive output of *B. medicagoense*.

4.4 Discussion

4.4.1 Green-bridge and abundance of *Balaustium medicagoense*

4.4.1.1 Potential diapause

Balaustium medicagoense does not have a cold temperature requirement as earth mites do. Earth mites hatch from over-summering eggs only if mean temperatures have been below 20.5 °C for a period of 7 days and there has been sufficient rainfall (Wallace 1970). *Balaustium medicagoense* were found to persist over a greater range of temperatures, suggesting temperatures do not influence the presence of this mite or initiate diapause.

Balaustium medicagoense has a diapause mechanism but *does* not appear to be obligatory as it is for *H. destructor* (Ridsdill-Smith *et al.* 2005; Wallace 1970). This mite was not found in the absence of plant material but was found to persist between cropping seasons and during the cropping season. Due to the addition of polybutene to the tops of the enclosures it is unlikely *B. medicagoense* were recolonising plots, it is more likely that this mite has a diapause mechanism, probably in the egg stage. According to Wohltmann *et al.* (2001), eggs of erythraeids undergo reversible cessation of development depending on relative humidity. This suggests the onset of laying of diapause eggs of *B. medicagoense* is associated with unfavourable climatic conditions associated with senesced plants and that diapause ceases when there is an increase in relative humidity following rain.

Higher numbers of *B. medicagoense* were found over all crop types at the end of the season. Similar patterns have been observed in earth mites, with abundance increasing prior to the onset of diapause and it has been postulated that this increase is to offset the high mortality rate of diapause eggs especially during a dry summer (Ridsdill-Smith and Annells 1997; Weeks and Hoffmann 2000).

Mortality of diapause eggs may also be a factor that may have led to decreased numbers of *B. medicagoense* in the 2007/8 diapause generation. In 2006/7 rain events occurred during summer and higher abundances were observed at the start of the 2007 season than were seen in the 2008 season.

4.4.1.2 Effect of controlling a green-bridge

Controlling weeds prior to planting has been an important factor for the control of many invertebrate pests in broad-acre cropping. This control has been found to be effective in the management of pests such as earth mites (Ridsdill-smith *et al.* 2008), lucerne flea (Michael 1984) and vegetable weevil (Micic *et al.* 2008). The presence of a green-bridge between cropping seasons did lead to increased numbers of *B. medicagoense* in the subsequent crop. However, planting the crops using herbicide applications led to a decrease in mite density. It is

the timing between herbicide applications to suppress weeds and the planting of crops that will be an important factor for a non-chemical control for this mite.

If weeds are controlled prior to planting, *B. medicagoense* motile adults or immature stages will not be present. However, it is highly probable that diapause eggs will be laid, as other species in the genus *Balaustium* lay diapause eggs if food sources are not available (Cadogan and Laing 1977). Consequently, it is important to know the length of time it takes for the eggs of *B. medicagoense* to hatch and reach adulthood, to determine if crops at germination will be at any risk of damage from *B. medicagoense*. In the case of earth mites, if conditions for hatching from diapause eggs occur in the absence of green plant material, the mites do not survive (McDonald *et al.* 1999; Ridsdill-smith *et al.* 2008). The results of this work support the notion that control of the green bridge, that consists of preferred plant hosts of *B. medicagoense* and earth mites, such as volunteer cereals and weed grasses, will be a useful technique for suppressing the numbers and damage caused by these pests.

4.4.2 Effect of plant hosts on persistence and reproduction of *Balaustium medicagoense*

Balaustium medicagoense is polyphagous having been observed feeding on canola, lupin, barley and pasture grasses and this mite also persisted on all crops trialled from 2006 to 2008. The reproductive output of *B. medicagoense* is strongly associated with plant hosts like that of earth mites (see Umina and Hoffmann 2005, Weeks and Hoffmann 1999; 2000). Grass is a preferred plant host with this mite having higher reproductive outputs on barley crops than in canola or lupin crops. Even though pastures had greater densities of this mite, the reproductive output was less than that on the other crops and there was also a corresponding decrease in the number of mites associated with pastures as the grass content decreased. Similarly, Arthur *et al.* (2010) found that *B. medicagoense* have a preference for grasses. This suggests that higher numbers of *B. medicagoense* will be found in crops planted after a barley crop or after a grass dominant pasture.

4.4.3 Potential thresholds for *Balaustium medicagoense*

Plant densities in this experiment decreased over time. It is unlikely that this was caused by mite feeding damage as the amounts of feeding damage assessed on crops was insufficient to cause plant mortality. Also the current threshold for earth mites on susceptible crops such as canola is 1000 earth mites per m² (Horne and Page 2008), which in this experiment, the number of earth mites in all plots only comprised 3.4% of the threshold. This decrease in plant density contributed to higher numbers of weeds post planting, as there was less crop competition to shade out weeds (see Weiner *et al.* 2001).

The presence of weeds may have impacted on the amount of feeding damage sustained by crop seedlings. The decreases in crop densities over years are more likely to be due to seasonal and agronomic factors such as disease, tillage and soil pests, rather than mite feeding damage. Even though disease occurrence was not scored and cultivars tested were chosen for their good disease resistance, it is still not recommended to plant the same crop type as the year before due to the high disease risk (e.g. black leg in canola (Khangura and Barbetti 1997) and brown spot of lupins (Sweetingham 1990)) that are spread from the stubble of the same crop type of the year before. Even though all care was taken when crops were hand harvested for all stubbles to be removed, the stalks were allowed to remain and this may potentially have provided an inoculum source for disease.

Glass house experiments conducted by Arthur *et al.* (2010) where 300 *B. medicagoense* were added to containers failed to cause crop death. Unfortunately, the paper does not specify how many plants were present in each container or the stage of the crop at which the mites were added. However, it does show the difficulty in inducing crop damage by this pest to cause crop death.

Feeding damage by *B. medicagoense* can cause significant reductions in crop height (Arthur *et al.* 2010). However, these reductions in plant height need to be equated to yield which is the main driver of economic effect. In this trial yields were taken and there was no significant difference between treatments or sub-treatments in each crop type. This indicates that the density of *B. medicagoense* in this experiment was below the economic threshold for this environment.

4.4.4 Competition niche theory

4.4.4.1 Inter-specific competition

The earth mite complex was not analysed with the individual species that comprise it. These individual species have different feeding preferences and survivorship on different host plants. For instance, *H. destructor* and *Penthaleus falcatus* are able to persist on canola though *P. major* and *Penthaleus sp. x* do not. Also *H. destructor* and *P. sp. x* persist on cereals, and all earth mites were found in high numbers on pasture (Umina and Hoffmann 2004). As *B. medicagoense* was found in this study to feed on all of these crops and this suggests that the differing species within the earth mite complex are potentially competitive with *B. medicagoense* for plant host resources.

There was only one instance of inter-specific competition between earth mites and *B. medicagoense* and this occurred on the lupin crop. The lack of evidence for competition on other crops could be due to a number of factors. According to Denno *et al.* (1995), phytophagous insects are more likely to compete if they are closely related (congeners),

introduced, aggregative and feed in identical niches. Even though earth mites and *B. medicagoense* are both exotic species, they are not closely related being in different families within the same sub-order (see Lindquist 1996). They do co-exist in the same feeding niche as both species feed on the same plant hosts (see Arthur *et al.* 2010; Umina and Hoffmann 2004), however, they do not explore exactly the same feeding niche. *Balaustium medicagoense* nymphs and adults are predatory (Arthur *et al.* 2010; James 1991, 1995; Micic *et al.* 2008) and have been observed feeding on green plant material (Arthur *et al.* 2010; Micic *et al.* 2008). However, *B. medicagoense* nymphs failed to develop to adults on plant material alone (Arthur *et al.* 2010; see Chapter 3) suggesting there is a requirement for an alternative food source (see Chapter 2) whereas Maclennan *et al.* (1998) showed that nymphs of *H. destructor* fed on microflora on the soil surface. Thus, the nymphal stages have low niche overlap and are unlikely to experience competition (Denno *et al.* 1995; Hairston *et al.* 1960; Schoener 1983). However, as adults share similar feeding niches, competition effects between these species should be evident (Caceres 1998). In this trial, this was not the case, the number of adult earth mites did not have an adverse effect on reproductive output of *B. medicagoense*.

Also the aggregating tendencies vary between these two mites. Earth mites occur in greater densities than *B. medicagoense*, suggesting that earth mites are better able to exploit feeding niches (Grimm unpublished data, Gaull and Ridsdill Smith 1996). If earth mites are controlled, it would be expected that densities of *B. medicagoense* would increase. The lack of statistical differences in this occurring, could be due to low mite densities, as inter-specific competition is not expected to occur at low densities of competitors (Caceres 1998; Connell 1983) and is more likely to occur when resources are limited (Schoener 1983). Even though earth mite numbers did differ between sub-treatments, these differences may not have been great enough to observe inter-specific competition.

Dry conditions can affect inter-specific competition (Caceres 1998; Connell 1983; Schoener 1983). In the case of earth mites, dry conditions lead to decreased fertility in diapause eggs (Weeks and Hoffmann 2000). However, the reproductive output of *B. medicagoense* decreased from 2007 to 2008. Even though 2006/7 was a relatively wet summer compared to 2007/8, the decrease in reproductive output was also found in plots with a green-bridge over summer. Consequently, adverse weather conditions are unlikely to have decreased any inter-specific competition affects.

It is unlikely that another mite species is competing with *B. medicagoense* in the exclusion plots. Even though only numbers of earth mites are reported here, counts of all mites to family were completed. Due to the density, abundance and feeding niches only earth mites were considered to be a candidate for inter-specific competition in these exclusion plots. However, it is possible under field conditions, that other mites or another invertebrate species do have a negative impact on *B. medicagoense* densities. For instance, control of *Sminthuris viridis* L.

(Lucerne flea) (Collembola: Sminthuridae) was observed to lead to increased numbers of *H. destructor* (Michael 1995, 1997).

4.4.4.2 Intra-specific competition

The results from this experiment provide evidence for intra-specific competition in *B. medicagoense* during the 2007 and 2008 season. The relationship between density and the reproductive rate was characteristic of contest competition (Begon *et al.* 2006). Even though, density-dependent competition will not occur when eggs are in the diapause stage, juveniles may compete for food sources once diapause breaks (Weeks and Hoffmann 2000). Results from this experiment suggest contest competition from diapause is variable occurring in some years and not others.

Contest competition has been defined as involving behavioural interference such as aggressive attack (Guedes *et al.* 2010); whereas Weeks and Hoffmann (2000) found that contest competition can occur without behavioural interference in earth mites. However, the actual behaviour underlying competition is usually poorly studied because the competition strategies are inferred from the relationship of surviving individuals to the initial number entering the resource (Guedes *et al.* 2010). For *B. medicagoense* this is the case. Adults are known to be predatory so it is highly probable that this species does exhibit behavioural interference however, displays of aggressive behaviours or cannibalism of eggs or larvae have not been directly observed.

4.5 Conclusion

Adult *B. medicagoense* are more likely to be present in higher numbers in crops if there has been a green-bridge present before crop establishment. Consequently, controlling weeds especially grasses that make up a green-bridge will lead to lower numbers of *B. medicagoense*.

Cropping rotations influence *B. medicagoense* populations. Crops planted after pasture and cereals will have higher numbers of *B. medicagoense*, whereas crops planted after canola or lupins will have lower numbers of *B. medicagoense*. If there are grassy weeds present in the crop during the growing season, there are likely to be higher numbers of *B. medicagoense* present within it at the diapause generation. Thus, controlling weeds during the growing season will lead to decreased numbers of *B. medicagoense* in the subsequent season.

The reproductive output of *B. medicagoense* is more affected by plant hosts and intra-specific competition than inter-specific competition. Control of earth mites during the growing season will have no effects on the reproductive output of *B. medicagoense* except in lupin crops where it will increase. However, it is possible that other invertebrate species have competition effects on *B. medicagoense*.

5 Chemical efficacy and effects of cropping rotations for control of *Balaustium medicagoense*

5.1 Introduction

Control of agricultural pests in Australian pastures and cropping environments relies heavily on pesticide applications (Arthur *et al.* 2008; Micic *et al.* 2008; Umina *et al.* 2004). These chemicals are inexpensive and routinely applied prophylactically for the control of pests (James 1991; Mangano and Micic 2008; Mangano and Severtson 2007). In Western Australia, prophylactic sprays tend to be applied with herbicide applications pre-planting to control potential pests (Appendix 1; Lawrence 2009; Micic *et al.* 2007). Throughout this thesis, the term prophylactic sprays, unless otherwise specified, are taken to be sprays applied pre-planting. The use of prophylactic sprays has increased in recent years as the amount of land cropped has increased (Hoffmann *et al.* 2008; Micic *et al.* 2008). However, only in the last decade has the number of reports of crop damage by *B. medicagoense* increased (Arthur *et al.* 2008; Hoffmann *et al.* 2008; Mangano and Severtson 2007; Micic *et al.* 2008).

Growers and agronomists anecdotally report that many pesticides registered for use on *Halotydeus destructor* are not effective against *B. medicagoense* (Arthur *et al.* 2008; 2010; Micic *et al.* 2008). This is supported by the laboratory bioassays conducted by Arthur *et al.* (2008) which have shown that *B. medicagoense* has a high tolerance to a range of pesticides registered for the control of *H. destructor* and *Penthaleus* spp. in Australia. For example, *B. medicagoense* has a 16-fold higher tolerance to alpha-cypermethrin and 26-fold higher tolerance to bifenthrin than *H. destructor*. According to Robinson and Hoffmann (2000) and Umina and Hoffmann (1999), invertebrates that exhibit a high tolerance to insecticides under laboratory conditions require higher rates of chemical applications for their control in the field. As such, there is a need to determine field rates of chemicals that have efficacy on *B. medicagoense* and to assess if current farming practices of prophylactic spray applications protect crops from *B. medicagoense* damage.

Reliance on pesticides alone is unlikely to provide sustainable pest management solutions (McDonald *et al.* 1999) as broad-scale applications of pesticides adversely impact on non-target organisms (Gu *et al.* 2007; Hoffmann *et al.* 2008; Umina and Hoffmann 1999; Umina *et al.* 2011). It is thought that the wide-spread practice of insecticide applications in broad-acre environs has selected for resistance in *H. destructor* (Edwards *et al.* 2008; Umina 2007; Umina *et al.* 2011). If insecticides are relied upon solely for the control of *B. medicagoense*, the grains industry in WA may yet see more pests develop resistance.

The undesirable effect of an agricultural system contributing to resistance of pests needs to be mitigated. Gu *et al.* (2007) suggest that this can only be achieved through the development of alternative control strategies that encompass integrated pest management (IPM) strategies. There are at least 21 definitions of IPM (Horne *et al.* 2008). For the purpose of this chapter, IPM is defined as the use of cultural, biological and chemical control methods to manage pest problems (Alston and Reading 1998; Horne and Page 2008; Horne *et al.* 2008). However, currently biological control is not a viable option for the control of *B. medicagoense* as there are no known predators. Hence, IPM strategies for *B. medicagoense* need to be based on the use of cultural control and for chemicals to only be applied to restrict pests from causing economic crop damage. The availability of such strategies would provide growers with opportunities to decrease pest abundance in crops thereby reducing the over-all reliance on pesticides.

To be widely adopted, IPM strategies need to fit into the frame-work of current cropping systems. In southern Australia, this consists of large-scale cropping systems (Gu *et al.* 2007; Hoffmann *et al.* 2008; Micic *et al.* 2008) based mainly on annual crops of wheat, barley and canola (ABARE 2010, 2017). Though pastures are still a part of some cropping systems, the amount of pastures grown has decreased in recent decades in response to low and/or variable returns from animal enterprises (ABARE 2010, 2017; Hill *et al.* 2005; Tilman *et al.* 2002). There is a need to explore which cropping rotations are best able to suppress *B. medicagoense* and this would form the basis of a cultural control strategy.

The effect of cropping rotations on *B. medicagoense* was investigated in a small scale experiment reported in Chapter 4. However, there is a need to see if results from this small scale experiment are applicable to a farming system. For some mite species, the mechanical tillage of soil associated with cropping as well as the cropping rotation itself affects their abundance. For instance, the mite *Anystis wallacei*, which is a biological control agent for *H. destructor*, was found to only persist in high numbers in pasture environments that had moderate grazing pressures and were not mechanically manipulated (Michael 1995). So, there is a need to determine if *B. medicagoense* is able to persist in farming systems that are continuously cropped.

Weed control is another strategy incorporated into IPM practices to decrease the abundance of pests. Results from Chapter 3 suggest that this cultural method may decrease *B. medicagoense* numbers sufficiently to prevent potential crop damage. Within southern Western Australia, a single herbicide application is common practice prior to planting crops (Moore and Moore 2017). The timing of this herbicide application, also known as the first knock-down, depends on when there has been sufficient rainfall for planting. It is common practice in some years to apply this knock-down 5-10 days prior to planting (Moore and Moore 2017). The effect of the timing of a herbicide application to control weeds on *B. medicagoense* numbers needs to be further explored.

Currently, many farming systems in southern Western Australia use minimum or zero tillage techniques (Crabtree 2000; D'Embden and Llewellyn 2006). Within WA, minimum or zero tillage is defined as the use of tillage machinery that has either knife-points (narrow planting points 16 mm in width that attach to a tyne) or zero-tillage discs that create a slot into which the seed and fertiliser is placed causing little soil disturbance (Crabtree 2000; Flower and Braslin 2006). These operations need to leave 30% or more plant residues on the soil surface to reduce erosion by water and wind (Derpsch 2003). Where plant residues are retained, studies have shown that within the following year, soil moisture is retained potential enabling planting to take place earlier and crop yields are increased (Gardner *et al.* 1994). The practice of leaving plant residues after harvest on the soil surface is known as stubble retention (Flower and Braslin 2006).

However, the retention of stubble may lead to greater numbers of pest mites. For instance the presence of mulch on the soil surface has been observed to lead to increases in fecundity of *H. destructor* (Thackray *et al.* 1997; Maclennan *et al.* 1998) and there is concern from growers that the practice of stubble retention reduces the efficacy of prophylactic insecticide applications.

5.1.1 Aims

The aims of the experiments in this chapter are to explore the effect of farming practices in suppressing *B. medicagoense* populations when used in tandem with conventional controls. This will be investigated by:

- Determining the efficacy of different chemical control options on *B. medicagoense*;
- Determining the effect of different management techniques for the control of *B. medicagoense* by:
 - Assessing the impact of prophylactic chemical applications on *B. medicagoense* populations;
 - Comparing cropping rotations for the suppression of *B. medicagoense*;
 - Assessing the impact of stubble retention on the efficacy of chemical control of *B. medicagoense*; and
 - Assessing the impact of the timing of herbicide applications for weed control on *B. medicagoense*.

5.2 Materials and methods

Two efficacy experiments for the control of *B. medicagoense* are detailed here. The first experiment was not conducted by the author of this thesis but is reproduced with permission of the researchers P.J. Michael and A. Heinrich who have not previously published results of their research. This first experiment was conducted to give the farming community an indication of

chemicals that could be used to control *B. medicagoense*. The second experiment investigated rates of chemicals that are registered for use in canola crops and as well as chemicals that have lower non-target effects.

Three farming systems experiments were conducted to determine the effects of prophylactic insecticide applications, stubble retention, weed control and cropping rotations on *B. medicagoense* numbers. Experiment 1 investigated the potential interaction of prophylactic spray applications and different types of stubble retention; experiment 2 looked at the impact of the timings of weed control and prophylactic insecticide applications on *B. medicagoense* populations in canola crops; and experiment 3 investigated the effects of cropping rotations using different break crops and pasture.

5.2.1 Field efficacy experiments

5.2.1.1 Chemical efficacy experiment 1

An efficacy experiment was conducted by P.J. Michael and A. Heinrich to determine the rates at which chemicals should be applied for the control of *B. medicagoense* on crops. The experiment was conducted at Gairdner, WA (33°36'10"S, 121°46'52"E) on wheat re-growth at least 35 cm in height intermixed with green annual ryegrass (*Lolium rigidum*).

The nine treatments outlined in Figure 22 were applied on 1 June 2000, in 37 L of water per hectare, using a 3.5 m boom, 50 cm above the ground surface. The experiment design was a randomised block design with 5 replications. Each plot was 20 m long by 3.5 m.

Block 1	Block 2	Block 3	Block 4	Block 5
4	7	8	4	6
9	4	2	3	7
1	9	7	5	9
5	3	1	1	3
6	6	5	9	1
2	8	4	6	5
3	5	9	2	4
8	1	3	7	2
7	2	6	8	8

Figure 22: Experimental design of 'Chemical Efficacy Experiment 1'.

Treatments:

1. Endosulfan (350 g.a.i./L) at 1000 mL/ha
2. Endosulfan (350 g.a.i./L) at 500 mL/ha
3. Alpha-cypermethrin (100 g.a.i./L) at 500 mL/ha
4. Alpha-cypermethrin (100 g.a.i./L) at 250 mL/ha
5. Esfenvalerate (50 g.a.i./L) at 150 mL/ha
6. Esfenvalerate (50 g.a.i./L) at 300 mL/ha
7. Chlorpyrifos (500 g.a.i./L) at 1200 mL/ha
8. Chlorpyrifos (500 g.a.i./L) at 600 mL/ha
9. Untreated (i.e. nil spray applications)

Three days after insecticide application, each treatment was suction sampled. Residual effects of insecticides were not assessed, primarily because crop damage by *B. medicagoense* occurs at the seeding stage (see Chapter 3, section 3.3.1.2) and if insecticides did not have efficacy within this time frame they would not be considered useful for the control of this mite pest.

The design of the suction sampler was based on Wallace (1972) with a collection aperture of 0.1 m diameter and containing a fine mesh sieve (~10 µm). Each suction sample was collected for 10 seconds and there were 10 suction samples per plot. Suction samples were placed into 150 mL labelled collection containers with 20 mL of 70% ethanol. The number of *B. medicagoense* in each sample was assessed using a dissecting microscope.

Treatment effects were compared by analysis of variance (ANOVA). The percentage control of *B. medicagoense* was calculated as the ratio of numbers of *B. medicagoense* in treated plots compared to untreated plots.

5.2.1.2 Chemical efficacy experiment 2

In a pasture paddock located at South Stirling, WA (34°40'5"S, 118°14'5"E), seven spray treatments were applied on the 27 July 2009 in a randomized block design with five replicates, as shown in Figure 23. Each plot was 10 m square and all sprayed treatments were applied in 37 L of water per ha using a 10 m boom at a height of 50 cm above the ground surface.

The 5 m by 5 m centre of each plot was suction sampled for mites 10 days prior to spray applications and 2 days after sprays were applied. Mites were suction sampled using the same technique as outlined in section 5.2.1.1.

Block 1	Block 2	Block 3	Block 4	Block 5
7	1	5	3	6
4	3	3	7	7
1	4	1	5	3
6	7	2	4	1
2	5	7	6	4
5	2	4	2	2
3	6	6	1	5

Figure 23: Experimental design of ‘Chemical Efficacy Experiment 2’.

Treatments:

1. Dimethoate (400 g.a.i./L) at 100 mL / ha
2. Untreated (i.e. nil spray applications)
3. Alpha-cypermethrin (100 g.a.i./L) at 400 mL/ ha and piperonyl butoxide (800 g.a.i./L) at 400 mL/ha
4. Alpha-cypermethrin (100 g.a.i./L) at 400 mL/ ha
5. Dicofol (240 g.a.i./L) at 200 mL/ ha
6. Chlorpyrifos (350 g.a.i./L) at 140 mL/ha

Chemical treatments were chosen based on current crop registration status, their extensive use in broad-acre cropping and/or their toxicity to non-target invertebrates i.e. potential pest selectivity. Non-target toxicities were based on a scoring system adapted for the cotton industry by Williams (2017). The following is the justifications for chemical choice:

Alpha-cypermethrin is used extensively in broad-acre cropping (see Arthur *et al.* 2008; Micic *et al.* 2008). It is considered to have low persistence in the soil (Roberts and Hutson 1999; Tomlin 2003) but affects non-target organisms (Williams 2017; Smith *et al.* 1997).

There have been reported spray failures associated with the use of alpha-cypermethrin for the control of *B. medicagoense* (A. Heinrich pers. comm. 2009; K. Sadler pers. comm. 2009), so the use of a synergist (piperonyl butoxide) with this chemical was investigated to determine whether it would enhance the efficacy of alpha-cypermethrin.

The organophosphates, chlorpyrifos and dimethoate, were chosen based on current registrations in crop for the control of *H. destructor*. According to Williams (2017) these chemicals have a short to medium duration of persistence and high non-target efficacy, but are widely used within the agricultural industry (A Heinrich pers. comm. 2009). Even so, these organophosphates are considered to have lower non-target effects than synthetic pyrethroids (Williams 2017).

Dicofol is considered to have very low non-target toxicities (Williams 2017) and, even though it is not registered for use in broad-acre cropping, it is a registered miticide (Moore and Moore 2017).

Prior to analysis, mite numbers were converted to the number per square metre. All data sets had a square root transformation applied to achieve normal distributions prior to analysis. Treatment effects were compared by analysis of variance (ANOVA) using the computer software package GenStat version 10.1.0.71.

5.2.2 Farming systems experiments

5.2.2.1 Experiment 1: Effect of prophylactic sprays and stubble retention on *Balaustium medicagoense*

This 2 year experiment was conducted at Esperance (33°36'44"S, 121°46'53"E) and focused on the persistence of *B. medicagoense* in canola from three cropping rotations i.e. canola planted after pasture, lupins or wheat, combined with the effect of prophylactic spray applications and stubble retention on the survival of *B. medicagoense*.

5.2.2.1.1 First year

5.2.2.1.1.1 Experiment design

In a pasture paddock, four strips of lupins or wheat were planted or pasture was allowed to remain. The experiment design was a randomised block design with four replications (Refer to Figure 24). Each cropped or pasture strip was 18 m by 120 m.

Block 1			Block 2			Block 3			Block 4		
W	P	L	P	L	W	L	P	W	L	W	P

Figure 24: Experimental design of ‘Farming Systems Experiment 1’ in Year 1.

Treatments: W = Wheat; L= Lupins; P = Pasture

5.2.2.1.1.2 Crop establishment and harvest details

Cropped plots were sprayed prior to planting with 0.1 L/ha of carfentrazone-ethyl (400 g.a.i./L) and 1 L/ha of glyphosate (510 g.a.i./L) on 8 May 2006. On 19 May, lupins treated with fungicide (iprodione (250 g.a.i./L) applied at 200 mL per 100 kg of seed) were planted at a rate of 110 kg/ha and wheat was planted at 80 kg/ha with 25 cm row spacings. Ten days after planting, the entire experiment site was top dressed with urea at a rate of 80 kg/ha. No insecticides were applied to any of the crops at planting or during the growing season. To simulate grazing, pastures were mowed bimonthly until 8 weeks prior to the harvest of lupin and wheat. In-season disease control was applied to wheat by spraying the fungicide propiconazole (250 g.a.i./L) at a rate of 0.5 L/ha. All crops were harvested on 27 November 2006.

5.2.2.1.1.3 Mite sampling technique

In each treatment, mite numbers were monitored using four pitfall traps per treatment. Pitfall traps were placed linearly in the centre of each treatment, the first pitfall trap was placed 40 m from the crop edge, and the rest were placed 10 m apart, similar to arrangements used by Tremelling *et al.* (2002). Pitfall traps consisted of PVC pipes of 7.5 cm diameter and 20 cm length. They were dug into the ground so that the top of the PVC pipe was flush with the ground. All soil was removed from the centre of the pipe. One plastic cup, with a 7.5 cm diameter and 15 cm length was placed into each pipe. The lip of the cup covered the top of the PVC pipe.

Pitfall traps were activated monthly for a period of 7 days by placing plastic cups into the poly pipe tubes. Each cup contained 15 mL of 70% ethanol with 1% glycol.

5.2.2.1.2 Second year

5.2.2.1.2.1 Experiment design

At harvest in Year 1 on 27 November 2006, treatments were split into sub-treatments as per Figure 25. Each sub-treatment plot measured 18 m by 30 m. For cropped plots with no stubble retention, a harvest cart collected ‘chaff’ from the back of the header. For pasture plots with a nil stubble retention sub-treatment, the pastures were mowed and all clippings were removed to simulate pasture grazed by stock. For sub-treatments with stubble retention, the cropped plots were harvested so that all the chaff remained on the plot and the pasture plots were mown and

clippings allowed to remain on the plot. Each sub-plot treatment consisted of plots that received an insecticide spray (as detailed below) or no spray.

5.2.2.1.2.2 Crop establishment and harvest details

On the 5 June 2007 a prophylactic spray application of 400 mL/ha of alpha-cypermethrin (100 g.a.i./L) was applied to selected plots as per Figure 25. On the same day, herbicide applications of 1 L/ha of glyphosate (510 g.a.i./L) and 0.55 kg/ha of atrazine (900 g.a.i./L) were applied to the entire site. On the 15 June 2007, a triazine tolerant canola with an imidacloprid seed dressing (600 g.a.i./L) applied at 40 mL per 10 kg seed, was planted at 3.5 kg/ha over the entire trial site.

Block 1			Block 2			Block 3			Block 4		
W (ii)	P (i)	L (iii)	P (iii)	L (i)	W (iv)	L (iii)	P (iii)	W (ii)	L (iv)	W (iii)	P (i)
W (iii)	P (iv)	L (i)	P (ii)	L (iv)	W (i)	L (i)	P (ii)	W (i)	L (iii)	W (i)	P (iv)
W (i)	P (ii)	L (iv)	P (iv)	L (ii)	W (ii)	L (iv)	P (i)	W (iv)	L (ii)	W (iv)	P (ii)
W (iv)	P (iii)	L (ii)	P (i)	L (iii)	W (iii)	L (ii)	P (iv)	W (iii)	L (i)	W (ii)	P (iii)

Figure 25: Experimental design of ‘Farming Systems Experiment 1’ in Year 2.

Treatments: W = Wheat; L = Lupins; P = Pasture

Sub-treatments:

- (i) Stubble retention without insecticide spray
- (ii) Stubble retention with insecticide spray
- (iii) No stubble retention with insecticide spray
- (iv) No stubble retention and nil insecticide applications

5.2.2.1.2.3 Pitfall trap sampling

In the second year pitfall traps were used as a sampling method to determine *B. medicagoense* numbers.

In each plot, mite abundance was monitored monthly during the growing season using four pitfall traps per plot. The traps were placed on the corners of a rectangle measuring 8 m by 10 m with each side being 5 m from the edge of the plot. Pitfall trap designs were as per section 5.2.2.1.1.3.

5.2.2.1.2.4 *Plant counts and mite feeding damage assessments*

Plant counts of seedling canola were conducted at 10, 15 and 25 days after planting. Ten counts were made per plot by placing a metre stick between the rows and all plants along each side of the metre stick were counted and rated for mite feeding damage. Damage was rated on a visual scale and the scale indicators used for this study were: 0 = nil damage; 2.5 = 50% damage and 5 = all plants dead or dying. This scale was modified from methodology described by Chapman *et al.* (2000), Gillespie (1991) and Umina and Hoffmann (2004) who rated damage by earth mites to pasture and crops using a scale of 0-10.

5.2.2.1.3 *Data analysis*

If mites were sampled using pitfall traps, all numbers were converted to the number per four pitfall traps, if mites were suction sampled numbers were changed to the number per square metre. Plant counts were converted to the number per square metre. In order to achieve normal distributions of the data sets prior to analysis, all data had a square root transformation applied. Treatment effects were compared by analysis of variance (ANOVA) in GenStat version 10.1.0.71.

5.2.2.2 *Experiment 2: Timing of herbicide and prophylactic insecticide applications*

5.2.2.2.1 *Experiment design*

In a pasture paddock at Esperance Downs Research Station (33°36'13"S, 121°46'10"E), the effect of weed control and prophylactic insecticide application was investigated using a randomised block design with four replicates of six treatments, as per Figure 26.

Block 1	Block 2	Block 3	Block 4
2	5	2	3
1	4	6	2
5	2	3	5
4	3	1	6
6	1	5	4
3	6	4	1

Figure 26: Experimental design of 'Farming Systems Experiment 2'.

Treatments:

1. Weed control 21 days prior to planting + 50 mL/ha of bifenthrin 3 days after planting
2. Weed control 39 days prior to planting + prophylactic spray of 400 mL/ha of alpha-cypermethrin with knockdown, 50 mL/ ha of bifenthrin 3 days after planting
3. Weed control 39 days prior to planting + no insecticide applications
4. Weed control 8 days prior to planting + 50 mL/ ha of bifenthrin 3 days after planting
5. Weed control 8 days prior to planting + prophylactic spray of 400 mL/ha of alpha-cypermethrin with knockdown, 50 mL/ ha of bifenthrin 3 days after planting
6. Weed control 8 days prior to planting + no insecticide applications

A knock-down herbicide (glyphosate (540 g.a.i./L) at 2 L/ha) was applied either 8 or 21 or 39 days prior to planting for weed control. At the same time, some treatments received a spray application of alpha-cypermethrin (100 g.a.i./L) at 400 mL/ha. The entire trial site was then bulk

sown with canola cultivar Tornado at a rate of 4.8 kg/ha. Three days after planting some treatments had 50 mL/ha of bifenthrin (100 g.a.i./L) applied (See Figure 26).

5.2.2.2.2 Suction sampling

Mites were suction sampled using a Stihl™ blowervac BG55. The nozzle of the blowervac had a sieve with fine mesh (holes at ~ 10 µm) placed 5 cm into the aperture of the blowervac. The nozzle of the blowervac was held on the ground for 2 seconds and 5 suction samples were taken per plot. Each plot was sampled one day prior to any herbicide applications.

5.2.2.2.3 Plant counts

Plant counts were as per section 5.2.2.1.2.4. Mite feeding damage to crops was not assessed in this experiment.

5.2.2.2.4 Data analysis

Data analysis was as per section 5.2.2.1.3.

5.2.2.3 Experiment 3: Effects of cropping rotations on *Balaustium medicagoense* numbers

5.2.2.3.1 Experiment design

This experiment ran over 3 years and was conducted at Esperance Downs Research Station (33°36'13"S, 121°46'10"E). In the first year, four crops (lupins, canola, wheat and barley) were planted into a pasture paddock or strips of pasture were allowed to remain. Each crop or pasture strip was 20 m by 100 m and was arranged in a strip plot design with four replicates as per Figure 27. No insecticides were applied to the site, except for a fipronil (200 g.a.i./L) seed dressing on canola. This was applied at 400 mL of fipronil (500 g.a.i./L) plus 600 mL of water applied to 100 kg seed for the control of earth mites. At harvest, cropped strips were harvested to allow all crop residues to remain on each strip. Pasture strips had the clippings from the final mowing left on the plot.

In the second year, the same combination of crops was planted or volunteer pasture was allowed to germinate perpendicular to the year 1 plots. This formed a 5-by-5 crop matrix by crop residue combination giving 25 plots with different cropping sequences (as per Tanaka *et al.* 2007). Each second year plot was 20 by 20 m and replicates were as per Figure 27.

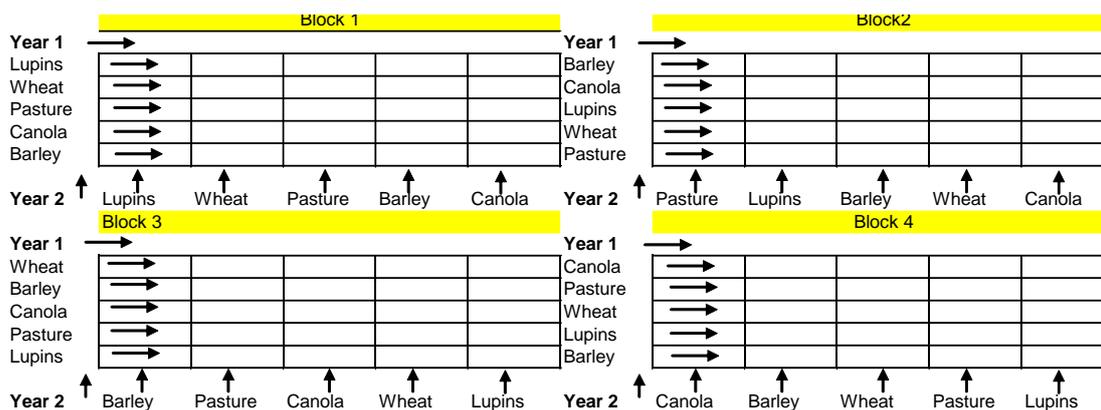


Figure 27: Experimental design of 'Farming Systems Experiment 3'.

Arrows indicate direction of planting.

In year three, canola was planted over the entire trial area on 14 May 2010. Thus, as in year two, there were 25 plots with different cropping sequences with each plot being 20 by 20 m with four replicates.

Each year, herbicides applied and the timings of planting and harvest differed. The timings of planting, species used and planting rates are outlined in Table 11.

5.2.2.3.2 Suction sampling

Populations of pest mites in crops were monitored each year by suction sampling 5 m of crop row by 6 rows, in the 10 by 10 m centre of each plot. In pasture, 5 m of pasture in 6 locations in the 10 by 10 m centre of each plot was suction sampled. Suction sampling was done at 14, 28 and 60 days post planting using a STIHL blowervac BG55 as per section 5.2.2.2.2.

Table 11: Crop type, planting rate, planting date and harvest date.

Crop	Planting rate	Planting date		Harvest date	
		2008	2009	2008	2009
Lupins	120 kg/ha	29/05/08	18/06/09	14/12/08	10/12/09
Canola	5 kg/ha	29/05/08	18/06/09	09/12/08	11/12/09
Wheat	80 kg/ha	01/06/08	20/06/09	15/12/08	06/12/09
Barley	80 kg/ha	01/06/08	20/06/09	13/12/08	05/12/09

5.2.2.3.3 Plant counts and mite feeding damage assessments

Each year, plant densities and damage by invertebrates were assessed at 14 and 28 days post planting. This was done by placing a 1 m stick in the middle of a crop inter-row and counting plants on either side of the metre stick. This was done at five separate points within the 10 by 10 m square centre of each crop plot. Also for each plant, any sucking damage was separately scored only at the cotyledon stage for lupins and canola and on the first two leaves of the cereals. The damage was scored using a scale of 0 – 5 as per section 5.2.2.1.2.4.

5.2.2.3.4 Data analysis

Data analysis was as per section 5.2.2.1.3.

5.3 Results

5.3.1 Field efficacy experiments

5.3.1.1 Chemical efficacy experiment 1

All insecticides caused a decrease in *B. medicagoense* numbers when compared to the untreated plots. The best control was achieved with 250 mL/ha (97% mortality) or more of alpha-cypermethrin, 500 mL/ha or more of endosulfan (98 % mortality) or 300 mL/ha esfenvalerate (92% mortality). Chlorpyrifos applied at 600 mL/ha and 1200 mL/ha had the lowest efficacy with a mean control of 57.1% and 72.2% respectively (Figure 28).

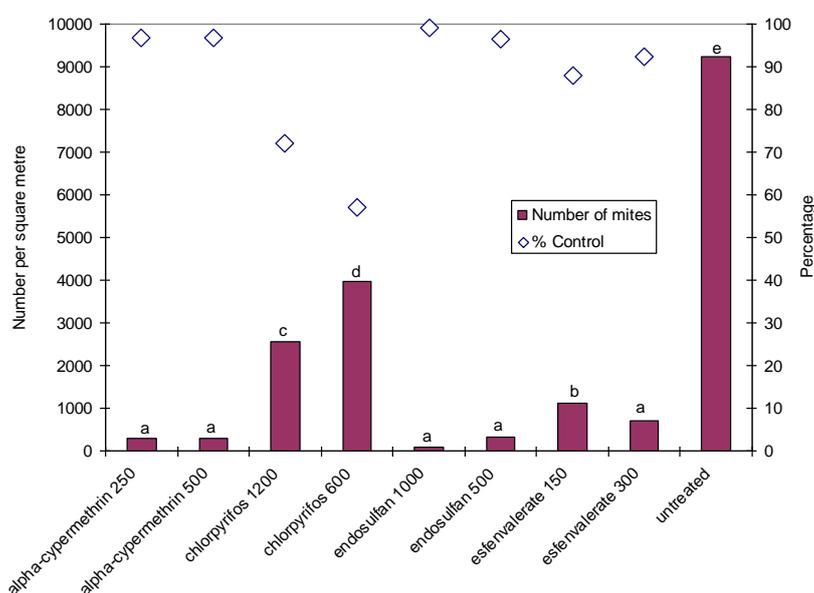


Figure 28: Mean number of *Balaustium medicagoense* 3 days after insecticide applications and percentage of control achieved by spray applications compared to untreated plots.

Letters indicate significantly different means. Numbers after insecticide names indicate application rates (mL product per ha).

5.3.1.2 Chemical efficacy experiment 2

Prior to the application of insecticides, untreated plots had lower mite numbers than the treatment plots, however this difference was not significant ($p=0.137$) (Figure 29). Plots with spray applications of alpha-cypermethrin had very high levels of control (92%) of *B. medicagoense* but were not significantly different to chlorpyrifos and dicofol ($p<0.001$). The addition of a synergist to alpha-cypermethrin did not increase the efficacy of this chemical (see

Figure 29) whereas dimethoate treated plots had similar mite numbers to untreated plots (Figure 29).

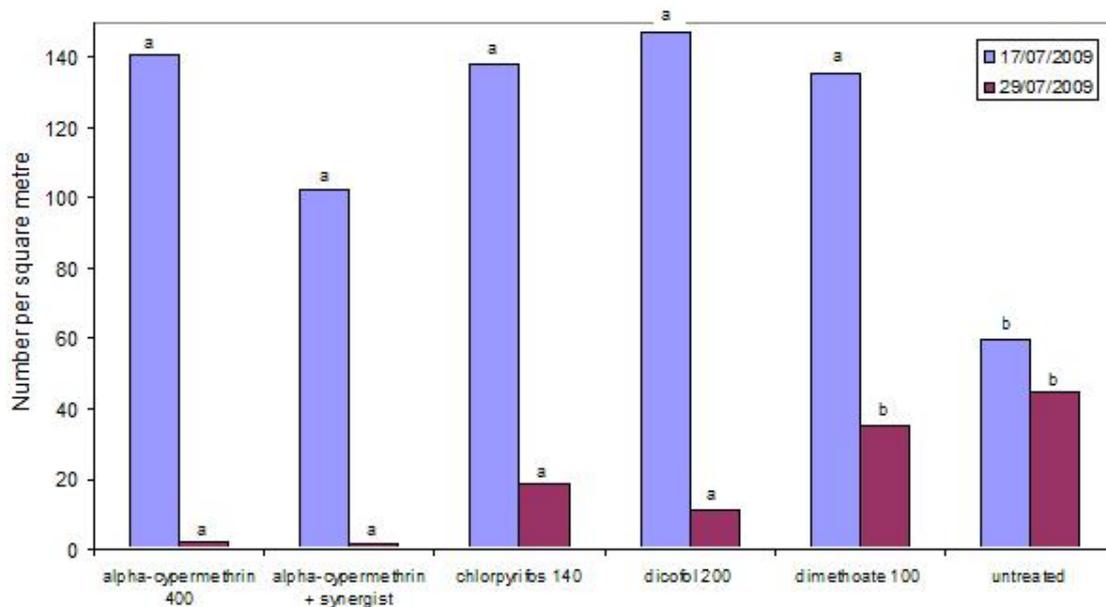


Figure 29: Mean number of *Balaustium medicagoense* before spray and 2 days after spray application.

Letters indicate significantly different means within sample dates not between samples dates. Numbers after insecticide names indicate application rates as mL product per ha.

The difference in numbers of *B. medicagoense* between experiment 1 and experiment 2, with experiment 2 having about 70 times less mites, does not influence the findings for chemical efficacy on this mite. The difference does highlight that *B. medicagoense* can be found at varying densities at different sites.

5.3.2 Farming systems experiments

5.3.2.1 Experiment 1: Effect of prophylactic sprays versus stubble retention on *Balaustium medicagoense*

5.3.2.1.1 Efficacy of pitfall trap catches versus suction sampling methods

The number of *B. medicagoense* captured using suction sampling and pitfall trap catches can not be compared directly. However, the qualitative responses of *B. medicagoense* to treatments using these two sampling techniques can be compared. For example, in the first year of the experiment, both of these sampling methods showed higher numbers of *B. medicagoense* in pasture than in lupins. However, the suction sampling method was considerably more precise with lower variance than pitfall trapping. As such using suction sampling significant effects of host types were evident between wheat than lupins, whereas the pitfall trapping did not show

these differences. Suction sampling has less variance and showed significant differences between treatments whereas pitfall sampling did not (Figure 30).

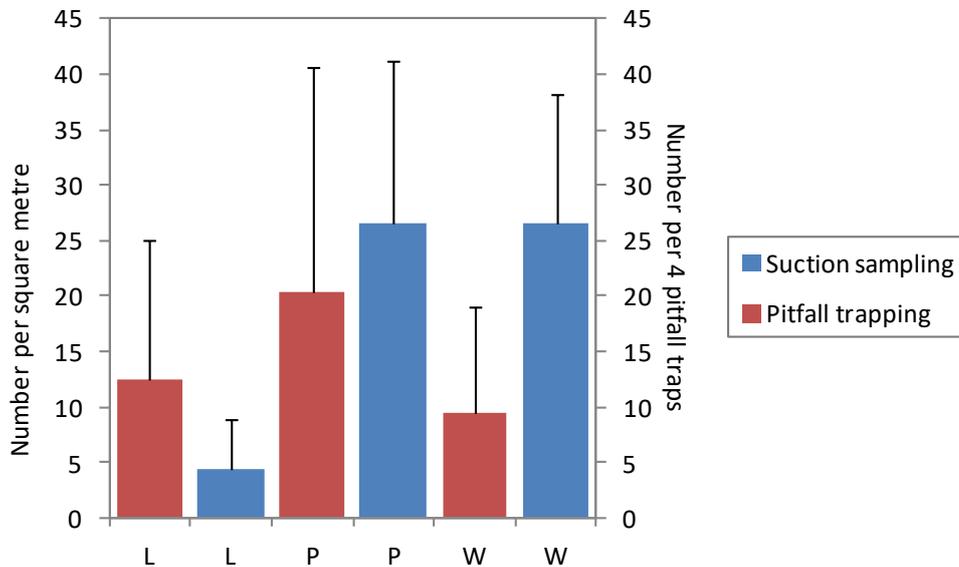


Figure 30: Number of *Balaustium medicagoense* (+SE) in pitfall trap catches versus suction sampling in Year 1 in wheat, lupins or pasture. Data are means (n = 20)

Where L is lupins, P is pasture, W is wheat.

5.3.2.1.2 Effect of treatments on numbers of *Balaustium medicagoense*

Balaustium medicagoense numbers varied significantly over the 2007 winter season ($p < 0.001$) (Figure 31). Analysis of the treatments applied was conducted for the May to June period when significant numbers of mites were present. There was no significant effect of previous crop type, retention of stubble or application of a prophylactic spray on *B. medicagoense* numbers for these times or when the data was analyzed over all times (Table 12). Even so, decreased population densities of *B. medicagoense* were observed following lupin crop or where stubble retention was practiced (Figure 31, Table 12).

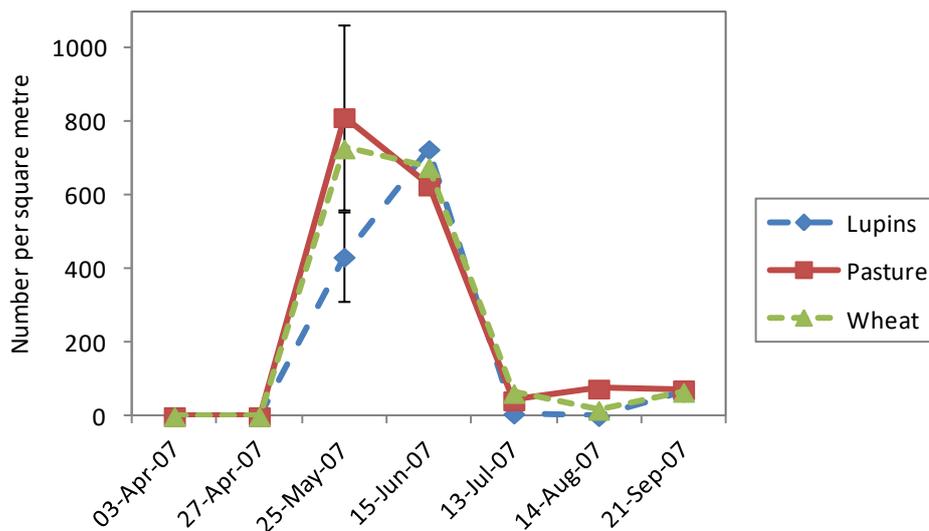


Figure 31: Average number of *Balaustium medicagoense* (\pm SE) on canola planted after different crops in Year 2.

Table 12: Mean number of *Balaustium medicagoense* per square metre in plots \pm stubble and \pm prophylactic spray applications over all times.

Previous years crop	No stubble retention		Stubble retention		Crop main effect
	- spray	+ spray	- spray	+ spray	
Lupins	135	143	163	265	176
Pasture	193	271	303	166	233
Wheat	244	182	209	253	222
Stubble x spray interaction	191	198	225	228	
Stubble main effect		194		226	

5.3.2.1.3 Mite feeding damage on canola seedlings

Prior crop type did not affect mite feeding damage on canola seedlings. Canola planted after pasture, lupins or wheat had similar mean mite feeding damage scores (Table 13). Even though the number of earth mites in pitfall trap catches was very low, it cannot be discounted that some of the feeding damage was from earth mites as well.

Overall the amount of mite feeding damage was not sufficient to cause seedling death. Even though canola seedlings in sprayed treatments sustained significantly ($p < 0.001$) less mite feeding damage (Table 13), a score of 5, which equates to 90% or more of the surface area of two cotyledons silvered, was not recorded. This suggests overall mite numbers were not sufficient to cause any seedling loss.

There were also no significant effects of stubble retention, prior crop type, or spray applications on canola seedling densities.

Table 13: Average score of mite feeding damage on canola seedlings in treatments \pm

different crop residues and ± spray applications.

Letters represent significantly different means.

Treatment	No stubble retention		Stubble retention		Effect of previous years crop
	- spray	+ spray	- spray	+ spray	
Canola after Lupin	2.25	1.67	2.25	1.92	2.02
Canola after Pasture	2.17	2.08	2.29	1.92	2.11
Canola after Wheat	2.29	1.63	2.38	1.75	2.01
Canola	2.24 ^a	1.79 ^b	2.31 ^a	1.86 ^b	

5.3.2.2 Experiment 2: Effect of weed control and insecticide spray applications

The numbers of *B. medicagoense* over the trial site were very low and consequently no treatment effects could be observed. However, earth mites consisting of *H. destructor* and *Penthaleus* spp. complex were found in abundance and treatment differences were observed (Table 14). Thus, results for earth mites are presented below. Micic *et al.* (2008) has shown *B. medicagoense* and earth mites occur in sympatry on green plant material, have the same plant hosts (see chapters 3 and 4) and that the chemical controls in this experiment were applied at rates that have efficacy on both mites (see chemical efficacy experiments 1 and 2 above; Moore and Moore 2017). Thus, any findings for earth mites may be extendable to *B. medicagoense*.

5.3.2.2.1 Weed control

Early weed control decreased earth mite abundance and increased canola plant densities ($p < 0.001$) when compared to weed control applied late, but did not significantly increase grain yield (Table 14).

Table 14: The effect of early versus late weed control before planting on earth mite numbers, canola plant densities and yields.

* indicates significance of $p < 0.05$

Parameter	Late weed control	Early weed control	LSD
Earth mites (per m ² , May 5)	4210	198	1589*
Earth mites (per pitfall, June 13)	979	358	504*
Canola plant density (per m ²)	45.2	69.8	13.01*
Canola yield (t per ha)	1.65	1.93	

Fewer earth mites and more canola plants established on plots that had early weed control (Table 14). Counts later in the season also showed higher numbers of canola plants in the plots that received insecticide sprays. There was little difference between the other treatments (Figure 32).

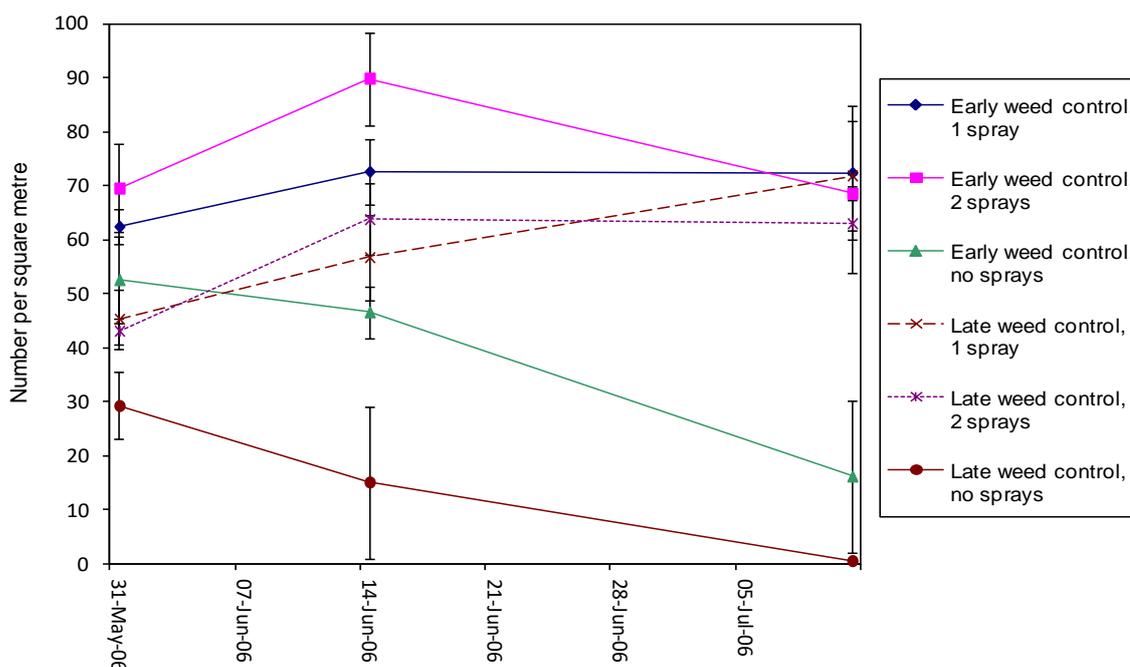


Figure 32: Canola density over time.

5.3.2.2.2 Prophylactic insecticide applications

Earth mites were the predominant pest in this experiment and differences in plant densities and yields are unlikely to be due to another canola pest. A single synthetic pyrethroid spray had the same effect on earth mite numbers, canola plant numbers and yield as two sprays (Table 15). Earth mite densities of 500 per square metre reduced the canola density by 61% and yield by 66% in untreated plots ($p < 0.001$), this equates to 25 earth mites per canola seedling (Table 15).

Table 15: The effect of prophylactic sprays on earth mite numbers (post planting), canola plant densities and yields.

Letters represent significance differences for each sample type where $p < 0.001$.

Count of:	No spray	1 Spray	2 Sprays
Earth mites (per pitfall, June 13)	1587 ^b	321 ^c	98 ^c
Earth mites (per m ² , July 12)	516 ^a	312 ^a	272 ^a
Canola plant density (plants per m ²)	10.8 ^d	28.1 ^e	28.5 ^e
Canola yield (t per ha)	0.74 ^f	2.21 ^g	2.32 ^g

5.3.2.2.3 Interactions of prophylactic insecticide applications and weed control

Statistically, there were no significant interactions between weed control and prophylactic insecticide sprays on earth mites, canola plant numbers or yields.

5.3.2.2.4 Pitfall trap catches versus suction sampling

Pitfall trap catches and suction sampling for earth mites were compared qualitatively. As in Farming system Experiment 1, suction sampling had less variance but this did not always result in significant differences between treatments e.g. Table 15 compared to Table 14.

5.3.2.3 Experiment 3: Effect of different cropping rotations on *Balaustium medicagoense* numbers

5.3.2.3.1 Crops and *Balaustium medicagoense* numbers

In the first year (2008) of the experiment, the lowest numbers of *B. medicagoense* were found in canola, lupins and wheat plots, which on average sustained 42% less mites than barley and 52% less mites than pasture (Figure 33).

Similarly in the second year (2009), pasture plots had significantly higher ($p < 0.001$, 80% more) numbers of *B. medicagoense* than other plant types and canola had the least number, on average of 85% less *B. medicagoense* than all other crops (Figure 33).

The previous year's crop type did not significantly influence *B. medicagoense* numbers. Statistically there were no significant interactions among crops grown in 2008 and crops grown in 2009 on mean *B. medicagoense* numbers (Table 16). It was expected that the impact of cropping rotations from 2008 may only be found early in the season. However, for all dates analysed, there was no significance difference found. This suggests that it is the current season's crop that influences *B. medicagoense* numbers rather than the previous year's crop.

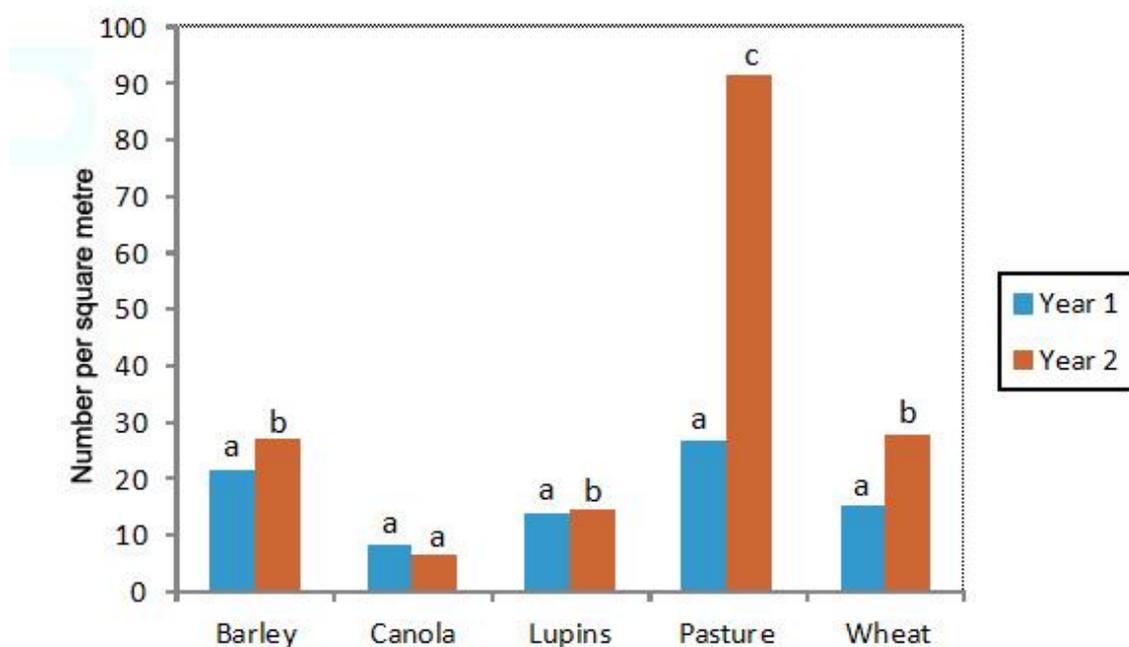


Figure 33: Mean number of *Balaustium medicagoense* from all sample dates in

different crops in year 1 and year 2.

Letters represent significantly different means, within years not between years where $p < 0.001$.
 Note: Year 2 crops have different crop histories to Year 1

Table 16: Mean number of *Balaustium medicagoense* per square metre from all sample dates in various crops in Year 2 after various crops in Year 1.

Crop in Year 2	Crop in Year 1					Mean
	Barley	Canola	Lupins	Pasture	Wheat	
Barley	30	32	57	51	27	39 ^b
Canola	5	15	17	9	3	10 ^a
Lupins	14	16	31	30	14	21 ^b

In the third year (2010) canola was planted over all plots and the effect of prior crop type on *B. medicagoense* density could therefore be determined in two separate seasons. In 2009 there were more *B. medicagoense* in canola that was planted into canola (40% more) or lupin stubbles (54% more) than in other crop rotations. Whereas, in 2010 more (66% more) *B. medicagoense* were found in canola planted on pasture. The prior crop type influenced *B. medicagoense* density but this varied both quantitatively and qualitatively from year to year (Figure 34).

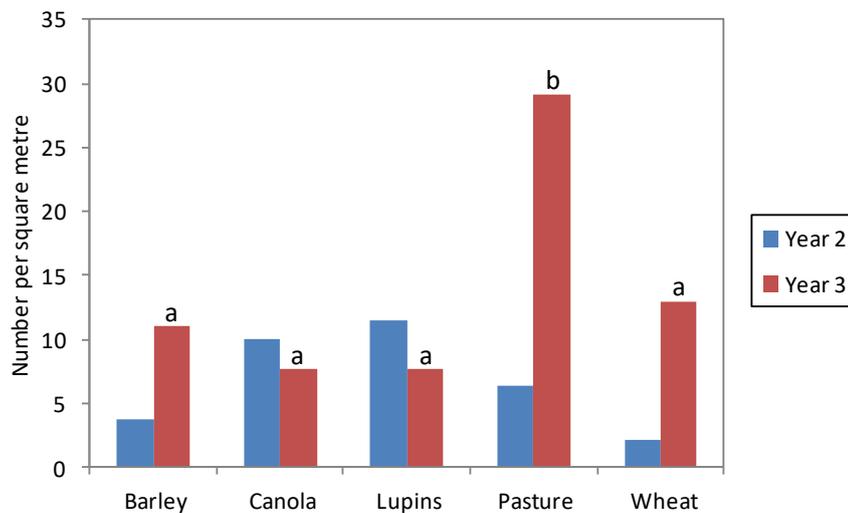


Figure 34: Number of *Balaustium medicagoense* in canola planted after pasture, barley, canola, lupins or wheat in Years 2 and 3.

Letters represent significantly different means, within years not between years where $p < 0.001$.

5.3.2.3.2 Mite damage to crops

Crops planted in Year 1 (2008) appeared to influence the amount of feeding damage observed in lupins but not other crops planted in Year 2 (2009). Lupins planted in 2009 sustained significantly more feeding damage than other crop types and the cropping rotation of lupins planted after pasture sustained the most feeding damage (Table 17).

Table 17: Mean mite damage score on seedling crops in Year 2 (2009).

Letters represent significantly different means where $p < 0.022$, LSD 0.375

Crop in Year 2	Crop in Year 1				
	Barley	Canola	Lupins	Pasture	Wheat
Barley	0.0	0.0	0.0	0.0	0.0
Canola	0.2 ^a	0.3 ^a	0.2 ^a	0.4 ^a	0.2 ^a
Lupins	1.1 ^b	0.8 ^b	1.1 ^b	1.9 ^c	1.1 ^b
Wheat	0.0	0.0	0.0	0.0	0.0

Canola planted after pasture sustained significantly ($p=0.003$) more mite feeding damage (Table 18) and these plots also had the greatest densities of mites in 2010 (Figure 33). In contrast in the previous year there was no effect of prior crop type on the damage that mites caused to canola (Table 17).

Overall the amount of feeding damage sustained by crops was low, with mean damage scores being below 2 (Table 18). A mite feeding damage score of 4 would be considered to have a significant impact on seedlings. This means the numbers of mites per square metre were below economic damage thresholds and any differences in plant densities between treatments are not due to mite feeding damage.

There were alternative plant hosts present for mites to feed on. However, there was no significant difference in the number of broadleaved weeds, e.g. capeweed, or grass weeds e.g. brome grass throughout the trial site.

Table 18: The effect of the previous year's crop type on mite feeding damage and canola density.

Letters indicate significant differences for each sample type where $p < 0.05$.

Count of:	Crop in Year 2				
	Barley	Canola	Lupins	Pasture	Wheat
Mite damage scores	0.51 ^a	0.71 ^a	0.62 ^a	1.42 ^b	0.60 ^a
Canola plant densities (per m ²)	28.25 ^c	49.36 ^e	31.44 ^d	39.17 ^f	34.81 ^e

5.3.2.3.3 Plant densities

There was no significant interaction with stubble type from 2008 and 2009 on the density of canola plants in 2010. However, there was a significant interaction with crop type from 2009 and the density of canola plants in 2010, with the crop rotation of canola on canola having significantly more canola seedlings and canola after barley the least (Table 18). Shedding of canola seed from harvest in the previous year may have contributed to the higher plant densities recorded. Allelopathy of barley stubble (Bertholdsson 2004; Paynter and Hills 2009) or the physical barrier of canola growing through stubble (Early 2004) is likely to have contributed to the lower canola densities following barley.

5.4 Discussion

5.4.1 Effect of insecticide applications on *Balaustium medicagoense* populations

5.4.1.1 Insecticide efficacy

The organochlorine endosulfan provided the best control for *B. medicagoense*, however, this chemical is no longer available for use in broadacre crops. Its residues have been detected in a wide range of commodities which have exceeded the maximum residue limit for foods as well as contaminated streams and rivers and this has led to it being phased out of use in Australia by the Australian Pesticide and Veterinary Medicines Authority (APVMA) (APVMA 2005).

The organochlorine dicofol has efficacy on *B. medicagoense* but, like endosulfan, is unlikely to be a viable option. This insecticide had lower efficacy in comparison to synthetic pyrethroids but had higher efficacy when compared to organophosphates in decreasing numbers of *B. medicagoense*. Even though dicofol is considered to have lower toxicity on non-target invertebrates than synthetic pyrethroids or organophosphates (Williams 2017), it bioaccumulates and is under review for being a ‘Persistent Organic Pollutant’ (POP) under the Stockholm Convention (Sanchez *et al.* 2010). Sanchez *et al.* (2010) suggest that a suitable substitute to dicofol is pyridaben. Pyridaben is non-systemic with rapid knock-down and long residual activity (Moore and Moore 2017) but short environmental persistence (Dekeyser 2005; Tomlin 2003). This chemical is not registered for use in broad-acre cropping (Moore and Moore 2017), but it readily degrades in the soil and environment and is reported to have efficacy against acari, hemiptera and thysanoptera (Tomlin 2003), suggesting that it has low toxicity on non-target invertebrates making it a potential candidate for use in an IPM system. Another insecticide pirimiphos-methyl has efficacy on *B. murorum* as a contact insecticide (Wilkin and Warner 1985), suggesting it possibly will also control *B. medicagoense*. This insecticide exhibits short acting translaminar action, but is primarily a contact insecticide (FAO 2007). Apart from not being registered for use in Australia (APVMA 2017; Moore and Moore 2017) it is not readily biodegradable and is a broad-spectrum insecticide (FAO 2007) suggesting it will affect non-target pests.

The synthetic pyrethroids esfenvalerate and alpha-cypermethrin provided better control alternatives for *B. medicagoense* than organophosphates or dicofol. Of these two chemicals, alpha-cypermethrin is used extensively in the agricultural sector and is considered to be of relatively low cost at \$(AUS) 6.71 /L (Moore and Moore 2017), and when applied at 400 mL/ha, with application costs of \$(AUS) 5.00 /ha the total cost is \$(AUS) 7.68/ha (Moore and Moore 2017). Esfenvalerate is not as commonly used as alpha-cypermethrin (A. Heinrich pers. comm. 2009) and has a higher cost at \$(AUS) 9.90 /L (Moore and Moore 2017), but has similar application costs of \$(AUS) 4.28 /ha, based on an application rate of 300 mL/ha (Robinson

2009). Synthetic pyrethroids have the disadvantage of having broad non-target effects (Williams 2017; Tomlin 2003), though they have low mammalian toxicity and low persistence in soil (Roberts and Hutson 1999; Tomlin 2003). However, esfenvalerate and alpha-cypermethrin need to be applied to green plant material to have good efficacy as they have limited residual activity on bare ground (Moore and Moore 2017; Tomlin 2003).

The only synthetic pyrethroid registered for use in broad-acre cropping that has efficacy on bare-ground is bifenthrin (Baskaran *et al.* 1999). Though bifenthrin is registered for the control of *H. destructor* (Moore and Moore 2017), it has limited efficacy on *B. medicagoense*. According to bioassays conducted by Arthur *et al.* (2008), *B. medicagoense* is more tolerant of bifenthrin than alpha-cypermethrin. This is also supported by field observations by agronomists e.g. Smith (2009) and by reports in PestFax, e.g. Mangano (2007). All synthetic pyrethroids have the same mode of action and bind to the voltage-sensitive sodium channels in the cell membrane, modifying their gating kinetics, thereby disrupting nerve function (Choi and Soderlund 2006; Moore and Moore 2017). Choi and Soderlund (2006) found that when pyrethroid insecticides bind to the sodium channels they produce currents that can be measured. Consequently, pyrethroids that are structurally distinct can be placed into two groups. The first type, found with cismethrin, allethrin, permethrin and tefluthrin, activated relatively rapidly and inactivated partially during a 40 μ s depolarization. The second type, found with cypermethrin, cyfluthrin, cyhalothrin, deltamethrin, fenpropathrin and fenvalerate, activated more slowly and did not detectably inactivate during a 40 μ s depolarization. Only bifenthrin did not produce modified currents that fit clearly into either of these categories. Even though Choi and Soderland (2006) did not test alpha-cypermethrin and esfenvalerate, these have very similar structures to cypermethrin and fenvalerate respectively (Tomlin 2003) and consequently, are also expected to act in the same way on sodium channels. The fact that bifenthrin did not produce modified currents (Choi and Soderland 2006) may explain why it is not as efficacious on *B. medicagoense* as esfenvalerate and alpha-cypermethrin. The work by Choi and Soderland (2006) would also suggest that the synthetic pyrethroids cyfluthrin, cyhalothrin, deltamethrin, fenpropathrin will also have efficacy on *B. medicagoense*. However, this requires further testing.

The organophosphates, chlorpyrifos and dimethoate were found to provide poor or variable control of *B. medicagoense*. These field results support laboratory bioassays conducted by Arthur *et al.* (2008), which also found that *B. medicagoense* had a high tolerance to organophosphates omethoate and chlorpyrifos whereas earth mites such as *H. destructor* did not. This suggests that all organophosphates will provide limited control of *B. medicagoense*, as these chemicals all have the same mode of action, i.e. they inhibit the function of acetylcholinesterase (Roberts and Hutson 1999; Tomlin 2003).

A single spray of alpha-cypermethrin at 400 mL/ha applied prior to planting will have efficacy on *B. medicagoense* if this mite is present at the time of application and there is green plant material present. This insecticide is a broad-spectrum insecticide with rapid knockdown and is only effective by contact and ingestion (Tomlin 2003) hence label rates recommend it be applied to green plant material (Moore and Moore 2017). A single spray application has been known to decrease earth mite populations as long as it is timed to occur when all mites have hatched from over-summering eggs (Michael 1991). However, alpha-cypermethrin does not have ovicidal activity (Tomlin 2003). Consequently, the effectiveness of a single spray application of alpha-cypermethrin in decreasing overall *B. medicagoense* populations will depend on the number of unhatched eggs present at the time of application.

The practice of applying a prophylactic spray with the first knock-down to control insect pests is generally considered to be cost effective, predominantly because the spray equipment is already being used to apply herbicides. Also synthetic pyrethroid insecticides are inexpensive, broad-spectrum and there is a perception that by applying insurance sprays this negates the need to monitor germinating crops such as canola for invertebrate pests (Micic *et al.* 2008). Currently (in 2010/2011), growers within the higher rainfall areas of southern WA are planting hybrid canola at rates of 2 kg per ha to give at least 40 seedlings per square metre (GRDC 2010). According to Seymour (2011), hybrid canola densities above this rate do not reliably produce higher economic returns and the economic optimum density is 30 plants per square metre. Thus growers planting at 2 kg per ha can incur few seedling losses. With the cost of hybrid canola seed at \$(AUS) 17 - 24 per kg (Seymour 2011), which is equivalent to \$(AUS) 34 - 48 per ha (based on a planting rate of 2 kg/ha), a spray application of alpha-cypermethrin at 400 mL per ha, which costs only \$(AUS) 4.00 per ha (Robinson 2009), is considered to be relatively inexpensive in comparison to having to re-seed a canola paddock due to invertebrate damage (J. Howard pers. comm. 2010).

To date there are no Erythraeid mites that have been recorded as having resistance to acaricides (Whalon *et al.* 2012), this is likely due to the fact that there are no species of mites in this family apart from *B. medicagoense* that have been recorded as crop pests. If *B. medicagoense* is exposed to regular applications of alpha-cypermethrin at sub-lethal doses i.e. at rates less than 400 mL per ha and/or alpha-cypermethrin continues to be applied at 400 mL per ha with the first knock-down, it can be expected that there will be increased selection pressure on *B. medicagoense* to develop resistance.

Within southern Western Australia and South Australia there are populations of *H. destructor* that are resistant to synthetic pyrethroids (Maino *et al.* 2018; Umina *et al.* 2012, 2017). It has been suggested that the practice of applying sprays for suppressing virus spread by aphids in cereal crops may have contributed to the development of resistance in these mites (Edwards *et al.* 2008; Umina 2007), even though these applications are above the registered rate for *H.*

destructor control. For instance, alpha-cypermethrin is registered in barley at 125 mL per ha to be applied twice at five to six weeks apart to prevent virus spread by aphids. This rate is 2.5 times more than required on the label rate of 50 mL/ha for the control of *H. destructor* (Moore and Moore 2017). Resistance in *H. destructor* has been found to the insecticides: bifenthrin, alpha-cypermethrin, gamma-cyhalothrin, lambda-cyhalothrin and esfenvalerate from the synthetic pyrethroid group, suggesting resistance is conferred to all insecticides in the synthetic pyrethroid group (Umina *et al.* 2012).

The most common form of resistance against pyrethroids in invertebrates is knockdown (kdr) resistance, which is caused by point mutations in domain II of the sodium channel gene (Davies *et al.* 2007; Soderland 2008). The kdr factor is a recessive allele conferring cross resistance to Group 3 insecticides which includes pyrethroids (Group 3A) and DDT (Group 3B) (Davies *et al.* 2007). However, mutations in the sodium channel gene that have been functionally characterised to confer pyrethroid resistance in Acari have also occurred in domains III and IV (van Leeuwen *et al.* 2010). It is highly improbable that mapping the sodium channel gene for *B. medicagoense* will give an indication of whether or not resistance to synthetic pyrethroids has occurred due to the number of possible areas on the gene where resistance to pyrethroids has been conferred.

All of these point mutations were detected after control failures were noted (Davies *et al.* 2007; Soderland 2008; van Leeuwen *et al.* 2010). In order to predict if spray failures are going to occur for the control of *B. medicagoense* it is necessary to determine baseline levels of susceptibility for *B. medicagoense* to alpha-cypermethrin. However, French-Constant and Rousch (1990) suggest that for a bioassay to be undertaken on a susceptible strain to detect resistant individuals using an LD₉₉ 1500 individuals are required to detect resistance at a frequency of 1%, whereas to detect resistance frequencies of 0.1% requires the collection of samples in the thousands. Based on the experiment data from this chapter and chapters 3 and 4, it is unlikely that an effective sampling strategy can be devised to collect sufficient individuals of *B. medicagoense* to predict the occurrence of resistance.

5.4.1.2 Efficacy of insecticides in the presence of stubble retention

Stubble retention did not affect the efficacy of a prophylactic spray applied with a herbicide on pest mites. This could be due to the timing of prophylactic spraying which failed to coincide with mites being found in plots. For crop residues to protect *B. medicagoense* from insecticides, this mite must be found in association with crop residues. For instance, *Forficula auricularia* L. (Dermaptera: Forficulidae) (European earwig) shelter under plant residues and, consequently, they do not come into contact with otherwise efficacious spray applications (Shaw and Wallis 2010; Widmer *et al.* 2008). However, unlike *F. auricularia*, results from Chapter 4 suggest that *B. medicagoense* adults are not found in the absence of green plant material. Unless green plant

material is found under crop residues, it is unlikely that the physical presence of crop residues will protect *B. medicagoense* from insecticide spray applications.

5.4.1.3 Efficacy of insecticidal seed dressings

Throughout the farming system experiments, canola was grown with either an imidacloprid or fipronil seed dressing. The results from these trials were also extended for other crop pests so it was critical for there to be crop residue present. Even so, commercially purchased canola seed such as hybrid cultivars can not be purchased without an insecticidal seed dressing. Consequently, any trials conducted in terms of a farming system need to replicate farmer practice so seed dressings could not be omitted.

Seed dressings do protect canola seedlings from earth mite feeding damage (Rohitha *et al.* 2003), however, this is only if mite numbers are low. Under high mite pressures seed dressings do not protect canola seedlings from death (Micic unpublished data 2009; 2010). This is also reflected in the chemical labels, for instance some labels of imidacloprid e.g. Titan® do not list mites under the pest column for canola, instead only listing control for aphids; whereas some fipronil labels e.g. Cosmos® stipulate that there needs to be another control applied if there are more than 8 earth mites per canola seedling are present (Moore and Moore 2017). The lack of efficacy of seed dressings on *B. medicagoense* has been observed and agronomists advise growers not to rely on currently available seed dressings for the control of this mite (W Smith pers. comm. 2012). Unfortunately, *B. medicagoense* numbers have never been sufficiently high enough in field trials and these mites did not persist under laboratory conditions to test the efficacy of seed dressings.

5.4.2 Effect of weed control on *Balaustium medicagoense* populations

Balaustium medicagoense is not found in the absence of host plants. Even though *B. medicagoense* and earth mites have different life cycles i.e. earth mites have a cold temperature requirement for hatching and are consequently not found in green-bridges over summer (Wallace 1970), whereas *B. medicagoense* does not have a cold temperature requirement for hatching and can be present all year round (refer to Chapter 4), neither of these mite species are found in the absence of green plant material. These mites occur in sympatry, are found on similar plant hosts (refer to Chapter 3) thus the effect of the presence or absence of green plant material on earth mites after hatching should have a similar effect on *B. medicagoense*.

Weed control will suppress pest mite populations to the same level as prophylactic spray applications. However, the efficacy of weed control on pest mites depends on the timing of the application. According to Corbett *et al.* (2004), herbicides can take up to 10 days to kill weed grasses and broad-leaf weeds but, depending on weed size, it can take longer for control to occur. Canola emergence, if there is sufficient soil moisture at planting, takes approximately 5

days regardless of canola variety (Linder and Schmitt 1995). Hence, paddocks with weed control applied at 8 days pre-planting would still have some green host plant material present or at least the weeds would be dying at the time of crop emergence. Thus any mites present on weeds would be able to move from dying weeds onto the emerging crop. As the majority of weed seedlings emerge within 2 weeks of the opening rains of the season, it is essential that these weeds be controlled to minimise weed competition effects on crops (Walsh *et al.* 2004). If a herbicide is applied to weeds 14 days prior to planting, then a fallow period will exist prior to crop germinating. In this scenario, if pest mites had hatched from diapause eggs, these mites would not persist in the absence of green plant material (see Chapter 4), hence, decreased numbers of pest mites would be found in the following crop. However, this scenario is unlikely to have uptake as delaying crop planting to enable weed control can result in significant yield penalties, as the earlier a crop is planted the better chance it has, within Mediterranean climates, of reaching its optimum yield capacity (Walsh *et al.* 2004).

5.4.3 Impact of cropping rotations on *Balaustium medicagoense* populations

Balaustium medicagoense is found in higher numbers in pasture and cereal crops than in lupins or canola, regardless of the previous season's cropping rotation. This suggests that pasture and cereals are the preferred host plants for this pest mite. This supports findings from Chapter 4 of this thesis and of Arthur *et al.* (2010).

Canola planted after pasture is at increased risk from mite feeding damage. Even though higher numbers of *B. medicagoense* are found in canola planted after pasture, other pest mites, such as earth mites were not excluded from any of the experimental sites. Consequently, the mite feeding damage scores also reflect host preferences for species within the earth mite complex, as well as *B. medicagoense*. According to Umina and Hoffmann (2004), species in the earth mite complex show a marked preference for pasture species over crop species. This suggests that cropping rotations of canola planted after pasture has an increased risk of being damaged, not only by *B. medicagoense*, but also by earth mites.

Lupin and canola crops showed more mite feeding damage (see 'Farming systems experiment 3'), than cereal crops. This is in contrast to plant feeding experiments in greenhouses (Arthur *et al.* 2010) and from results in Chapter 3, that have demonstrated that *B. medicagoense* causes more feeding damage to wheat and lupins than it does to canola. This may be due to a number of reasons. Firstly, as mentioned previously, *B. medicagoense* was not the only mite species present within the experimental site so feeding damage observed may not be solely due to *B. medicagoense*. For instance, *H. destructor* has a host plant preference for canola and lupins over cereals (Umina and Hoffmann 2004). Also, cereals are more likely to out-grow mite feeding damage than canola or lupins, as cereals have their growing point located below the ground and produce more leaves than canola or lupins over the same growing period (Dracup and Kirby

1996; Duff *et al.* 2006; Setter and Carlton 2000). Even so, lupins are less susceptible to mite feeding damage than canola. This is primarily due to the morphological structure of lupin plants as lupin seedlings possess two fleshy cotyledons (Dracup and Kirby 1996) that are larger in size and thicker than canola cotyledons, therefore enabling lupins to tolerate more feeding damage than canola.

It is likely that the lower levels of mite feeding damage observed on the canola seedlings may be due to the application of insecticidal seed dressings. Canola in 'Farming systems experiment 3' was planted with a fipronil seed dressing. Rohitha *et al.* (2003) showed that seed dressings do decrease the amount of mite feeding damage on canola seedlings, whereas glasshouse trials (S. Micic unpubl. data 2009; 2011) show that fipronil seed dressings are not as efficacious as other seed dressings such as imidacloprid at reducing feeding damage if earth mites are above damaging thresholds, i.e. 10 mites per 100 square centimetres (Horne and Page 2008).

5.4.4 Damage thresholds for *Balaustium medicagoense*

Overall mite feeding damage scores were low and there was no difference in plant densities based on *B. medicagoense* numbers. However, results from 'Farming system experiments' suggest that the economic injury levels for crops, i.e. the lowest population density of *B. medicagoense* that will cause economic damage (Ellis *et al.* 2009), in this case the death of seedlings; *B. medicagoense* must exceed: 10 *B. medicagoense* per seedling in canola crops; 20 *B. medicagoense* per seedling in lupin crops; or 30 *B. medicagoense* per seedling in cereal crops to cause seedling loss.

The fact that canola has the lowest mite threshold, shows that canola is the least able to compensate for mite feeding damage. This could be in part due to canola having a smaller seed size and subsequently has less growth vigour, than lupin or cereals. Studies conducted by Chapman *et al.* (2000) in pasture, concluded that small seeded pasture varieties are more susceptible to mite feeding damage when moisture stressed, than larger seeded varieties.

Mites caused insufficient feeding damage to lead to seedling crop loss. This is unlikely to be due to the presence of seed dressings (see section 5.4.1.3), rather mite densities were not high enough and there was sufficient moisture for seedling crops to out-grow any mite feeding damage. Results from Chapter 3 suggest that crop damage from *B. medicagoense* is more likely to be observed if crops are stressed. If crops were stressed during this trial it is probable seedlings may not have been able to out-grow mite feeding damage.

5.5 Conclusions

The most efficacious chemical for the control of *B. medicagoense* was endosulfan. However, due to its withdrawal from broadacre use in Australia use it is not a viable control option. The

synthetic pyrethroids, esfenvalerate and alpha-cypermethrin have similar efficacies and are better suited for use in broad-acre cropping. However, these chemicals have broad non-target effects and have high toxicity to aquatic invertebrates. Further research is required for a more specific miticide.

Prophylactic spray applications may not be the best choice of control option for the control of *B. medicagoense*. The application of 400 mL/ha of alpha-cypermethrin has efficacy on *B. medicagoense*, though a second spray may be required to control any subsequent hatchings. These sprays, based on the current market value of seed and chemicals, are economical. However, their over-use may lead to increased selection pressure on *B. medicagoense* to develop resistance to all synthetic pyrethroids. If this does occur, alternative chemical groups for the rotation of insecticides are limited. The organochlorines tested, endosulfan and dicofol, are no longer registered for use in food production and organophosphates have limited efficacy on *B. medicagoense*. Alternative chemical strategies need to be investigated, but other management practices for the control of this pest need to be implemented to decrease the likelihood of resistance developing.

Unless green plant material is found under crop residues, it is unlikely that the physical presence of crop residues will protect *B. medicagoense* from insecticide spray applications. Rather weed control was effective in controlling pest mites. As both *B. medicagoense* and earth mites are reliant on green plant material for survival, the control of host plants should have the same impact on both of these pest mites. If a green-bridge exists, weed control needs to be applied at least 14 days prior to planting to ensure most host plants have died or fast acting herbicides need to be used. Having a fallow period prior to planting will decrease the numbers of *B. medicagoense* present in paddocks at crop germination.

Cropping rotations that have pasture or cereal are more favourable to the increase of *B. medicagoense*. Crops planted after pastures are more likely to have increased pest mite feeding damage. There needs to be further work to determine how much feeding damage from *B. medicagoense* leads to seedling crop loss in a range of broad-acre crops and pastures.

6 Recommendations for an integrated approach for the control of *Balaustium medicagoense*

6.1 Introduction

Control of agricultural pests in Australian pastures and cropping environments relies heavily on pesticide applications (Arthur *et al.* 2008; Micic *et al.* 2008; Umina *et al.* 2004). These pesticides are routinely applied prophylactically for the control of pests, applications which often occur regardless of pest densities (James 1991; Mangano and Micic 2008; Mangano and Severtson 2007). In Western Australia, the opportunity for the prophylactic use of insecticides is enabled by the demand for early season weed control and the compatibility of herbicide/insecticide tank mixes (Lawrence 2009; Micic *et al.* 2007). A survey of growers (see Appendix 1) found that most pre-plant sprays were a mixture of insecticide and herbicide with a residual action. Combined prevention of pests and weeds with a single spray operation minimised the number of operations required to successfully establish crops, reduced the costs of application (labour, fuel and equipment) and the requirement to monitor crops once they had emerged. These sprays were primarily directed at pests such as *B. medicagoense*, *H. destructor* and weevils (see Appendix 1) and there remains a low level of awareness of such practices on the potential to develop insecticide resistance among field populations.

Balaustium medicagoense is not a ‘key pest’ of broadacre crops and only requires control in some years. A key pest is considered to be one that is persistent, occurs perennially and usually reaches economically damaging levels (Hearn and Fitt 1992). Even though this mite species is persistent, occurs perennially and is polyphagous, results from this thesis suggest that it is only in some years i.e. those with a dry start that *B. medicagoense* causes sufficient feeding damage to lead to seedling crop loss (Refer to Chapter 3). The application of prophylactic sprays is likely to increase the selection pressure for resistance to develop in *B. medicagoense*.

Worldwide there are over 300 agricultural pest species now resistant to insecticides (Whalon *et al.* 2008), however, in Australia, for broad-acre crop mite pests, resistance to insecticides has only been identified in *H. destructor* to the synthetic pyrethroid group (Umina *et al.* 2007) and tolerances identified to the organophosphate omethoate (Umina *et al.* 2017). To date no insecticide resistance has been recorded in *B. medicagoense*.

However, there is a need to develop strategies that do not solely rely on insecticides for the control of this pest. The findings from experiments within this thesis lead to the following recommendations for control of *B. medicagoense* that fit into an IPM frame work:

Recommendation 1: Control host plants before sowing

Background

Balaustium medicagoense is a resident pest able to persist in the cropping environment between seasons. It has the ability to survive hot dry summers which is characteristic of a Mediterranean climate. This mite is not found in the absence of plant hosts suggesting that the length of time host plants are present within a farming system impacts on *B. medicagoense* numbers. If these host plants are weeds then controlling weeds will lead to a decrease in *B. medicagoense* numbers. However, if there has been sufficient summer rain for weed germination, this can lead to the establishment of a green-bridge, if the green-bridge consists of preferred plant hosts of *B. medicagoense*, such as volunteer cereals then higher numbers of this pest mite can be expected to be present in paddocks.

Commercial farming enterprises generally aim to only leave a green-bridge intact if stock is present in the system to utilise the green-bridge for grazing. Otherwise, a green-bridge depletes the available stored soil moisture for subsequent crops (Bastiaans 2008; Walsh *et al.* 2004). The success of herbicide applications for the control of a green-bridge depends on the weed-seed bank that may germinate with subsequent rainfall events, as well as the size of the weeds present. Established weeds are more difficult to control than weeds at emergence (Bastiaans 2008; D'Embden and Llewellyn 2006; Walsh *et al.* 2004). This suggests that a single herbicide application, if there are a number of summer rain-events, is unlikely to lead to the eradication of a green-bridge. Rather, herbicides would need to be applied after each germination of weeds because residual herbicides are not commonly used for summer weed control.

How this should be applied

The timing of herbicide applications is important to stop pest mites transferring from dying plant hosts onto germinating crops (see Micic 2005). The optimum time to apply herbicides is 14 days or more prior to planting. This will lead to a fallow period of at least 10 days prior to crop emergence, thereby reducing numbers of pest mites. Fast acting herbicides may be required where timings are tight because a fallow period prior to cropping is required.

However, in paddocks destined for cropping, summer weeds should be controlled soon after each summer emergence. This ensures the maximum length of fallow to suppress the mites and ensures the maximum amount of water is conserved to reduced early moisture stress of crops. Where conditions have not been conducive to breaking *B. medicagoense* diapause then the first germination of weeds should be controlled with fast acting knockdown herbicides such as Spray.Seed® or cultivation and planting delayed for at least 10 days.

Limits to recommendations

Even if weed control is successful and there is a fallow period prior to crop emergence, *B. medicagoense* may still be present at crop emergence. Species within the genus *Balaustium*, such as *B. putmani*, enter diapause at both egg and hexapod larval stages when food sources are not available (Cadogan and Laing 1977). Even though larval *B. medicagoense* are partly herbivorous (Arthur *et al.* 2010), results from Chapter 3 suggest that crops are more likely to be damaged if *B. medicagoense* are present at crop emergence and crops are moisture stressed. So, unless crops are stressed, a second hatching of *B. medicagoense* is unlikely to cause economic crop damage.

Future work

The exact environmental precursors that trigger hatchings of *B. medicagoense* and laying of potential diapause eggs have only been surmised. Once these are known, herbicides or insecticides can be timed to control adults prior to diapause egg laying and/or when peak hatchings of *B. medicagoense* have occurred. This can prevent the subsequent population from building up in high numbers. This has been successful in other mite species; for instance summer diapause egg production in *H. destructor* is best predicted by changes to day length in spring. Subsequently a model was created to predict when diapause egg production would commence, so a single spray could be applied in spring to kill female mites before diapause egg production occurred (Ridsdill-Smith *et al.* 2005).

Another option is to use livestock to graze host plants of *B. medicagoense* to suppress populations. However, while grazing has been found to be as effective as insecticides in controlling *H. destructor* (see Michael 1987) the effectiveness of this as a control strategy for *B. medicagoense* needs to be assessed.

Recommendation 2: Don't grow canola after grass based pastures

Background

Balaustium medicagoense is polyphagous having been observed feeding on canola, lupin, barley and pasture grasses and this mite also persisted on all crops trialled from 2006 to 2008 (see Chapter 4). However, its reproductive output is strongly associated with barley crops and it is more abundant on grasses. Consequently, higher numbers of this mite have been found in grass-based pastures. This is likely to be because pastures can be relatively static systems while they remain un-cropped, and hence can sustain higher numbers of resident pests (Micic 2005). So crops planted after pastures especially grass-based pastures can have higher numbers *B. medicagoense* (see chapters 3 and 4).

The cereal phase of a cropping rotation supports more *B. medicagoense* than canola or lupin phases. Consequently, crops following a cereal crop may have higher numbers of *B. medicagoense* than crops that do not (see chapters 3 and 4). Of all the crops grown, canola is the most susceptible to mite feeding damage and is the crop most likely to have an insecticide applied to protect it from pest damage (see Appendix 1).

How this should be applied

Crop rotations should be arranged so that crops susceptible to *B. medicagoense* feeding damage such as canola are not sown after barley, other cereals or grass based pastures but after lupins. The manipulation of pastures to decrease the grass component will also suppress *B. medicagoense* numbers.

Limits to recommendations

Recommendations for cropping rotations need to maximize farm profits in order to be widely adopted. One of the easiest methods of determining the profit is to look at the gross margin of the different crops trialled in this thesis. The gross margin is the revenue produced from the commodity less the variable costs from growing it (DAFWA 2017). The crop with the highest gross margin is canola (Table 19) and therefore it is most profitable to protect canola seedlings from extensive damage from *B. medicagoense*.

Table 19: Average prices for crops grown in 325-750 mm rainfall in Western Australia

Adapted from P Mattingly pers. comm. 2012

Commodity	Average price (\$AU) /t	Average gross income (\$AU)/ha	Average variable costs (\$AU)/ha	Average gross margin (\$AU)/ha
Barley (malt)	220	468	349	120
Barley (feed)	180	465	348	117
Canola	580	870	460	410
Wheat	213	458	360	100
Lupin	233	291	255	47

The best-practice cropping rotation to reduce *B. medicagoense* in canola is to plant it after a lupin crop (Chapters 3 and 4). However, in southern Western Australia, the gross margin for lupin crops is significantly less than for cereal crops (Table 19) and this is one of the main reasons cereals are more commonly grown than lupin crops (ABARE 2017; Table 19). However, lupin crops increase the fertility for the following years crop which can lead to less nitrogenous fertiliser applications (Reeves *et al.* 1984; Rowland *et al.* 1988; Whitbread *et al.* 2000). A reduction in fertiliser inputs can increase the gross margins of the following years crop and this suggests that the best cropping rotation for *B. medicagoense* suppression is a cereal,

lupin and then canola rotation. If it is not profitable to sow lupins then it is preferable to plant canola after a wheat crop, compared to planting it after a barley crop or a grass based pasture.

The manipulation of pastures to decrease the amount of grass present to suppress *B. medicagoense* species may not be profitable. For pastures to fit into a cropping system and be profitable there needs to be a 3 year pasture phase (Monjardino *et al.* 2004). And diverse pastures, those that contain a mix of species that provide additional forage for livestock, are more productive than simple pastures (for example Pembleton *et al.* 2015).

Future work

Selection of varieties that are resistant to pests and diseases is an important cultural control. However, there are no crop varieties with increased tolerances to mite feeding damage (Liu and Ridsdill-Smith 2001; Moritz and McDonald 1995; Ridsdill-Smith *et al.* 2008). Even so, if crop varieties are chosen that match the predicted growing season and have good disease tolerance then they are likely to be healthy (Williams 2017). The healthier a crop is, the more likely it is to outgrow mite feeding damage (Refer to Chapter 3).

Legume-dominant pastures, like lupins provide nitrogen for the following crops. Further research is required to unravel the economics of these complex system relations. As the returns from stock are increasing relative to crops more growers will be looking to running more stock.

Recommendation 3: Monitor plant number and assess ability of plants to outgrow damage rather than relying on damage and/or population thresholds

Background

Despite the potential to lower the costs of production and safeguard the efficacious use of important chemicals, thresholds for early season pest numbers are not widely used by growers in southern Western Australia when applying insecticides (see Appendix 1). Horne and Page (2008) found that growers did not have the confidence to withhold spray for early season pests in crops such as canola. This is possibly because thresholds for many pests require more research (Gu *et al.* 2007) and early season infestations occur at a time when growers are sowing crops and hence time for insect scouting is limited (Appendix 1). Reviews of integrated pest management in Australia highlight the success of using thresholds of pest numbers to control pests in cotton and horticulture (see Horne and Page 2008; Williams and Il'ichev 2003). Horne and Page (2008) suggest that one of the factors for the poor adoption of thresholds for early season pests in broad-acre cropping has been that researchers have concentrated on a single pest and have not dealt with all of the pests in a crop.

However, the numbers of *B. medicagoense* reportedly causing damage to crops tends to vary with crop stage as well as the seasonal conditions (see Chapter 3). The development of an

economic threshold for *B. medicagoense* was not possible in this thesis, primarily due to the inability of the mites to persist on crop seedlings alone especially under laboratory conditions.

One way to overcome the use of a single 'count' threshold for a single pest is to apply an insecticide application based on the amount of plant damage and plant loss occurring to the crop at establishment (Arthur *et al.* 2015). An approach such as this relies on identifying pests that are present in a paddock from their feeding damage to the crop and applying an appropriate insecticide application only if plant numbers fall below the optimum density for yield (Arthur *et al.* 2015).

The optimum plant density depends on the target grain yield, for example 40 plants/m² of wheat are required in Western Australia for each tonne of target grain yield (Anderson *et al.* 2004), the target is for 100 wheat plants per square metre (Anderson *et al.* 2000). For canola (conventional and hybrids) it is not to be below 20 plants per square metre (DAFWA 2015); for lupins 35 plants (O'Connell *et al.* 2003) and for barley 120 plants per square metre (Trainor and Paynter 2013).

How this should be applied

In high risk situations, for instance if grass-based pastures or cereals were grown in the previous year, increase seeding rates of crops so that some crop seedling losses can be accepted without loss of yield. Then at crop emergence determine the plant density, amount of feeding damage and crop stress or potential stress from weather forecasts and stored soil moisture estimates.

If the crop density is close to the minimum required for optimum yield and feeding damage is evident and the crop is not out-growing the feeding damage then consideration should be given to the application of a synthetic pyrethroid.

Limits to recommendation

Using plant density as the indicator can require the use of a higher seeding rate to allow for some seedling loss. For instance, prior to hybrid canola seed coming on the market, the recommendations was for seeding at 5 kg/ha to have at most 50 seedlings per square metre (Micic 2005). The cost of hybrid canola seed is now \$(AUS) 34 - 48 per ha based on a planting rate of 2 kg/ha which results in the germination of only 30 seedlings per square metre (Seymour 2011). With an optimal seedling density of 30 or more seedlings per square metre (Seymour 2011), there is little leeway for crop loss to occur. Consequently, the use of a prophylactic application of alpha-cypermethrin at 400 mL/ha at the crop seedling stage, which costs about \$(AUS) 7.61 per ha (Robinson 2009; Moore and Moore 2017), is an attractive option compared to having to replant a crop. However, this can be offset by the benefits of using increased plant numbers at establishment for in-crop weed management (see Radford *et al.* 1980; Lemerle *et al.* 2004; Yenish and Young 2004; Walsh and Minkey 2006).

Future work

The crops most prone to damage by *B. medicagoense* are those at the seedling stage (see Chapter 3). At this time it can be difficult to determine what the crop density is especially if there has been a staggered germination in the paddock. An accurate and effective method to determine what the crop density is throughout a paddock is required and the ability to determine what control measures, if any, should be applied before a suboptimum plant density is reached in the paddock.

Recommendation 4: Apply synthetic pyrethroids for control of *B. medicagoense* only to prevent crop loss

Background

Balaustium medicagoense has a higher tolerance to insecticides compared to *H. destructor* (Arthur *et al.* 2008; 2010; 2011; Micic *et al.* 2008; see Chapter 3). The application of prophylactic insecticides early in the season, is unlikely to coincide with *H. destructor* emergence from over-summering diapause eggs (see Wallace 1970) rather, it is more likely that *B. medicagoense* will be present in the landscape. Prophylactic insecticides such as alpha-cypermethrin are usually applied at 400 mL/ha, but if *B. medicagoense* is exposed to sub-lethal doses i.e. at rates less than 400 mL per ha and/or alpha-cypermethrin continues to be applied at 400 mL per ha with the first knock-down, it can be expected that there will be increased selection pressure on *B. medicagoense* to develop resistance. Even though there are no Erythraeid mites that have been recorded as having resistance to acaricides (Whalon *et al.* 2012), this is likely due to the fact that there are no species of mites in this family apart from *B. medicagoense* that have been recorded as crop pests.

Currently, there are only two chemical groups, synthetic pyrethroids and organochlorines, which have good efficacy against *B. medicagoense* (Arthur *et al.* 2008; see Chapter 3). Consequently, a resistance management strategy that relies on the rotation of chemical groups to manage resistance development in *B. medicagoense* is unlikely to succeed due to the limited number of efficacious chemicals available.

How this should be applied

Insecticides should be applied as per recommendation 3 for the control of this pest. The most efficacious registered insecticides are from the synthetic pyrethroid group (see Chapter 5).

If pests other than *B. medicagoense* are found causing crop damage, selective control measures rather than synthetic pyrethroids should be used. This will decrease selection pressure for resistance developing in *B. medicagoense*. For instance, for aphids not only are synthetic pyrethroids registered but selective controls such as pirimor and sulfoxaflor are also registered

(Table 1, APVMA 2017) which provide a viable alternative to synthetic pyrethroids for aphid control.

Alternatively insecticides with the active ingredients such as bifenthrin and chlorpyrifos, could be applied for the control of pests such as weevils for which there are no selective insecticides registered (Table 1, APVMA 2017). These insecticides have limited efficacy on *B. medicagoense* (Chapter 5).

Limits to recommendations

An insecticide resistance prevention strategy based on the rotation of chemistry groups and mixtures for pests other than *B. medicagoense*, relies on the grower applying measures that are currently more expensive than synthetic pyrethroids (see Table 1). It also relies on stopping the practice of applying a prophylactic spray with the first knock-down to control insect pests (Appendix 1) because there is a perception that applying these sprays negates the need to monitor germinating crops such as canola for invertebrate pests (Micic *et al.* 2008).

Future work

Further research into the insecticide groups that have limited non-target effects is needed. A component of IPM is the preference to use insecticides that have limited non-target effects and are pest-specific (Williams 2017; Thomson 2006; 2007). The specificity of an insecticide can be measured according to its beneficial disruption index (BDI). This is benchmark to measure the overall impact of insecticides on beneficial insects within a cropping system (Williams 2017). Insecticides used in seed dressings have a low BDI as they have very low non-target effects, are compatible within an IPM framework (Williams 2017; Horne and Page 2008; Smith *et al.* 1997) and are registered for use in broad-acre cropping (Moore and Moore 2017) but those trialled in this thesis, imidacloprid and fipronil did not have efficacy on *B. medicagoense* at the registered rates (see Chapter 5). Further trial work on the use of seed dressings at higher rates than those registered on *B. medicagoense* is needed. These two seed dressings are from different mode of action groups (see Table 2) and the ability to rotate between seed dressings is a useful insecticide resistance strategy.

Other potential candidates could include mite growth inhibitors (Group 10A) in particular hexythiazox which may be suitable for broadacre use as they are stable in sunlight and the mitochondrial complex I electron transport inhibitors (Group 21) especially pyridaben (Group 21A) and azadirachtin (Group UN) which is derived from neem (APVMA 2017; FAO2007; Tomlin 2003). Miticides such as bifenazate (Group UN) and emamectin (Group 6) have been trialled on *B. medicagoense* (Unpublished data, Micic 2012) and were not efficacious at normal rates.

The timing of insecticide applications should also be investigated to determine if control of adult *B. medicagoense* prior to diapause egg laying and/or after peak hatchings have occurred is possible. Results from this thesis have only surmised the environmental precursors that trigger hatchings of *B. medicagoense* and when the laying of potential diapause eggs has occurred.

6.2 Concluding remarks

The grains industry is one of the largest primary industries in Western Australia, with exports in excess of \$(AUS) 2 billion each year and over 8 million hectares planted annually (ABARE 2017). However, the long range rainfall out-look is for drier winters with higher median temperatures. In dry conditions growers are more likely to dry-seed crops so that germination takes place as soon as there is sufficient soil moisture. This leads to crops germinating with the first opening rains, which can coincide with *B. medicagoense* hatching from diapause eggs. This scenario of warmer weather, combined with potentially moisture stressed crops, is likely to lead to *B. medicagoense* causing more crop damage (refer to Chapter 3).

If crop damage is economically significant, the only option available for controlling *B. medicagoense* in germinating crops is chemical control. Synthetic pyrethroids will have efficacy on *B. medicagoense*, but the success of these chemicals in protecting seedling crops relies on the chemical adhering to green plant material (Tomlin 2003). At crop germination the majority of the chemicals applied falls onto bare-ground (Pimental 1995) and not on the target pest. If there is a rain event soon after application, environmental contamination is very possible, as insecticides in the synthetic pyrethroid group are often water soluble and highly toxic to aquatic invertebrates (Tomlin 2003). The only other chemical group that has efficacy on *B. medicagoense* are the organochlorines. Organochlorines have been withdrawn from use in broadacre crops (APVMA 2017; Sanchez *et al.* 2010). Other insecticide treatments such as seed dressings, bare earth insecticides or applications to control the previous generations need to be investigated and/or registered.

The focus needs to be on suppressing *B. medicagoense* populations before they can cause crop damage regardless of the season. This could be achieved by using cultural controls and requires planning as it cannot be applied in the year that economic damage is observed. The manipulation of plant hosts is the most effective cultural control for *B. medicagoense* management.

This can be achieved through removal of weed species that act as hosts. However, it is not only the weed hosts that are present in paddocks prior to planting, the in-crop weed species especially grasses can be a potential host for *B. medicagoense* and aid carry-over into the following year. For instance a weedy lupin crop increases the risk of *B. medicagoense* being present in the following year. If herbicides are relied on to control these weed species, the propensity of the

species to develop resistance to herbicides needs to be taken into account (e.g. Owen *et. al.* 2018). If weeds are not controlled effectively crops will not be protected from damage by *B. medicagoense*. Alternatively, cropping rotations can be used to suppress *B. medicagoense* by ensuring susceptible crops are planted after non-preferred host crops.

Even though this mite will only be a pest in some years, the reliance on insecticide applications for its control needs to be carefully planned to reduce the risk of resistance in this and companion species. Consequently, farming in the future is going to be more reliant on the implementation of cultural controls for the suppression of *B. medicagoense* populations.

7 References

- ABARE (2010) Australian crop report. Catalogue No. 154. Australian Bureau of Agricultural and Resource Economics, Canberra, ACT.
- ABARE (2017) Australian crop report. Catalogue No. 183. Australian Bureau of Agricultural and Resource Economics, Canberra, ACT.
- Abrol D, Shankar U (2012) History, overview and principles of ecologically based pest management. In *Integrated Pest Management, Principles and Practice* (eds. D Abrol and U Shankar) pp. 1-26 (CAB International: Wallingford, England).
- Agriculture Western Australia (2000) Pest web database entry: *Balaustium mite Balaustium medicagoense*. Available at http://agspsrv34.agric.wa.gov.au/ento/pestweb/Query1_1.idc?ID=-1792933947 [Verified 14 November 2017].
- Alston DG, Reading ME (1998) Factors influencing the adoption and educational outreach of integrated pest management. *Journal of Extension* **36** Available at <http://www.joe.org/joe/1998june/a3.php> [Verified 7 November 2017].
- Anderson WK, Hoyle FC, Armstrong L, Shackley BJ (2000) Crop Management. In *The Wheat Book: Principles and Practice*. (Eds WK Anderson, JR Garlinge) pp. 133-163 (Department of Agriculture, Western Australia: Perth).
- Anderson WK, Stephens D, Siddique KHM (2016) Dryland agriculture in Australia: Experiences and Innovations. In *Innovations in Dryland Agriculture*. (Eds M Farooq, KHM Siddique) pp. 299-320 (Springer Nature: Charn, Switzerland).
- Anon. (1992) Report of the joint meeting of the FAO panel of experts on pesticide residues in food and the environment and the WHO expert group on pesticide residues. FAO Plant Production and Protection Paper 116. Food and Agriculture Organisation of the United Nations: Rome, Italy.
- APVMA (2005) The reconsideration of approval of the active constituent Endosulfan, registrations of products containing Endosulfan and their associated labels. Final Review Report and Regulatory Decision, Review Series 2. Australian Pesticides and Veterinary Medicines Authority, Canberra, ACT. p. 13.
- APVMA (2017) Public chemical registration information system search. Available at <https://portal.apvma.gov.au/pubcris> [verified 4 June 2017]
- Arthur A, Hoffmann AA, Umina PA, Weeks AR (2008) Emerging pest mites of grains (*Balaustium medicagoense* and *Bryobia* spp.) show high levels of tolerance to currently registered pesticides. *Australian Journal of Experimental Agriculture* **48**, 1126–1132.
- Arthur A, Weeks AR, Umina PA, Hoffmann AA (2010) Survival and reproduction of the pest mites *Balaustium medicagoense* and *Bryobia* spp. on winter grain crops. *Experimental and Applied Acarology* **52**, 141-153.

- Arthur A, Weeks AR, Hill MP, Hoffmann AA (2011) The distribution, abundance and life cycle of the pest mites *Balaustium medicagoense* (Prostigmata: Erythraeidae) and *Bryobia* spp. (Prostigmata: Tetranychidae) in Australia. *Australian Journal of Entomology* **50**, 1-15.
- Arthur AL, Hoffmann AA and Umina PA (2015) Challenges in devising economic spray thresholds for a major pest of Australian canola, the redlegged earth mite (*Halotydeus destructor*). *Pest Management Science* **71**, 1462-1470.
- Baskaran S, Kookana R, Naidu R (1999) Degradation of bifenthrin, chlorpyrifos and imidacloprid in soil and bedding materials at termiticidal application rates. *Pesticide Science* **55**, 1222-1228.
- Bastiaans L (2008) Focus on ecological weed management: What is hindering adoption. *Weed Research* **42**, 177-193.
- Begon M, Townsend C, Harper J (2006) *Ecology: From Individuals to Ecosystems*. (Blackwell: London, United Kingdom).
- Berlandier F (2004) Aphid management in canola crops. Farmnote No. 45, Department of Agriculture, Perth, Western Australia.
- Berlandier FA, Baker GJ (2007) Winter oilseeds. In *Pests of Field Crops and Pastures: Identification and Control*. (Ed. PT Bailey) pp. 144-145. (CSIRO Publishing: Melbourne, Vic).
- Bertholdsson NO (2004) Variation in allelopathic activity over 100 years of barley selection and breeding. *Weed Research* **44**, 78-86.
- Brennan A, Fortune T, Bolger T (2006) Collembola abundances and assemblage structures in conventionally tilled and conservation tillage arable systems. *Pedobiologia* **30**, 135-145.
- Caceres CE (1998) Seasonal dynamics and interspecific competition in Oneida Lake Daphnia. *Oecologia* **115**, 233-244.
- Cadogan BL, Laing JE (1977) A technique for rearing the predaceous mite *Balaustium putmani* (Acarina: Erythraeidae), with notes on its biology and life history. *Canadian Entomologist* **109**, 1535-1544.
- Cadogan BL, Laing JE (1981) A study of *Balaustium putmani* (Acarina: Erythraeidae) in apple orchards in Southern Ontario. *Proceedings of the Entomological Society of Ontario* **112**, 13-22.
- Chapman R, Ridsdill-Smith TJ, Turner NC (2000) Water stress and redlegged earth mites affect the early growth of seedlings in a subterranean clover/capeweed pasture community. *Australian Journal of Agricultural Research* **51**, 361-370.
- Childers CC, Rock GC (1981) Observations on the occurrence and feeding habits of *Balaustium putmani* (Acari: Erythraeidae) in North Carolina apple orchards. *International Journal of Acarology* **7**, 63-68.
- Choi J, Soderlund DM (2006) Structure–activity relationships for the action of 11 pyrethroid insecticides on rat Nav1.8 sodium channels expressed in *Xenopus* oocytes. *Toxicology and Applied Pharmacology* **211**, 233-244.

- Connell JH (1983) On the prevalence and relative importance of interspecific competition: Evidence from field experiments. *The American Naturalist* **122**, 661-696.
- Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for Bromoxynil, Glufosinate, Glyphosate, Pyriithiobac, and Sulfosate. *Weed Technology* **18**, 443-453.
- Crabtree B (2000) Joys and sorrows of no-tillage in Western Australia. *Sustainable Development International* 2000, 99-102.
- Cramb J (2000) Climate in relation to agriculture in south-western Australia. In *The Wheat Book: Principles and Practice*. (Eds WK Anderson, JR Garlinge) pp. 3-9 (Department of Agriculture, Western Australia: Perth).
- DAFWA (2015) Information for the canola seeding rate calculator. Available at: www.agric.wa.gov.au/canola/information-canola-seeding-rate-calculator [Verified 4 November 2017].
- DAFWA (2017) Improvement tools: Gross margin analysis. Available at: www.agric.wa.gov.au/improvement-tools-gross-margin-analysis [Verified 4 November 2017].
- Davies TGE, Field LM, Usherwood PNR, Williamson MS (2007) DDT, pyrethrins, pyrethroids and insect sodium channels. *IUMB Life* **59**, 151-162.
- D'Embden FH, Llewellyn RS (2006) No-till adoption decisions in southern Australian cropping and the role of weed management, *Australian Journal of Experimental Agriculture* **46**, 263-569.
- Denno RF, McClure MS, Ott JR (1995) Interspecific interactions in phytophagous insects: competition re-examined and resurrected. *Annual Review of Entomology* **40**, 297-331.
- Dent D (2000) *Insect Pest Management* (2nd edition). (CAB International: Wallingford, England).
- Derpsch R (2003) Conservation tillage, no-tillage and related technologies. In *Conservation Agriculture: Environment, Farmer Experiences, Innovations, Social Economy, Policy*. (Eds L Garcia-Torres, J Benites, A Martinez-Vilela, A Holgado-Cabrera) pp. 183-190 (Kluwer Academic Publishers: Dordrecht, Netherlands).
- Dracup M, Kirby EJM (1996) *Lupin Development Guide*. (University of Western Australia Press: Perth, Australia).
- Duff J, Sermon D, Walter G, Mangano P, Barbetti M, Addison B, Eksteen D, Pol E, Leach B, (2006) *Growing Western Canola*. (Oilseeds Industry Association of WA: Perth, Australia).
- Early R (2004) Leaching stubbles spell death for weeds. *Farming Ahead* **149**, 50-51.
- Edwards O, Franzmann B, Thackray D, Micic S (2008) Insecticide resistance and implications for future aphid management in Australian grains and pastures: a review. *Australian Journal of Experimental Agriculture* **48**, 1523-1530.
- Emery R, Mangano P, Michael P (2005) *Crop Insects: The Ute Guide*. (Department of Agriculture Western Australia: Perth).

- Emmanuel N, Curry JP, Evans GD (1985) The soil acari of barley plots with different cultural treatments. *Experimental and Applied Acarology* **1**, 101-113.
- FAO (2007) FAO specifications and evaluations for agricultural pesticides: pirimiphos-methyl. Available at http://www.fao.org/fileadmin/templates/agphome/documents/Pests_Pesticides/Specs/pirimiphos_07.pdf [Verified 4 June 2017].
- Fick GW, Power AG (1992) Pests and integrated control. In *Ecosystems of the World: Field Crop Ecosystems, vol. 18*. (Ed CJ Pearson) pp. 59-83 (Elsevier Science: Amsterdam, Netherlands).
- Flint ML, Daar S, Milinar R (2003) Establishing integrated pest management policies and programs: A guide for public agencies. Publication 8093. University of California, Oakland, California, USA.
- Flint ML, Gouveia P (2001) IPM in practice: Principles and methods of integrated pest management. Publication 3418. University of California, Oakland, California, USA.
- Flower K, Braslin T (2006) The future of no-tillage systems in Western Australia. In *Proceedings of the 13th Australian Agronomy Conference*, held in Perth, Western Australia, 10-14 September. (Eds N Turner and T Acuna) (The Regional Institute Ltd: Canberra, Australia).
- French B, White P (2008) Environmental influences on lupin growth. In *Producing Lupins*. (Eds P White, B French, A McLarty) pp. 27-35 (Department of Agriculture and Food, WA: Perth).
- Fuentes-Quintero LS, Muñoz-Cárdenas K, Combita O, Jimeno E, De La Hoz JC, Cantor F, Rodríguez D, Makol J (2014) A re-description of *Balaustium leanderi* Comb. Nov. (Actinotrichida, Erythraeidae) with first report on characteristics of all active instars and taxonomic notes on the genus. *Florida Entomologist* **97**, 937-951.
- Gabrys G (2016) Commentaries on synonyms within Palaearctic Erythraeidae (Acari: Actinotrichida: Parasitengona). *Rocznik Muzeum Górnośląskiego w Bytomiu Przyroda* **22**, 1-8.
- Gaull KR, Ridsdill-Smith TJ (1996) The foraging behaviour of redlegged earth mite, *Halotydeus destructor* (Acarina: Penthaleidae) in an annual subterranean clover pasture. *Bulletin of Entomological Research* **86**, 247-252.
- Gardner WK, Drendel MF, McDonald GK (1994) Effects of sub-surface drainage on cultivation and stubble retention on soil porosity and crop growth in a high rainfall area. *Australian Journal of Experimental Agriculture* **34**, 411-418.
- Gillespie DJ (1991) Identification of resistance to redlegged earth mites (*Halotydeus destructor*) in pasture legumes. *Plant Protection Quarterly* **6**, 170-171.
- Glen DM (2000) The effects of cultural measures on cereal pests and their role in integrated pest management. *Integrated Pest Management Reviews* **5**, 25-40.
- Glencore Australia (2017) Western Australia grower bids. Available at https://portal.glencoregrain.com.au/downloads/bid_sheet/public_pdf/WA%20Ports%20Contract%20Prices_17112017.pdf [Verified 14 November 2017].

- Godfrey L, Natwick E, Wright S, Jackson L (2006) Small grain production manual part 7: Pest management of small grains – insects. Publication 8170. University of California, Oakland, California.
- GRDC (2010) Growing hybrid canola. Canola Factsheet: August 2010. Grains Research and Development Corporation, Kingston, ACT.
- Gu H, Edwards O, Hardy AT, Fitt GP (2008) Host plant resistance in grain crops and prospects for invertebrate pests management in Australia: an over view. *Australian Journal of Experimental Agriculture* **48**, 1543-1548.
- Gu H, Fitt GP, Baker GH (2007) Invertebrate pests of canola and their management in Australia: a review. *Australian Journal of Entomology* **46**, 231-243.
- Guedes N, Guedes R, Campbell J, Throne J (2010) Contest behaviour of maize weevil larvae when competing within seeds. *Animal Behaviour* **79**, 281-289.
- Hadley P, Pearson S (1999) Physiology. In *Biology of Brassica Coenospecies*. (Ed C Gomez-Campo) pp. 144-145 (Elsevier Science: Barcelona, Spain).
- Hagley EAC and Simpson CM (1977) Effect of insecticides on predators of the pear psylla, *Psylla pyricola* (Hemiptera: Psyllidae), in Ontario. *Canadian Entomologist* **115**, 1409-1414.
- Hairston NG, Smith FE, Slobodkin LB (1960) Community structure, population control and competition. *The American Naturalist* **94**, 421-425.
- Halliday RB (1998) *Mites of Australia: A checklist and bibliography*. (CSIRO Publishing: Melbourne).
- Halliday RB (2000) Additions and corrections to mites of Australia: A checklist and bibliography. *Australian Journal of Entomology* **39**, 233-235.
- Halliday RB (2001) Systematics and biology of the Australian species of *Balaustium* Von. Heyden (Acari: Erythraeidae). *Australian Journal of Entomology* **40**, 326-330.
- Halliday RB (2005) Predatory mites from crops and pastures in South Africa: Potential natural enemies of redlegged earth mites *Halotydeus destructor* (Acari: Pentheleidae). *Zootaxa* **1079**, 11-68.
- Halliday RB, Paull C (2004) Assessment of *Chausseria capensis* (Acari: Anystidae) as a predator of *Halotydeus destructor* (Acari: Pentheleidae). *African Entomology* **23**, 286-290.
- Hayes JL (1985) The predator-prey interaction of the mite *Balaustium* sp. and the pierid butterfly *Colias alexandra*. *Ecology* **66**, 300-303.
- Hearn AB, Fitt GP (1992) Cotton cropping systems. In *Ecosystems of the World: Field Crop Ecosystems, vol. 18*. (Ed CJ Pearson) pp. 85-142 (Elsevier Science: Amsterdam, Netherlands).
- Hedges BZ, Rosselot AE, Tomko PM, Yoder JA, Benoit JB (2012) High temperature and dehydration tolerance of the red velvet mite, *Balaustium* sp. (Erythraeidae), permit the exploitation of extremely hot, dry microhabitats. *International Journal of Acarology* **38**, 89-95.

- Helle W, Bolland HR, Jeurissen SHM, van Seventer GA (1984) Chromosome data of the Actinedida, Tarsonomida and Oribatida. In *Acarology VI*. (Eds DA Griffiths, CE Bowman) pp. 449-454 (Ellis Horwood Ltd.: Chichester, England).
- Hill DS (1987) *Agricultural Pests of Temperate Regions and their Control*. (Cambridge University Press: Cambridge, UK).
- Hill NJ, Zhang H, Trezise T, Young J, Moyes N, Carslake L, McTaggart R, Turner NC, Anderson W, Poole M (2005) Successful cropping in the high rainfall zone of Western Australia. Bulletin No. 4661. Department of Agriculture, Perth, Western Australia.
- Hoffmann AA, Weeks AR, Nash MA, Mangano GP, Umina PA (2008) The changing status of invertebrate pests and the future of pest management in the Australian grains industry. *Australian Journal of Experimental Agriculture* **48**, 481-1493.
- Hopkins DC, McDonald G (2007) Cereals- pests and benefits in the field. In *Pests of Field Crops and Pastures: Identification and Control*. (Ed. PT Bailey) pp. 144-145 (CSIRO Publishing: Melbourne, Australia).
- Horne PA, Page J (2008) *Integrated Pest Management for Crops and Pastures*. (Landlinks Press: Collingwood, Australia).
- Horne PA, Page J, Nicholson C (2008) When will integrated pest management strategies be adopted? Example of the development and implementation of integrated pest management strategies in cropping systems in Victoria. *Australian Journal of Experimental Agriculture* **48**, 1601-1607.
- Hoy M (2011) *Agricultural Acarology: An Introduction to Integrated Mite Management*. (CRC Press: Boca Raton, Florida).
- Hu M, Li SQ, Liu FY (1987) Law of growth and decline on *Petrobia latens* and its integrated control. *Insect Knowledge* **24**, 201-204.
- IRAC International MoA Working Group (2012) IRAC MoA classification scheme. Available at: <http://www.iraac-online.org/documents/moa-classification/?ext=pdf> [Verified 20 June 2012].
- James DG (1991) Abundance and phenology of earth mites (Acari: Penthalidae) and predatory mites in pesticide treated and pesticide-free grassland habitats in southern New South Wales, Australia. *International Journal of Acarology* **26**, 363-369.
- James DG (1995) Biological control of earth mites in pasture using endemic natural enemies. *Plant Protection Quarterly* **10**, 58-59.
- James DG, O'Malley K, Rayner M (1995) Effect of alpha-cypermethrin and bifenthrin on the survival of five acarine predators of *Halotydeus destructor* (Acari: Penthalidae). *Experimental and Applied Acarology* **19**, 647-654.
- Jenkins CFH (1945) DDT as an agricultural insecticide. *Journal of Agriculture-Western Australia* **22**, 229-232.
- Jeppson LR, Keifer HH, Baker EW (1975) *Mites Injurious to Economic Plants*. (University of California Press: Berkeley, USA).

- Khangura R, Barbetti M (1997) Prevalence of blackleg (*Leptosphaeria maculans*) on canola (*Brassica napus*) in Western Australia. *Australian Journal of Experimental Agriculture* **41**, 71-80.
- Kirby EJM, Appleyard M (1987) *Cereal Development Guide*. (National Agricultural Centre Arable Unit: Kenilworth, England).
- Kingwell R, Pannell D (2005) Economic trends and drivers affecting the wheatbelt of Western Australia to 2030. *Australian Journal of Agricultural Research* **56**, 553-561.
- Knight J, Thackray DJ (2007) Decision support systems. In *Aphids as crop pests*. (Eds HF van Emden, R Harrington) pp. 677-688 (CAB International: Oxfordshire, UK).
- Krantz GW, Lindquist EE (1979) Evolution of phytophagous mites (Acari). *Annual Review of Entomology* **24**, 121-158.
- Lamb RJ (1989) Entomology of oilseed brassica crops. *Annual Review of Entomology* **34**, 211-219.
- Lawrence L (2009) Protecting germinating grain crops in southern Australia. *Outlooks on Pest Management* **20**, 178-181.
- Leonard E (2009) Green-bridge- The essential crop management tool. Fact sheet. Grains Research and Development Corporation (GRDC).
- Leonard L (1993) Managing for stubble retention. Bulletin 4271. Department of Agriculture, Western Australia, Perth.
- Linder CR, Schmitt J (1995) Potential persistence of escaped transgenes: Performance of transgenic, oil modified brassica seeds and seedlings, *Ecological applications* **5**, 1056-1068.
- Lindquist EE (1996) Phylogenetic relationships. In *Eriophyoid Mites: Their Biology, Natural Enemies, and Control*. (Eds EE Lindquist, MW Sabelis, J Bruin) pp. 301-327 (Elsevier Science: Amsterdam, Netherlands).
- Liu A, Ridsdill-Smith TJ (2001) Comparisons of feeding damage by redlegged earth mite *Halotydeus destructor* (Tucker) (Acari: Pentheleidae) to different grain legume species as an indicator of potentially resistant lines. In *Acarology: Proceedings of the 10th International Congress*. (Eds RB Halliday, DE Walter, HC Proctor, RA Norton, MJ Colloff) pp. 83-99 (CSIRO Publishing: Melbourne).
- MacLennan KE, McDonald G, Ward SA (1998) Soil microflora as hosts of redlegged earth mite (*Halotydeus destructor*). *Entomological Experimentalis Applicata* **86**, 319-323.
- Makol J (2010) A redescription of *Balaustium murorum* (Hermann, 1804) Acari: Prostigmata: Erythraeidae) with notes on related taxa. *Annales Zoologici* **60**, 439-454.
- Maino J, Binns M, Umina P (2018) No longer a west-side story – pesticide resistance discovered in the eastern range of a major Australian crop pest, *Halotydeus destructor* (Acari: Pentheleidae). *Crop and Pasture Science* **69**, 216-221.
- Mangano GP (2007) Pestfax, Issue 3, 18 May 2007. Department of Agriculture and Food, Western Australia, Perth.

- Mangano GP, Micic S (2008) Redlegged earth mite resistance and integrated strategies for their control in Western Australia. In *Proceedings of Agribusiness Crop Updates* pp. 39-42 (Department of Agriculture and Food, Western Australia: Perth).
- Mangano GP, Severtson DL (2007) A review of pest and disease occurrence in 2006. In *Proceedings of Agribusiness Crop Updates*. (Ed. D Arbrecht) pp. 88-94 (Department of Agriculture and Food, Western Australia: Perth).
- Mangano GP, Micic S, Botha J (2008) Insect and allied pests. In *Producing Lupins*. (Eds P White, B French, A McLarty) pp. 121-136 (Department of Agriculture and Food, WA: Perth).
- Mayoral JG, Barranco P (2009) Description of the larva *Balaustium bisculatae* sp. n. (Acari: Erythraeidae) from the southeast of Spain, *Biologia*, **64**, 1161—1164.
- McCornack BP, Zukoff S, Whitworth RJ, Michaud JP, Schwarting HN (2017) *Wheat Insect Management 2017*, Kansas State University. Available at: <https://www.bookstore.ksre.ksu.edu/pubs/mf745.pdf> [Verified 7 November 2017].
- McDonald G, Hoffmann AA, Ridsdill-Smith TJ (1999) Managing earth mites as establishment pests of Australian canola: A gradual path towards IPM. In *Proceedings of the 10th International Rapeseed Congress*. (Eds N Wratten, PA Salisbury) pp. 9. (The Regional Institute Ltd: Canberra).
- McMullen G (2003) Prospects for grain marketing in 2010. In *Proceedings of the Australian Postharvest Technical Conference*. (Eds EJ Wright, MC Webb, E Highly) pp. 10-11. (CSIRO Stored Research Laboratory: Canberra).
- Merton E, McDonald G, Hoffmann AA (1995) Cultural control of redlegged earth mite, blue oat mite and lucerne flea in canola. *Plant Protection Quarterly*, **19**, 65–66.
- Metcalf RL (1980) Changing the role of insecticides in crop protection. *Annual Review of Entomology*, **25**, 215-250.
- Michael PJ (1987) Broad-acre pest control after DDT. *Journal of Agriculture-Western Australia* **28**, 75-80.
- Michael PJ (1991) Season-long effects of four chemicals on redlegged earth mite and lucerne flea. In *Proceedings of a National Workshop on Redlegged Earth Mite, Lucerne Flea and Blue Oat Mite*. (Ed. J Ridsdill-Smith) pp. 63-65. (Department of Agriculture, Western Australia: Perth).
- Michael PJ (1995) Biological control of redlegged earth mite and lucerne flea by the predators *Anystis wallacei* and *Neomologus capillatus*. *Plant Protection Quarterly* **10**, 55-57.
- Michael PJ (1997) Effects of pasture pest damage and grazing management on efficiency of animal production. DAW048 a joint project of Agriculture Western Australia and Meat Research Corporation. Department of Agriculture, Perth, Western Australia.
- Michael PJ, Ramsey D, Boyd C (1984) A case of agricultural practice versus pest management. In *Proceedings of the Fourth Australian Applied Entomological Research Conference*. (Eds P Bailey and D Swincer) pp. 48-55. (South Australian Department of Agriculture: Adelaide).

- Micic S (2005) Identification and cultural control of insect and allied pests of canola. Bulletin No. 4650. Department of Agriculture, Perth, Western Australia.
- Micic S, Lord A (2015) Update on redlegged earth mite resistance in WA. *2015 WA Agribusiness Crop Updates*. Available at: http://www.giwa.org.au/pdfs/CR_2015/REVIEWED.20.02.2015/Micic,%20Svetlana_Update%20on%20redlegged%20earth%20mite%20resistance%20in%20WA_FINAL_.pdf [Verified 7 November 2017].
- Micic S, Mangano P (2006) Pest mites of broad-acre crops. Farmnote No. 165. Department of Agriculture, Perth, Western Australia.
- Micic S, Dore A, Strickland G (2007) The effect of rotation crops, trash retention and prophylactic sprays on arthropod abundance in a following canola crop. In *Agribusiness Crop Updates: Lupins, Pulses and Oilseeds Updates*. (Ed. W Parker) pp. 75-78. (Department of Agriculture and Food, Western Australia).
- Micic S, Hoffmann AA, Strickland G, Weeks AR, Bellati J, Henry K, Nash MA, Umina PA (2008) Pests of germinating grain crops in southern Australia: an overview of their biology and management options. *Australian Journal of Experimental Agriculture* **48**, 1560-1573.
- Miles MM, Baker GJ, Hawthorne W (2007) Pulses-winter. In *Pests of Field Crops and Pastures: Identification and Control*. (Ed. PT Bailey) pp. 144-145. (CSIRO Publishing: Melbourne).
- Monjardino M, Pannell DJ, Powles SB (2004) The economic value of pasture phases in the integrated management of annual ryegrass and wild radish in a Western Australian farming system. *Australian Journal of Experimental Agriculture* **44**, 265-271.
- Moritz K, McDonald G (1995) Developing redlegged earth mite resistance in canola. In *Proceedings of the Australian research assembly on Brassicas*. (Ed. TD Potter) pp. 30-35. (South Australian Research and Development Institute: Adelaide).
- Moore CB, Moore JH (2017) *HerbiGuide - The Pesticide Expert on a Disk. Version. 20.5*, (PO Box 44, Albany, Western Australia, 6331, HerbiGuide, www.herbiguide.com.au).
- Moore JC, Snider RJ, Robertson LS (1985) Effect of different management systems on collembola and acarina in corn production systems. *Pediobiologia* **26**, 143-152.
- Munoz-Cardenas K, Fuentes LF, Cantor RF, Rodriguez CD, Jansseb A, Sabelis MW (2014) Generalist red velvet mite predator (*Balaustium* sp.) performs better on a mixed diet. *Experimental and Applied Acarology* **62**, 19-32.
- Munoz-Cardenas K, Fuentes-Quinteros LS, Rueda-Ramirez D, Rodriguez D, Cantor RF (2015) The Erythraeoidea (Trombidiformes: Prostigmata) as biological control agents, with special reference to the genus *Balaustium*. In *Prospects for Biological Control of Plant Feeding Pests and Other Harmful Organisms*. (Eds. D Carrillo, J de Moreaes, JE Pena) pp. 207-240 (Springer International Publishing: Switzerland).
- Murray D, Clark M, Ronning D (2012) Current and potential costs of invertebrate pests in grain crops. Publication AEP001. Grains Research and Development Corporation, Canberra, ACT, Australia.

- Murdoch WW, Chesson J, Chesson PL (1985) Biological control in theory and practice. *The American Naturalist* **125**, 344-366.
- Mutisya DL, Molo R, El-Banhawy EM, Miano D, Kariuki CW, Owiti A, Aool W (2016) Phylogenetic diversity of cassava green mite, *Mononychellus progresivus* from different geographical sites in east Africa. *African Crop Sciences Journal* **24**, 63-71.
- Nawaz A, Gogi MD, Sufyan M (2016) Insect-pests in dryland agriculture and their integrated management. In *Innovations in Dryland Agriculture*. (Eds M Farooq, KHM Siddique) pp. 299-320 (Springer Nature: Charn, Switzerland).
- Newman LJ (1923) Redlegged velvet earth mite. Bulletin No. 106. Department of Agriculture, Perth, Western Australia.
- Newman LJ (1936) Red-legged earth mite. *Journal of Department of Agriculture-Western Australia* **8**, 49-54.
- Newell IM (1963) Feeding habits in the Genus *Balaustium* (Acarina, Erythraeidae), with special reference to attacks on man. *Journal of Parasitology* **49**, 498-502.
- Nichols PGH, Dear BS, Hackney BF, Craig AD, Evans PM, de Koning CT, Foster KJ, Barbetti MJ, You MP, Micic S (2009). New subterranean clovers with reduced cotyledon susceptibility to redlegged earth mites. *SABRAO Journal of Breeding and Genetics, Special Supplement, August 2009* **41**, 16.
- Nichols PGH, Revell CK, Humphries AW, Howie JH, Hall EJ, Sandral GA, Ghamkhar K, Harris CA (2013) Temperate pasture legumes in Australia – their history, current use and future prospects. *Crop and Pasture Science* **63**, 691-725.
- Norton RA, Kethley JB, Johnston DE, O'Connor BM (1993) Phylogenetic perspectives on genetic systems and reproductive modes of mites. In *Evolution and Diversity of Sex Ratio in Insects and Mites*. (Eds DL Wrensch, MA Ebbert) pp. 8-99. (Chapman and Hall: New York, USA).
- O'Connell M, Pannell DJ, French RJ (2003) Are high lupin seeding rates more risky in Western Australian wheatbelt? *Australian Journal of Experimental Agriculture* **42**, 1137-1142
- O'Connor BM (1984) 'Phylogenetic relationships among higher taxa in the Acariformes, with particular reference to the Astigmata. In *Acarology VI, Vol. I*. (Eds DA Griffiths, CE Bowman) pp. 19-27. (Ellis-Horwood Ltd.: Chichester, England).
- Ochoa R, Vargas C, Aguilar H (1994) *Phytophagous mites of Central America: An Illustrated Guide*. (CATIE: Costa Rica).
- Oerke EC (2005) Crop losses to pests. *Journal of Agricultural Science* **144**, 31-43.
- Oliver JH (1977) Cytogenetics of ticks and mites. *Annual Review of Entomology* **22**, 407-429.
- Owen M, Powles SB (2018) Current levels of herbicide resistance in key weed species in the WA grain belt. *Agribusiness Crop Updates*. Available at: <http://www.grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/02/Current-levels-of-herbicide-resistance-in-key-weed-species> [Verified 7 November 2018].

- Pavri C (2007) Legume pastures. In *Pests of Field Crops and Pastures: Identification and Control*. (Ed. PT Bailey) pp. 412. (CSIRO Publishing: Melbourne, Vic).
- Paynter BH and Hills AL (2009) Barley and rigid ryegrass (*Lolium rigidum*) competition is influenced by crop cultivar and density. *Weed Technology* **23**, 40-48.
- Pembleton KG, Tozer KN, Edwards GR, Jacobs JL, Turner LR. (2015) Simple versus diverse pastures: opportunities and challenges in dairy systems. *Animal Production Science* **55**, 893-901.
- Perring, TM, Archer TL, Krieg DL, Johnson JW (1983) Relationships between the Banks grass mite (Acariformes: Tetranychidae) and physiological changes of maturing grain sorghum. *Environmental Entomology* **12**, 1094-1098.
- Perring TM, Holtzer TO, Kalisch JA, Norman JM (1984) Temperature and humidity effects on ovipositional rates, fecundity, and longevity of adult female Banks grass mites (Acari: Tetranychidae). *Annals of the Entomological Society of America* **77**, 581-586.
- Pianka ER (1974) Niche overlap and diffuse competition. *Proceedings of the National Academy of Sciences of the United States of America* **71**, 2141-2145.
- Pimentel D (1995) Amounts of pesticides reaching target pests: Environmental ethics. *Journal of Agricultural and Environmental Ethics* **81**, 17-29.
- Plum Grove (2017) Plum grove: Indicative grower bids. Available at <https://www.plumgrove.com.au/BidSheet/WABidSheet-2017-18.pdf> [Verified 14 November 2017].
- Poole ML, Turner NC, Young JM (2002) Sustainable cropping systems for high rainfall areas of southern WA. *Agricultural Water Management* **53**, 201-211.
- Proctor H (1998) Parasitengona. Velvet mites, chiggers, water mites. Version 09. Available at <http://tolweb.org/Parasitengona/2581/1998.08.09> [Verified date 13th January 2017].
- Putman WL (1970) Life history and behavior of *Balaustium putmani* (Acarina: Erythraeidae). *Annals of the Entomological Society of America* **63**, 76-81.
- Putman WL and Herne DHC (1966) The role of predators and other biotic agents in regulating the population density of phytophagous mites in Ontario peach orchards. *Canadian Entomologist* **98**, 808-820
- Qin TK, Halliday RB (1996) Revision of the Australian and South African species of *Halotydeus* Berlese (Acarina: Penthaleidae). *Bulletin of Entomological Research* **86**, 441-450.
- Reeves TG, Ellington A, Brooke HD (1984) Effects of lupin-wheat rotations on soil fertility, crop disease and crop yields. *Australian Journal of Experimental Agriculture* **24**, 595-600.
- Ridsdill-Smith TJ (1997) Biology and control of *Halotydeus destructor* (Tucker) (Acarina: Penthaleidae): a review. *Experimental and Applied Acarology* **21**, 195-224.
- Ridsdill-Smith TJ, Annells AJ (1997) Seasonal occurrence and abundance of redlegged earth mite, *Halotydeus destructor* (Acarina: Penthaleidae) in annual pastures of south-western Australia. *Bulletin of Entomological Research* **87**, 413-423.

- Ridsdill-Smith J, Hoffmann AA, Mangano P, Gower JM, Pavri C, Umina PA (2008) Review of strategies for control of the redlegged earth mite in Australia. *Australian Journal of Experimental Agriculture* **48**, 1506-1513.
- Ridsdill-Smith J, Pavri C, De Boer E, Kriticos D (2005) Predictions of summer diapause in the redlegged earth mite, *Halotydeus destructor* (Acari: Pentheleidae), in Australia. *Journal of Insect Physiology* **51**, 717-726.
- Roberts TR, Hutson DH (1999) *Metabolic Pathways of Agrochemicals: Insecticides and Fungicides, Part Two*. (The Royal Society of Chemistry: Cambridge, UK).
- Robinson C (2009) Early season insects and strategies. Farmanco Facts 29, Available at https://farmanco.com.au/wp-content/uploads/237_NewsApr09.pdf [Verified 14 June 2017].
- Robinson MT, Hoffmann AA (2000) Additional tests on the effect of pesticides on cryptic species of blue oat mite (*Penthaleus* spp.) and the red legged earth mite (*Halotydeus destructor*) in south-eastern Australia. *Australian Journal of Experimental Agriculture* **40**, 671-678.
- Rohitha HB, Mott J, Hoffmann AA (2003) Effect of large seed size, post-sowing compaction and chemical seed dressings on the survival of canola seedlings in the presence of earth mite damage. In *Solutions for a Better Environment: Proceedings of the 11th Australian Agronomy Conference*. (eds M Unkovich, G O'Leary) (The Regional Institute Ltd: Canberra, Australia).
- Rowland IC, Mason MG, Hamblin J (1988) Effect of lupins and wheat on the yield of subsequent wheat crops grown at several rates of applied nitrogen. *Australian Journal of Experimental Agriculture* **28**, 91-97.
- Sanchez AI, Hernando MD, Vaquero JJ, Garcia E, Navas JM (2010) Hazard assessment of alternatives to dicofol. *Journal of Environmental Protection* **1**, 231-241.
- Schoener TW (1983) Field experiments on interspecific competition. *The American Naturalist* **122**, 240-285.
- Seymour M (2011) Defining economic plant densities of open pollinated and hybrid canola in WA. In *Proceedings of Agribusiness Crop Updates*. (Eds J Paterson, C Nicolls) pp. 213-216 (Department of Agriculture and Food, Western Australia: Perth).
- Setter TL, Carlton G (2000) Germination, vegetative and reproductive growth. In *The Wheat Book: Principles and Practice*. (Eds WK Anderson, JR Garlinge) pp. 39-53. (Department of Agriculture, Western Australia: Perth).
- Shaw PW, Wallis DR (2010) Susceptibility of the European earwig *Forficula auricularia* to insecticide residues on apple leaves. *New Zealand Plant Protection* **63**, 55-59.
- Smith D, Beattie GAC, Broadley RH (1997) *Citrus Pests and Their Natural Enemies: Integrated Pest Management in Australia*. (Department of Primary Industries, Queensland: Brisbane, Australia).
- Smith W (2009) Agronomic Acumen Newsletter, 163 Available at <http://www.agronomy.com.au/Archive/163Jun2009LR.PDF> [Verified 14 June 2011].

- Soderlund DM (2008) Pyrethroids, knockdown resistance and sodium channels. *Pest Management Science* **64**, 610-616.
- Soller R, Wohltmann A, Witte H, Blohm D (2001) Phylogenetic relationships within terrestrial mites (Acari: Prostigmata, Parasitengona) inferred from comparative DNA sequences and analysis of the mitochondrial cytochrome oxidase subunit I gene. *Molecular Phylogenetics and Evolution* **18**, 47-53.
- Southcott RV (1961) Studies on the systematics and biology of the Erythraeoidea (Acarina) with a critical revision of the genera and subfamilies. *Australian Journal of Zoology* **9**, 367-610.
- Southcott RV (1997) Dismelia and other developmental abnormalities in prostigmatid mites (Acari). *International Journal of Acarology* **23**, 93-102.
- Stinner BR House GJ (1990) Arthropods and other invertebrates in conservation-tillage agriculture. *Annual Review of Entomology* **35**, 299-318.
- Stern VM (1973) Economic thresholds. *Annual Review of Entomology* **18**, 259-280.
- Symondonson WOC, Sunderland KD, Greenstone MH (2002) Can generalist predators be effective biocontrol agents? *Annual Review of Entomology* **47**, 561-594.
- Sweetingham MW (1990) Coping with brown spot and root rots of lupins. *Journal of Agriculture Western Australia* **31**, 5-13.
- Tanaka DL, Krupinsky JM, Merrill SD, Liebig MA, Hanson JD (2007) Dynamic cropping systems for sustainable crop production in the Northern Great Plains. *Agronomy Journal* **99**, 904-911.
- Thackray DJ, Ridsdill-Smith TJ, Gillespie DJ (1997) Susceptibility of grain legume species to redlegged earth mite (*Halotydeus destructor* Tucker) damage at the seedling stage. *Plant Protection Quarterly* **12**, 141-144.
- Thackray DJ, Diggle AJ, Jones RAC (2004) Forecasting aphid outbreaks and epidemics of cucumber mosaic virus in lupin crops in narrow-leaved lupins (*Lupinus angustifolius*). *Virus Research* **100**, 67-82.
- Thackray DJ, Diggle AJ, Jones RAC (2008) 'BYDV PREDICTOR: a simulation model to predict aphid arrival, epidemics of barley yellow dwarf virus and yield loss in wheat crops in a Mediterranean type environment. *Australian Journal of Agricultural Research* **56**, 1089-1099.
- Thomson LJ, Hoffmann AA (2006) Field validation of laboratory-derived IOBC toxicity ratings for natural enemies in commercial vineyard. *Biological Control* **39**, 507-515.
- Thomson LJ, Hoffmann AA (2007) Ecologically sustainable chemical recommendations for agricultural pest control? *Journal of Economic Entomology* **100**, 1741-1750.
- Tilman D, Cassman K, Matson P, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* **418**, 671-677.
- Tomlin CDS (2003) *The World Compendium: The Pesticide Manual 13th edition* (British Crop Protection Council: Hampshire, UK).

- Trainor G, Paynter B (2013) What is the optimum plant density for your barley variety? Available at <https://www.agric.wa.gov.au/barley/what-optimum-plant-density-your-barley-variety> [Verified 8 July 2017]
- Tremelling MJ, McSorely R, Gallaher RN, Tubbs RS (2002) Effects of cover crop residue management on the soil surface invertebrate community. In *Proceedings of the 25th Annual Southern Conservation Tillage Conference: Making Conservation Tillage Conventional-Building on a Future on 25 years of Research*. (Ed. E van Santen) pp. 250-254. (Auburn University: Alabama, USA).
- Tuck B, Bohle M, Dreves A, Fisher G (2009) Winter Grain Mite. Available at: <https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em8976.pdf> [Verified 8 November 2017].
- Ugalde D, Brungs A, Kaebernick M, McGregor A, Slattery B (2007) Implications of climate change for tillage practice in Australia. *Soil and Tillage Research* **97**, 318-330.
- Umina PA (2007) Pyrethroid resistance discovered in a major agricultural pest in southern Australia: the redlegged earth mite *Halotydeus destructor* (Acari: Pentheleidae). *Pest Management Science* **63**, 1185-1190.
- Umina PA, Hoffmann AA (1999) Tolerance of cryptic species of blue oat mites (*Penthaleus* spp.) and the redlegged earth mite (*Halotydeus destructor*) to pesticides. *Australian Journal of Experimental Agriculture* **39**, 621-628.
- Umina PA, Hoffmann AA (2003) Diapause and implications for control of *Penthaleus* species and *Halotydeus destructor* (Acari: Pentheleidae) in south eastern Australia. *Experimental and Applied Acarology* **31**, 209-223.
- Umina PA, Hoffman AA (2004) Plant host associations of *Penthaleus* species and *Halotydeus destructor* (Acari: Pentheleidae) and implications for integrated pest management. *Experimental and Applied Acarology* **33**, 1-22.
- Umina PA, Hoffmann AA (2005) Competitive interactions among four pest species of earth mites (Acari: Pentheleidae). *Journal of Economic Entomology* **98**, 307-316.
- Umina PA, Micic S, Fagan L (2011) Control of insect and mite pests in grains- insecticide resistance and integrated pest management (IPM). In *Proceedings of the 2011 Agribusiness Crop Updates, Western Australia*. (Eds J Paterson, C Nicholls) pp. 98-100. (Department of Agriculture, Western Australia: Perth).
- Umina PA, Lord A, Micic S, Edwards O (2017) Discovery and characterisation of field resistance to organophosphorus chemicals in a major mite pest, *Halotydeus destructor*. *Pest Management Science* **73**, 1719-1724.
- Umina PA, Weeks AR, Roberts J, Jenkins S, Mangano GP, Lord A, Micic S (2012) The current status of pesticide resistance in Australian populations of the redlegged earth mite (*Halotydeus destructor*). *Pest Management Science* **68**, 889-896.
- Wallace MM (1970) The influence of temperature on post-diapause development and survival of aestivating eggs of *Halotydeus destructor* (Acari: Eupodidae). *Australian Journal of Zoology* **18**, 315-329.

- Wallace MM (1972) A portable power-operated apparatus for collecting epigaeic collembolla and acari. *Australian Journal of Entomology* **11**, 261-263.
- Wallace MM, Mahon JA (1971) The distribution of *Halotydeus destructor* and *Penthaleus major* (Acari: Eupodidae) in Australia in relation to climate and land use. *Australian Journal of Zoology* **19**, 65-76.
- Walsh MJ, Devlin RD, Powles SB (2004) Potential for pre-season herbicide application to prevent weed emergence in the subsequent growing season. 1. Identification and evaluation of possible herbicides. *Weed Technology* **18**, 228-235.
- Walter D (2005) Glossary of Acarine Terms. Available at: http://itp.lucidcentral.org/id/mites/invasive_mite/Invasive_Mite_Identification/key/0_Glossary/Mite_Glossary.htm [Verified 7 July 2017].
- Walter D, Krantz G, Lindquist E (1996) Acari. The Mites. Version 13. Available at <http://tolweb.org/Acari/2554/1996.12.13> [Verified 13 November 2010].
- Way MJ, van Emden HF (2000) Integrated pest management in practice - pathways towards successful application. *Crop Protection* **19**, 81-103.
- Weeks AR, Hoffmann AA (1999) The biology of *Penthaleus* species in south eastern Australia. *Entomologia Experimentalis et Applicata* **92**, 179-189.
- Weeks AR, Hoffmann AA (2000) Competitive interactions between two pest species of earth mites, *Halotydeus destructor* and *Penthaleus major* (Acarina: Penthaleidae). *Journal of Economic Entomology* **93**, 1183-1191.
- Weeks AR, Turelli M, Hoffmann AA (2000) Dispersal patterns of pest earth mites (Acari: Penthaleidae). *Journal of Economic Entomology* **93**, 1415-1423.
- Weiner J, Griepentrog H, Kristensen L (2001) Suppression of weeds by spring wheat *Triticum aestivum* increases with crop density and spatial uniformity. *Journal of Applied Ecology* **38**, 784-790.
- Weiss MJ, Knodel JJ, Olsen D (2006) Insect pests of canola. In *Radcliffe's IPM World Textbook*. (Eds EB Radcliffe, WD Hutchinson, RE Cancelado) (University of Minnesota: St Paul, Minnesota). Available at: <https://ipmworld.umn.edu/> [Verified 7 November 2017].
- Welbourn WC, Jennings DT (1991) Two new species of Erythraeidae (Acari: Prostigmata) associated with the spruce budworm, *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae), in Maine. *Canadian Entomologist* **123**, 567-580.
- Whalley, RDB, Friend DA, Sanford P, Mitchell ML (2005) Evaluation of native and introduced grasses for low-input pastures in temperate Australia: rationale and scope. *The Rangeland Journal* **27**, 1-9.
- Whalon ME, Mota-Sanchez D, Hollingworth RM (2008) Analysis of global pesticide resistance in arthropods. In *Global Pesticide Resistance in Arthropods* (eds. ME Whalon, D Mota-Sanchez and RM Hollingworth) pp 5-31 (CAB International: Wallingford, England).
- Whalon ME, Mota-Sanchez D, Hollingworth RM, Duynslager L (2012) Arthropod Pesticide Resistance Database. Available at <http://www.pesticideresistance.org> [Verified 14 November 2017].

- Whitbread AM, Blair GJ, Lefroy RDB (2000) Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia 2. Soil physical fertility and carbon. *Soil and Tillage Research* **54**, 77-89.
- Wheeler J, Marchant N, Lewington M (2002) *Flora of the South West, Volume 1: Introduction, Keys, Ferns to Monocotyledons*. (University of Western Australia Press: Crawley, Western Australia) pp. 394-439.
- Widmer M, Micic S, Dore T (2008) European earwigs-pests of crops. Farmnote No. 322. Department of Agriculture and Food, Perth, WA.
- Wilkin DR and Warner JL (1985) Control of mites invading buildings. *International Pest Control* **27**, pp 8-9.
- Williams DG, Il'ichev AL (2003) Integrated pest management in Australia. In *Integrated Pest Management in the Global Arena*. (Eds KM Maredia, D Dakouo, D Mota-Sanchez) pp. 371-384. (CABI International: Wallingford, England).
- Williams S (2017) Key insect and mite pests of Australian cotton. In *Cotton Pest Management Guide* (Eds S Maas and R Redfern) pp. 5-9. (Cotton Research and Development Corporation: Narrabri, Australia).
- Wohltmann A, Witte H, Olomski R (2001) Organismal patterns causing high potential for adaptive radiation in Parasitengonae (Acari: Prostigmata). In *Acarology: Proceedings of the 10th International Congress*. (Eds RB Halliday, DE Walter, HC Proctor, RA Norton, MJ Colloff) pp. 83-99 (CSIRO Publishing: Melbourne).
- Yaninek JS (2007) Biological control of cassava green mite in Africa: overcoming challenges to implementation. In *Biological Control: A global perspective*. (Eds. C Vincent, MS Goettel, G Lazorovits) pp. 28-37 (CAB International: Wallingford, United Kingdom).
- Yoder JA, Rigsby CM, Tank L (2008) Function of the urnulae in protecting the red velvet mite, *Balaustium* sp., against water loss and in enhancing its activity at high temperatures'. *International Journal of Acarology* **34**, 419 - 425.
- Yoder JA, Benoit JB, Rellinger EJ, Ark JT, Halloran MC, Gribbins KM (2006) Structure and function of the urnulae in *Balaustium* sp. (Parasitengona: Erythraeidae) featuring secretion of a defensive allomone and alarm pheromone. *International Journal of Acarology* **32**, 3-12.
- Yoder JA, Schumaker LK, Tank JL (2009) Potential for spread of plant pathogens by presence of red velvet mite (*Balaustium* sp.) in an Ohio landscape. *International Journal of Acarology* **35**, 19-24.
- Yoder JA, Dobrotka CJ, LeBarge AP, Yoder TG, Bachinski GJ (2017) Arrestment and detection of excreta by the terrestrial red mite *Balaustium murorum* (Erythraeidae) to mark suitable crevices for survival. *International Journal of Acarology* **43**, 393-398.

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

Appendix 1: Feedback from Western Australian canola growers survey on the use of insecticides

Introduction

Farmers were surveyed on their use of insecticides in production of canola. Questionnaires were distributed to canola growers during field days at Ravensthorpe, Jerramungup, Mt Barker and Esperance in September. The questionnaires asked for information for farmers to provide without reference to records, enabling the forms to be returned on the same day. More than one answer was possible for each question asked.

Results

A total of 56 growers were surveyed. Of the growers surveyed 78% (42 growers) used prophylactic sprays to protect canola crops from damage caused by insect pests. The most commonly applied insecticide was alphacypermethrin (66%; 37 growers). The majority of farmers applied prophylactic sprays with the knockdown herbicide prior to planting (67%, 34 growers), 32% (18 growers) applied it at crop emergence and only 8% (4 growers) applied prophylactic sprays at the flowering stages of canola.

The reasons for applying prophylactic sprays differed. The majority of canola growers (70%; 40 growers) applied insecticides to prevent problems as they did not have time to monitor their crops for insect pests; 68% (38 growers) applied it because insects had been identified in the paddock prior to seeding; 40% (22 growers) applied it because there was insect damage identified in the crop.

The majority of canola growers monitored their canola crops at emergence (76%; 43 growers) and/or at the 1-3 leaf stage (64%; 36 growers). A sizable minority monitored their crops for insect pests at seeding (43%; 24 growers) and/or flowering (43%; 24 growers).

Most growers (90%) surveyed received their insect control recommendations from agronomists (90%), themselves (39%) and the Department of Agriculture and Food, Western Australia (14%).

Conclusion

Growers are monitoring canola crops, however, the majority apply prophylactic insecticides.

If changes are made to insect control recommendations, agronomists must be informed early in the extension program since the majority of growers receive advice from them.

