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The distribution, abundance and life cycle of the pest mites *Balaustium medicagoense* (Prostigmata: Erythraeidae) and *Bryobia* spp. (Prostigmata: Tetranychidae) in Australia

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Abstract *Balaustium medicagoense* and *Bryobia* spp. have recently been identified by the Australian grains industry as emerging pests of winter grain crops and pastures. While reports of damage by these mites appear to have increased in the last decade, limited research has been conducted on their biology and ecology. Here the distribution and seasonal abundance patterns of *Bryobia* spp. and *Ba. medicagoense* in southern Australia are investigated. *Bryobia* spp. had a more widespread distribution than *Ba. medicagoense*. An Ecological Niche Model for the distribution of *Ba. medicagoense* constructed using MAXENT predicted the distribution of this species well, and identified associated climatic factors including summer and winter temperature variables and winter precipitation. Monthly sampling suggested that *Ba. medicagoense* had two generations per year and was active from March until December, with a likely diapause period in summer. The seasonal abundance and life cycle of two species of *Bryobia* (*Bryobia* sp. IX and *Bryobia* sp. I) differed. *Bryobia* sp. IX had two generations per year, was active from March until December, and was likely to be in diapause over summer. *Bryobia* sp. I did not appear to have a diapause stage, and had approximately four generations per year. Activity periods of these mites overlapped with those of the pest mite species *Halotydeus destructor* and *Penthaleus major*. A survey of pest outbreaks and chemical control failures suggested that while *H. destructor* and the *Penthaleus* species remained important pests, outbreaks of *Ba. medicagoense* and *Bryobia* spp. had increased. The findings highlight the need to develop effective and sustainable management strategies for these mites.

Key words biology, crop, emerging pest, pest status.

INTRODUCTION

Evolving management practices and climate change have in recent times led to a shift in invertebrate pest complexes within the Australian grains industry. *Balaustium medicagoense* (Acari: Prostigmata: Erythraeidae) and *Bryobia* spp. (Acari: Prostigmata: Tetranychidae) have been recently identified as emerging pests of winter grain crops and pastures, whose relative importance within the Australian grains industry has increased within the last decade (Hoffmann *et al*. 2008). However, there is very little information on the biology or control of these species.

In Australia, *Ba. medicagoense* is the only species of the genus *Balaustium* that has been identified morphologically (Halliday 2001). This is supported by molecular markers that indicate a single species of *Balaustium* (*Ba. medicagoense*) in broad acre agriculture in southern Australia that reproduces by obligate parthenogenesis (A Arthur unpubl. data 2010). *Ba. medicagoense* is thought to have been introduced from South Africa along with *Halotydeus destructor* (Tucker) and is now found throughout the winter growing periods from autumn to spring in the Mediterranean climate areas of southern Australia (Halliday 2001). *Ba. medicagoense* is unusual in having generalised feeding behaviour, and has been regarded as both a beneficial predator (James 1995; James *et al*. 1995; Halliday & Paull 2004) and more recently a crop pest (Hoffmann *et al*. 2008; Micic *et al*. 2008).

Bryobia mites are polyphagous and belong to the economically damaging spider mite family, Tetranychidae. The genus includes ~130 morphologically described species (Bolland *et al*. 1998), with four species recorded in Australia (Halliday 1998, 2000); however, recent molecular data have indicated additional species (A Arthur unpubl. data 2010). Given the small size of these mites and the limited number of suitable morphological characters, identification can be problematical (Ros *et al*. 2008). This is further complicated by the asexual nature of the mites and lack of males (Norton *et al*. 1993; Weeks & Breeuwer 2001; Ros *et al*. 2008). In Australia, *Bryobia* mites have been found throughout the winter growing season from March until November; however, little is known about their life cycle and seasonal distribution. Studies

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overseas have shown that the life cycle of *Bryobia* mites is complex and differs markedly between species (Mathys 1957; Anderson & Morgan 1958; Helle & Sabelis 1985).

Over the past decade, reports of damage caused by these mites to a variety of winter crops and pasture have increased (Hoffmann *et al*. 2008). The economic impact and pest status of the mites in the Australian grains industry is currently unknown and difficult to assess given that they are often misidentified and confused with other major pest mites, including the redlegged earth mite (*H. destructor*) and blue oat mite species (*Penthaleus* spp.). Both *Ba. medicagoense* and *Bryobia* sp. have shown high natural tolerance levels to currently used pesticides, suggesting that they are difficult to control in the field through chemical applications (Arthur *et al*. 2008), and emphasising the need for alternative control strategies. Information is currently lacking on life cycle, seasonal abundance patterns, distribution and pest status in Australia.

In this study we mapped the distribution of *Ba. medicagoense* and *Bryobia* spp. within southern Australia. We constructed an Ecological Niche Model (ENM) for the distribution of *Ba. medicagoense* to identify climatic variables correlated with the species' geographic distribution within Australia. We also investigated the seasonal abundance patterns and life cycle of *Ba. medicagoense* and two species of *Bryobia* mites by undertaking monthly year-round sampling. The seasonal abundance patterns of other pest mites present at these sites, which included *H. destructor* and/or *Penthaleus major*, were also investigated to determine the relative abundance of the different mite species throughout the year. Finally, we undertook surveys to determine the pest status of *Ba. medicagoense* and *Bryobia* spp. relative to other pest mites and to test the mite species responsible for control failures in the field. Results are compared to earlier published data (Umina & Hoffmann 1999; Robinson & Hoffmann 2001) to determine whether the pest status of the different mite species has changed over the last 8–10 years.

MATERIALS AND METHODS

Species distribution

During 2005–2007, field collections of *Ba. medicagoense* and *Bryobia* spp. were undertaken throughout Western Australia, South Australia, New South Wales and Victoria, between April and November (Fig. 1a). In total 901 sites were sampled for mite presence. Following Robinson and Hoffmann (2001), roadside or paddock suction samples were collected every 10 to 50 km using a Stihl SH55 blower vacuum (Andreas Stihl AG & Co. KG, Waiblingen, Germany). Sites were chosen based on the presence of vegetation and/or plant types where *Ba. medicagoense* and *Bryobia* spp. are commonly found (Arthur *et al*. 2010). Plants that were commonly surveyed included lucerne (*Medicago sativa*), clover (*Trifolium* spp.), vetch (*Vicia* spp.), barley grass (*Hordeum leporinum*), capeweed (*Arctotheca calendula*), wild radish (*Raphanus*

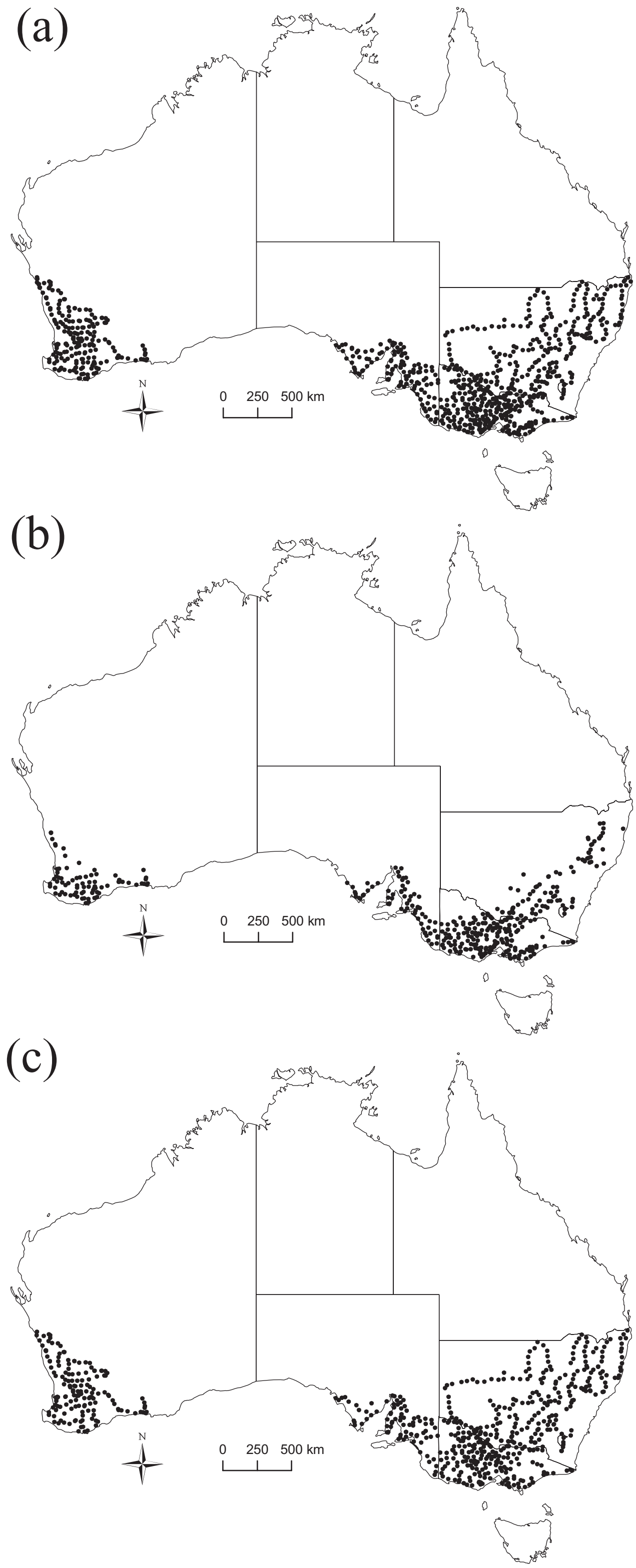

Fig. 1. Map of Australia showing the distribution of (a) the sampling sites, (b) *Balaustium medicagoense* and (c) *Bryobia* spp.

raphanistrum), wild oats (*Avena* spp.), couch (*Cynodon* dactylon) and pasture. Each sample was collected by suction for at least 10 s using the blower vacuum. Mites were identified using a stereo microscope at ×20 magnification either in the field or in the laboratory and were then stored in 70% ethanol.

Climatic variables associated with *Ba. medicagoense* distribution

To assess how climate might influence the distribution of *Ba. medicagoense*, we obtained spatial layers for monthly maximum and minimum temperatures and precipitation from WorldClim (http://www.worldclim.org, accessed: October 2009; Hijmans *et al*. 2005). Layers consist of grid cells that are interpolations of monthly averaged climate data (1950–2000) from globally distributed station data points (Hijmans *et al*. 2005). We spatially limited the layers to the Australian continent, at a resolution for each grid cell of 5 arc minutes in size, roughly 8.3 km^2 at the equator. From these layers, 19 bioclimatic layers were derived as described for BIOCLIM (Busby 1991) to use as predictor variables in an ENM for *Ba. medicagoense*. The software package MAXENT (Version 3.3.1 (Phillips *et al*. 2004, 2006)) was used to construct a model of habitat suitability from the points surveyed for *Ba. medicagoense*. The model incorporated all data points where *Ba. medicagoense* was found ($n = 419$). MAXENT incorporates presence-only points for a species distribution and through a machine-learning, maximum entropy algorithm correlates the distribution with the given predictor variables. This makes this model suitable for our study as not all areas where *Ba. medicagoense* may be present were sampled. MAXENT has been used widely across studies of plants and animals including invertebrate distributions (Ward 2007; Buermann *et al*. 2008; Hoffman *et al*. 2008; Hinojosa-Díaz *et al*. 2009; Kharouba *et al*. 2009). MAXENT has also been shown to perform well against other ENM methods and has been found to be the most effective model using presence-only data for predicting species distributions (Elith *et al*. 2006; Hernandez *et al*. 2006, 2008). MAXENT allows for each predictor variable to be assessed in terms of model contribution through the built-in jackknife procedure. We used this jackknifing feature to assess contribution of climatic variables through examining the test gain of the area under the curve (AUC) value for the receiver-operator characteristic score. To eliminate the climatic variables that were not contributing substantially, we employed a stepwise process of elimination. The model was initially run with all 19 variables and the MAXENT-produced graph of test gain of the AUC was used to identify which variables were adding the least unique information and the least to model performance (shortest bars). The output was compared to the previous run to identify any possible artefacts from the reduced variable dataset. The model was then run again on the reduced layer set, and the process repeated until a set of the most informative layers remained. The distribution model was then run for the reduced layer set ten times, each time a random subset of 30% of the distribution was set aside as a test data set, and the model trained on the remaining data points. Each run of the model was assessed through examining the AUC, and a final AUC was calculated as the mean of all runs. All parameters otherwise were left as default, and model output was in logistic format. ArcGIS (ESRI, Version 9.2) was used to determine four classes of habitat suitability threshold, through even division of minimum-maximum suitability scores of model output. MAXENT models were not constructed for *Bryobia* spp., as species identification in this group is difficult because of the presence of morphologically cryptic species (Weeks & Breeuwer 2001; Ros *et al*. 2008).

Seasonal abundance patterns and life cycle

The seasonal abundance patterns and life cycle of *Ba. medicagoense* and *Bryobia* spp. were investigated at six different pasture or lucerne sites in Victoria, between 2005 and early 2008 (Fig. 2). Two separate sites were set up at Rokewood (sites 1 and 2) and at each of these sites, three 15 m × 15 m plots were sampled from July 2005 until January 2008. Rokewood site 1 consisted of mainly tall wheatgrass (*Thinopyrum ponticum*) and phalaris (*Phalaris* spp.) whereas Rokewood site 2 consisted of lucerne (*Medicago sativa*). At Koondrook two 15 m × 15 m plots were set up, and sampling in one plot started in July 2005 and in the other plot in February 2006. Both plots were sampled until January 2008. The major plant types present at this site were tall wheatgrass (*Thinopyrum ponticum*), clover (*Trifolium* spp.) and various grasses (*Poaceae* spp.). Two 15 m × 15 m plots were set up at each of the Quambatook and Irrewarra sites. At the Quambatook site sampling commenced in August 2005 and ended in January 2008 and the major plant types present were clover (*Trifolium* spp.), barley grass (*Hordeum leporinum*) and other grasses (*Poaceae* spp.). At Irrewarra sampling commenced in April 2006 and ended in July/August 2007 and lucerne (*Medicago sativa*) predominated. At Wandong one 15 m × 15 m plot was sampled from March 2006 until December 2007 and the major plant types present were grasses (*Poaceae* spp.). *Ba. medicagoense* was collected from Koondrook, Rokewood site 1, Rokewood site 2 and Wandong.

Bryobia species were identified using the mitochondrial gene cytochrome c oxidase subunit I (COI) (A Arthur unpubl. data 2010). *Bryobia* from the Irrewarra site had a COI sequence that was very similar (<0.4% difference) to a species found in Ros *et al*. (2008) and is here referred to as *Bryobia* sp. I. *Bryobia* from Quambatook represent a common species present in broad acre environments in Australia (A Arthur unpubl. data 2010) and is here referred to as *Bryobia* sp. IX (following the notation of Ros *et al*. (2008)). In Australia, there are four morphologically described species of *Bryobia* mites recorded; these include *B. praetiosa*, *B. rubrioculus*, *B. kissophila* and *B. graminum* (Halliday 1998, 2000). However, the *Bryobia* species in this study represent new species that have not been previously described in Aus-

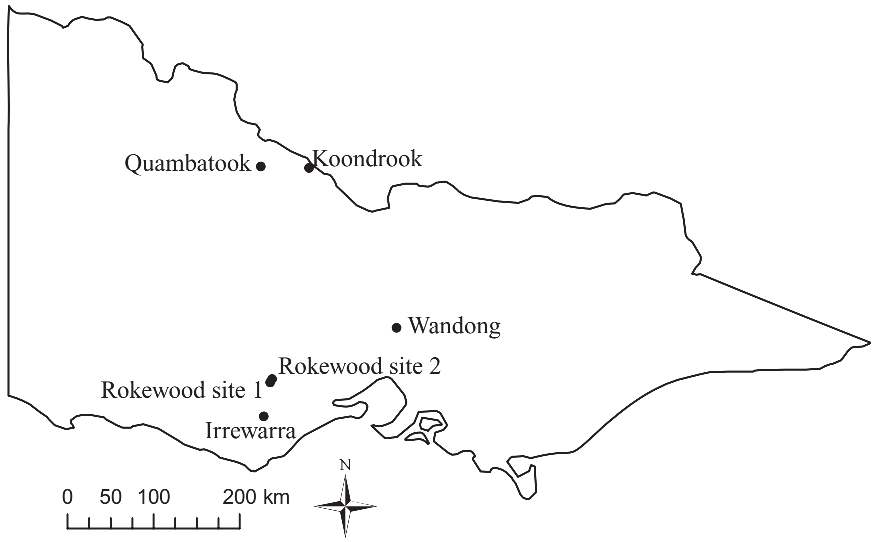

Fig. 2. Map of Victoria showing the location of the seasonal abundance sites.

tralia. Greater than 90% of the *Bryobia* species present at Rokewood site 1 in plot 3 and Rokewood site 2 in plot 1 were *Bryobia* sp. IX.

At each site we collected 10 samples randomly every month in a 900 cm^2 frame in each plot using a Stihl SH55 blower vacuum. All mites within the 900 cm^2 frame were collected by suction. Samples were put in 70% ethanol and taken back to the laboratory for later identification and all pest mites present (*Ba. medicagoense*, *Bryobia* spp., *H. destructor* and *P. major*) were counted using a stereo microscope at ×20 magnification. For *Ba. medicagoense*, *Bryobia* sp. IX and *Bryobia* sp. I, mites were separated and counted into three different life cycle classes, consisting of larvae (3 pairs of legs), nymphs (all sizes between larvae and adults) and adults (≥1.5 mm for *Ba. medicagoense* and 0.7 mm for *Bryobia* mites). For the seasonal abundance data, the average number of mites per m^2 from the 10 suction samples was calculated for each monthly sampling period. To visualise seasonal abundance patterns, data was log transformed. For the life cycle data, the average proportion of immatures (larvae + nymphs) was calculated for each monthly sampling period.

Pest status survey

Surveys were undertaken between 2005 and 2007 throughout southern Australia (Vic, NSW, WA and SA) in order to monitor mite pest outbreaks and chemical control failures.

Agronomists, grower groups, agricultural departments and consultants throughout southern Australia were contacted and asked to collect samples of mites and provide information about the paddock history from any reported outbreaks or control failures. Mites were identified using a stereo microscope at ×20 magnification. Control failures were defined as sites where a second pesticide application was required and applied within two weeks of the first application. In total 43 outbreak samples and 13 control failure samples were collected over the 3 years.

To determine whether the pest status of the mite species had changed over the last 10 years, we compared our data to surveys from Umina and Hoffmann (1999) and Robinson and Hoffmann (2001). To test for differences in the incidence of mite species causing outbreaks or control failures between the studies, a contingency analysis was run using SPSS for Windows version 15 with Monte Carlo randomisations to assess significance of the chi-square statistic because of the small sample size in some of the cells.

RESULTS

Species distribution

Balaustium medicagoense and *Bryobia* spp. occurred in all Australian states sampled (Fig. 1b,c); however, *Bryobia* spp. were more common and widespread. *Bryobia* spp. were found throughout nearly all areas of Victoria, Western Australia, South Australia and New South Wales sampled, both inland and along the coast. *Ba. medicagoense* was less common in inland areas but it did occur in most areas in Victoria except the mallee. This species was found as far north as the New South Wales/Queensland border. In South Australia it was restricted to the southern coastal areas and also in the Eyre Peninsula region. In Western Australia it was found only in the southern parts and did not extend northwards beyond Badgingarra (30°21′52.8″S, 115°28′58.8″E).

Climatic variables associated with *Ba. medicagoense* distribution

Through the jackknife procedure, MAXENT identified three predictor climatic variables that are highly correlated with the observed distribution of *Ba. medicagoense*, maximum tem-

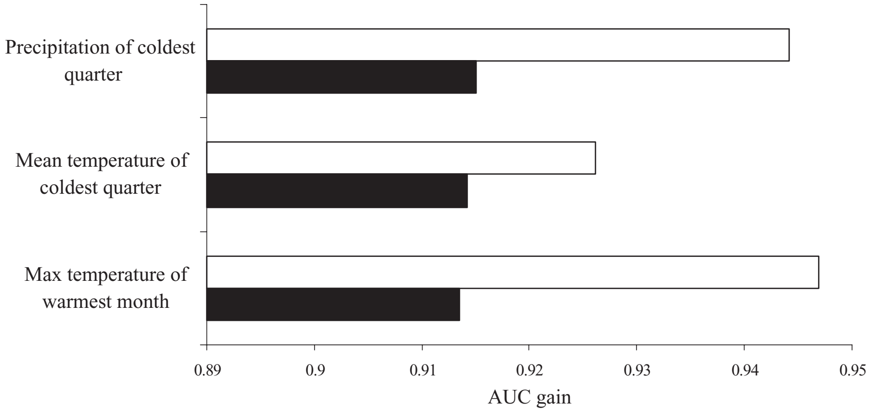

Fig. 3. Results of a jackknife test of variables associated with the distribution of *Balaustium medicagoense*. Bars represent the average area under the curve (AUC) gain of 10 runs without (□) and with only (■) variables.

perature of warmest month, mean temperature of coldest quarter and precipitation of coldest quarter. We examined training, test and AUC gain for each of the jackknife tests, but only present the AUC values here as other values were in agreement with these (Fig. 3).

The mean AUC for the model was 0.947, which indicates a high level of confidence in the model. Suitability scores for the habitat values of model output for Australia ranged from 0 (unsuitable habitat) to 0.72 (highly suitable habitat). The predicted distribution obtained in the MAXENT model matched well with the actual *Ba. medicagoense* distribution. The MAXENT model suggested that southern regions such as Kangaroo Island and King Island as well as the north-eastern coast of Tasmania may have a suitable climate for *Ba. medicagoense*, although these areas have not yet been sampled. The model also showed that the species may extend further north into southern Queensland than indicated by their current distribution (Fig. 4).

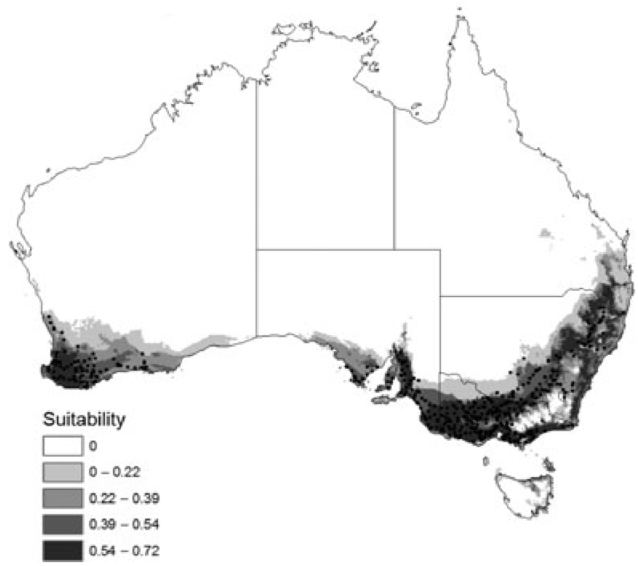

Fig. 4. MAXENT model for *Balaustium medicagoense*. The solid circles indicate the sample locations of *Ba. medicagoense* obtained in the distribution survey.

Seasonal abundance patterns and life cycle

Balaustium medicagoense

For this species a similar overall seasonal abundance pattern was found across all sites and plots within each site (Fig. 5). The mites emerged in March/April and were present until December, although at Wandong they were only present from April until November. Mites were generally absent during January and February, which probably coincided with a diapause stage, and this period was extended in some of the plots at some sites. At Rokewood site 2 in Plot 2 (Fig. 5b), there was an isolated case where *Ba. medicagoense* was found in February 2007; however, no mites were found in March. *Ba. medicagoense* numbers peaked in autumn around May at all sites and again in spring around October/November at the Rokewood sites. At Koondrook this second peak varied between August and October. At Wandong the spring peak in numbers differed between the 2006 and 2007 seasons. Nevertheless, the presence of two peaks in numbers across the four sites, the plots within each site and the different years sampled all point to *Ba. medicagoense* having two generations per year.

The proportion of *Ba. medicagoense* that were immature across the sites and plots within each site were relatively consistent across seasons, with proportions tending to peak twice a year (Fig. 6). The first peak occurred at emergence at the start of the season in autumn between March and May, followed by a second peak in spring between September and November. This is also consistent with the notion that *Ba. medicagoense* completes two generations a season, with the second generation occurring in spring. At Rokewood site 2 there were two small peaks in immature proportions in February 2007 in plot 2 and March 2006 in plot 1, which represented an early hatching of a small number of larvae; however, these larvae did not appear to survive and contribute to the next generation.

***Bryobia* sp. IX**

This species was present at both the Quambatook (Fig. 7a) and Rokewood sites (Fig. 7b). The mite showed similar patterns across the three sites. At Quambatook patterns were identical

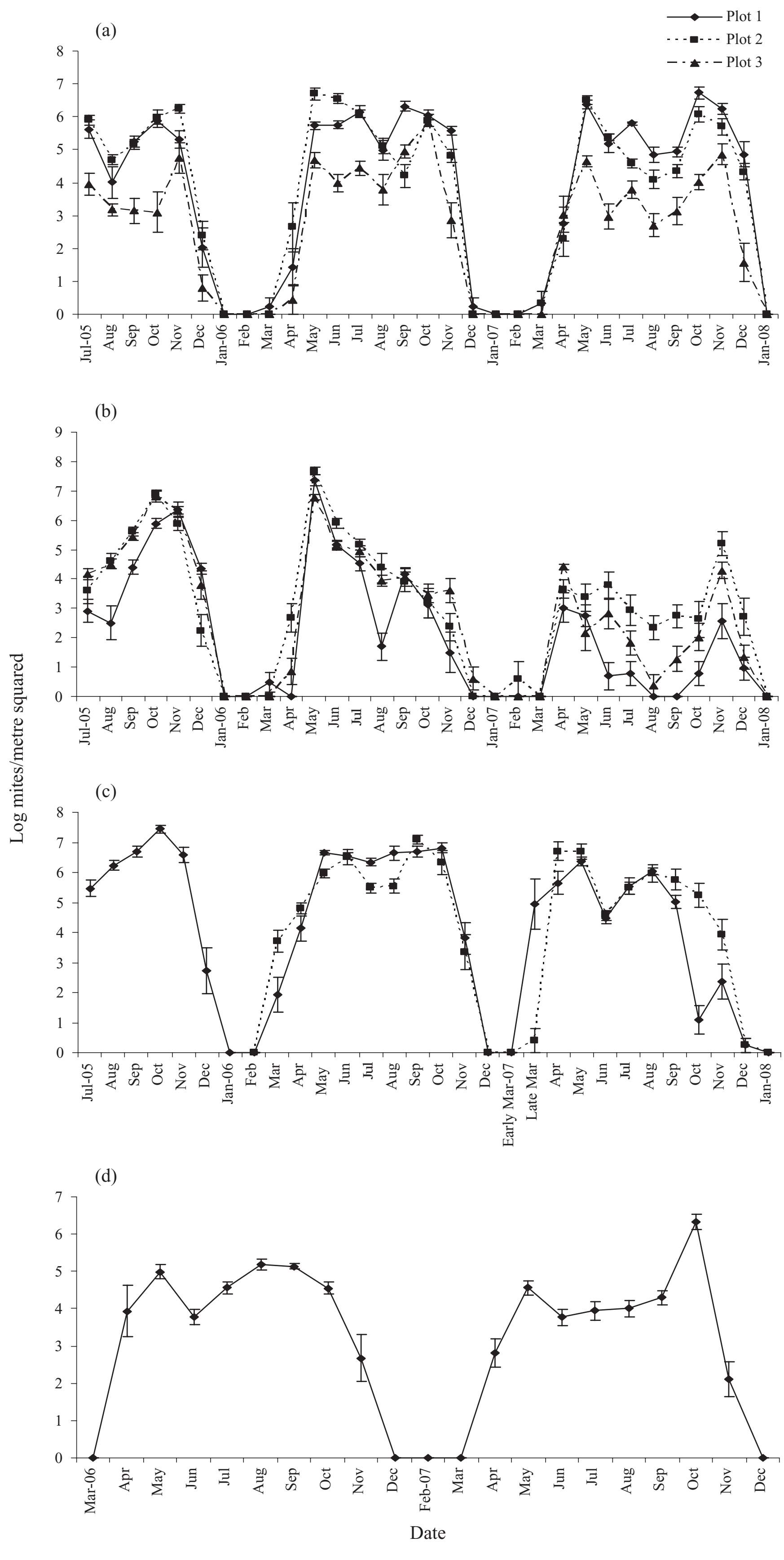

Fig. 5. Seasonal abundance patterns of *Balaustium medicagoense* at (a) Rokewood site 1, (b) Rokewood site 2, (c) Koondrook and (d) Wandong.

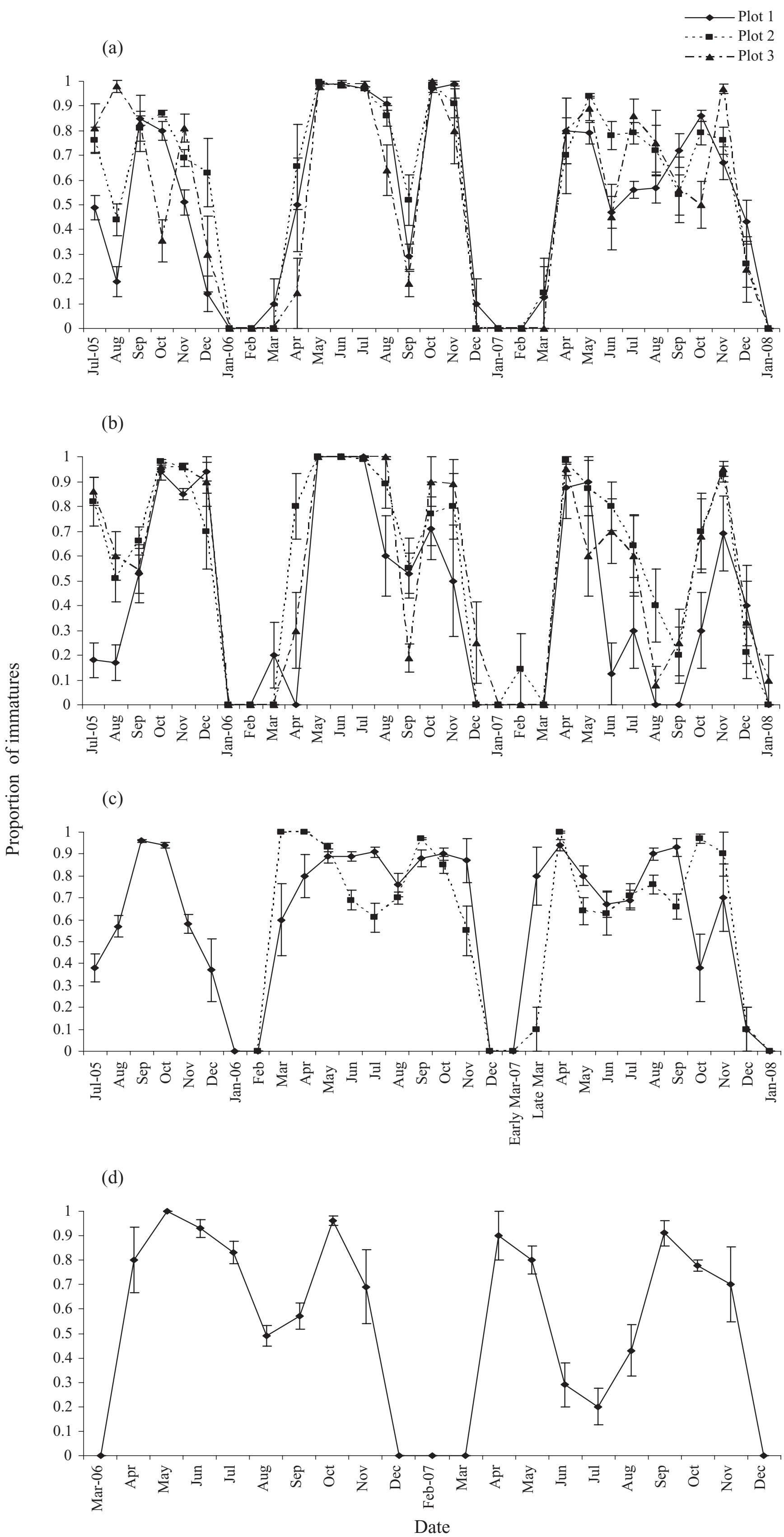

Fig. 6. Proportion of *Balaustium medicagoense* immature stages at (a) Rokewood site 1, (b) Rokewood site 2, (c) Koondrook and (d) Wandong.

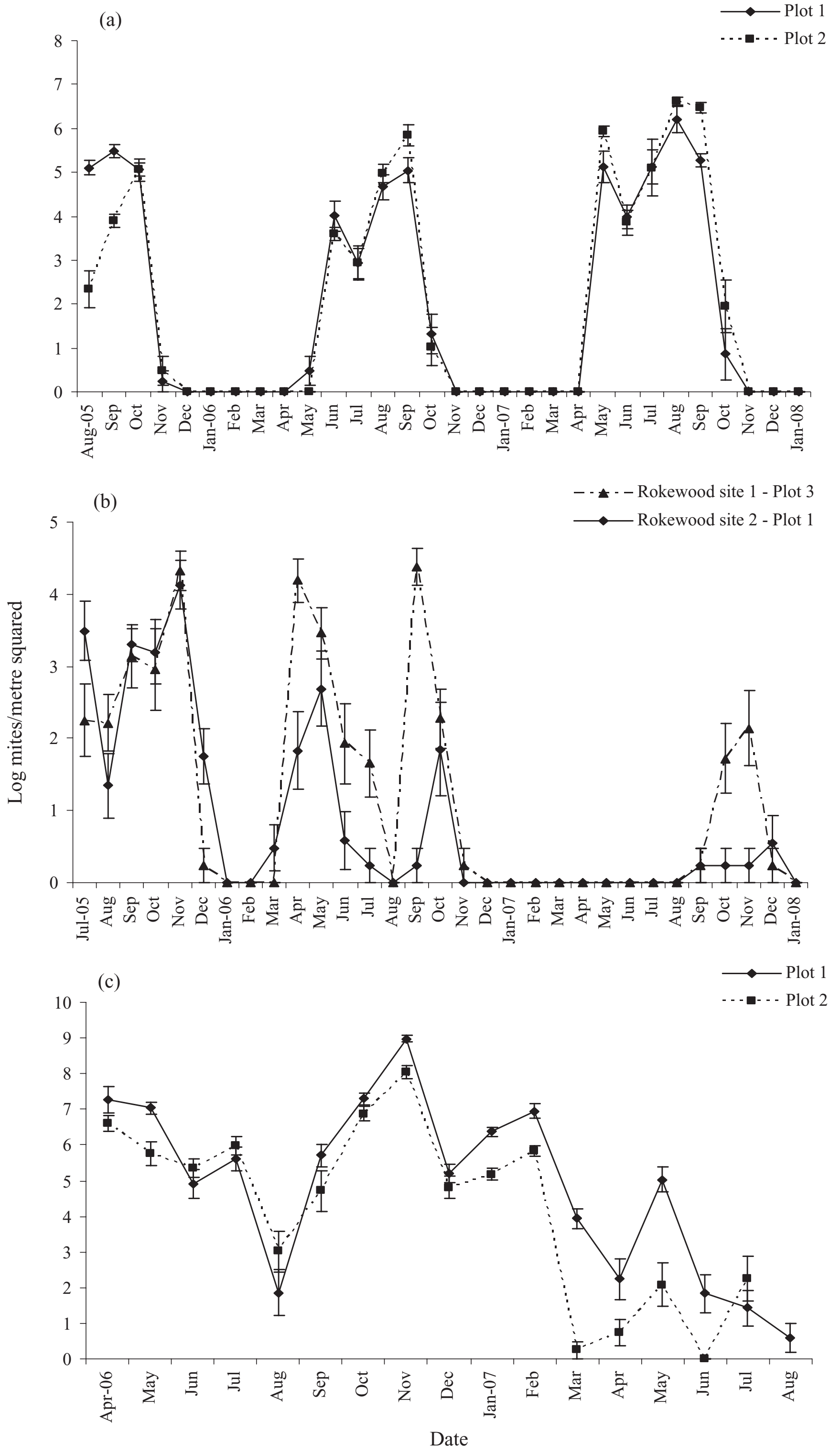

Fig. 7. Seasonal abundance patterns of (a) *Bryobia* sp. IX at Quambatook, (b) *Bryobia* sp. IX at Rokewood site 1 and 2, and (c) *Bryobia* sp. I at Irrewarra.

across both plots and were consistent across years, with mites emerging in autumn and persisting until October or November. They then appeared to go through a diapause period when no mites were active from November or December until April (Fig. 7a). Patterns were similar at both Rokewood sites, although mites were active for a longer period. At Rokewood site 1, *Bryobia* sp. IX emerged in April in 2006, but in 2007 they did not emerge until spring in September. This same pattern was also found at Rokewood site 2, but mites emerged earlier in 2006 in March. At both Rokewood sites mites were active until December, although they were active for a shorter period in 2006. They then appeared to diapause from January until February/March, although this period was extended in the 2006/2007 season when no active mites were present from

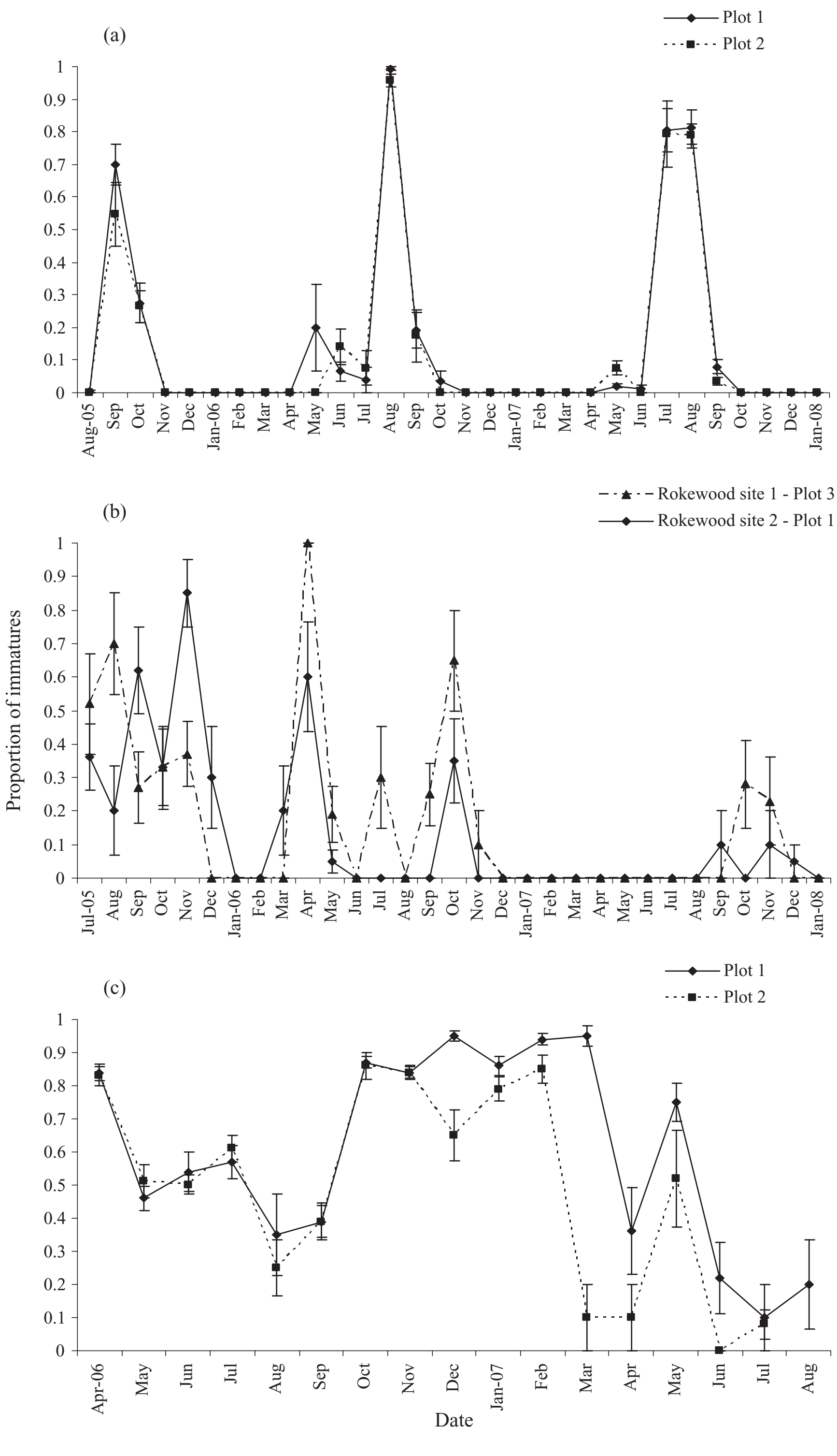

Fig. 8. Proportion of immature stages of (a) *Bryobia* sp. IX at Quambatook, (b) *Bryobia* sp. IX at Rokewood site 1 and 2, and (c) *Bryobia* sp. I at Irrewarra.

November/December 2006 until August 2007 (Fig. 7b). Throughout the active period there were two peaks, although the timing of these differed slightly. At Quambatook the first peak occurred between May and June and the second peak occurred between August and October. At both Rokewood sites, the first peak occurred earlier in autumn between April and May and the second spring peak occurred between September and November. Mite numbers declined dramatically over the winter months from June until August at both Rokewood sites.

The two plots at Quambatook showed consistent patterns in the proportion of *Bryobia* sp. IX immatures between the seasons (Fig. 8a). At this site there were two peaks each season, most likely reflecting two generations. The first generation started in autumn in May when mites emerged, and the second generation emerged around late winter or spring between July and September. At both Rokewood sites *Bryobia* sp. IX also appeared to go through at least two generations in the 2006 season (Fig. 8b). In 2006, patterns were similar across the two sites and were similar to Quambatook, with two peaks in the proportion of immatures. However, at the Rokewood sites, the first peak occurred earlier than at Quambatook and the second peak was later in spring in October. At Rokewood site 1 there was an extra peak in July; however, this only reflected a couple of immature individuals found at a time when the population size was small. In 2007 at both Rokewood sites only one generation occurred in spring at the time when mites became active.

Bryobia sp. I

This species was present at the Irrewarra site (Fig. 7c) where population patterns were very different than those for *Bryobia* sp. IX. *Bryobia* sp. I was active throughout all seasons sampled from April 2006 until July/August 2007 (Fig. 7c). In only one case (June 2007 in plot 2) was there an absence of mites in samples. Patterns were similar across the two plots at Irrewarra, with numbers generally peaking every 3 to 4 months in July, November, February and May (Fig. 7c).

The proportion of immatures of *Bryobia* sp. I at Irrewarra (Fig. 8c) was similar across the two plots and high in April 2006, July 2006, October 2006 until February 2007 and May 2007. The proportion of immatures peaked approximately every third month, suggesting that *Bryobia* sp. I completes a generation at similar intervals throughout the year.

Relative abundance of the different mite species

To compare activity patterns of the different species, the abundance patterns of all pest mites over the sampling period were compared at sites where multiple species were present. Data are only presented from Rokewood site 1, where the different types of pest mites were present in at least one plot (Fig. 9). Here *Ba. medicagoense* had the longest active period. This species emerged 0–2 months prior to *H. destructor* and *P. major*, and stayed active 1–3 months longer than these species. *Bryobia* sp. IX was active for the same time as *Ba. medicagoense*. In all plots *H. destructor* and *P. major* emerged around the same time in April–May and were active until August–November. *P. major* was the most abundant mite in most cases during the winter months whereas *Ba. medicagoense* was generally more abundant earlier and later in the season in the autumn and spring months. *Bryobia* sp. IX tended to be more abundant than *P. major* and *H. destructor* in early autumn and spring. In all plots the abundance of *H. destructor* peaked around late winter/early spring and in some cases numbers also peaked in autumn. The abundance of *P. major* stayed relatively stable across the years and plots, although numbers started to decline after August/September.

Pest status survey

All earth mite groups present in broad acre crops and pastures are pests and capable of causing pest outbreaks (Table 1). The most commonly attacked crops were canola, wheat and pasture. *H. destructor* caused the majority of outbreaks, followed by *Ba. medicagoense*, *Penthaleus tectus* (previously known as *P.* sp. *x*) and then *P. major*. This survey also showed that all mite species except *P. tectus* were responsible for control failures (Table 2). *Ba. medicagoense* was responsible for the majority of control failures – five out of the thirteen failures identified. Alpha-cypermethrin was the most common pesticide associated with control failures involving *Ba. medicagoense*. *H. destructor* was the second most common species responsible for control failures including four cases involving alpha-cypermethrin and dimethoate. The two control failures reported for *Bryobia* spp. both involved the pesticide bifenthrin.

The status of mite species responsible for outbreaks differed from findings reported in the survey conducted by Robinson and Hoffmann (2001) (Table 1), with significant differences between the studies for the mite species causing outbreaks ($\chi^2 = 50.881$, d.f. = 5, $P < 0.001$). Robinson and Hoffmann (2001) found *P. major* to be responsible for the majority of outbreaks, whereas we found *H. destructor* to be relatively more important. Robinson and Hoffmann (2001) did not report any outbreaks to involve *Ba. medicagoense* and *Bryobia* spp., whereas our results showed that these mites were as important as the *Penthaleus* species. The pest mite species responsible for control failures has changed from the surveys conducted by Umina and Hoffmann (1999) and Robinson and Hoffmann (2001) to this present study (Table 3). There were significant differences in the mite species causing control failures between the three studies ($\chi^2 = 27.753$, d.f. = 10, $P = 0.002$). Umina and Hoffmann (1999) found *H. destructor* and *Penthaleus falcatus* to be responsible for control failures, whereas Robinson and Hoffmann (2001) found *H. destructor* and all the *Penthaleus* species to be involved. The present study is the first to report control failures involving *Ba. medicagoense* and *Bryobia* spp., with *Ba. medicagoense* being particularly important, although there were also two control failures associated with *P. falcatus*. Control failures involving *H. destructor* were found in all three studies. Canola was the most common crop type involved in control failures in our study, as also found by Robinson and Hoffmann (2001). Lupins were the most common crop associated with control failures involving *Ba. medicagoense*.

DISCUSSION

We have found that *Ba. medicagoense* and *Bryobia* spp. are now established pests within Australia capable of causing damage, and they are likely to pose a problem for chemical control strategies. Our findings show that these mites differ in their distribution, seasonal abundance patterns, life cycle and pest status when compared to *H. destructor* and the *Penthaleus* species.

Ba. medicagoense and *Bryobia* spp. are widely distributed over Mediterranean-type climate areas, which are characterised by hot dry summers and cool moist winters. *Bryobia* spp. are broadly distributed over southern Australia, but the exact

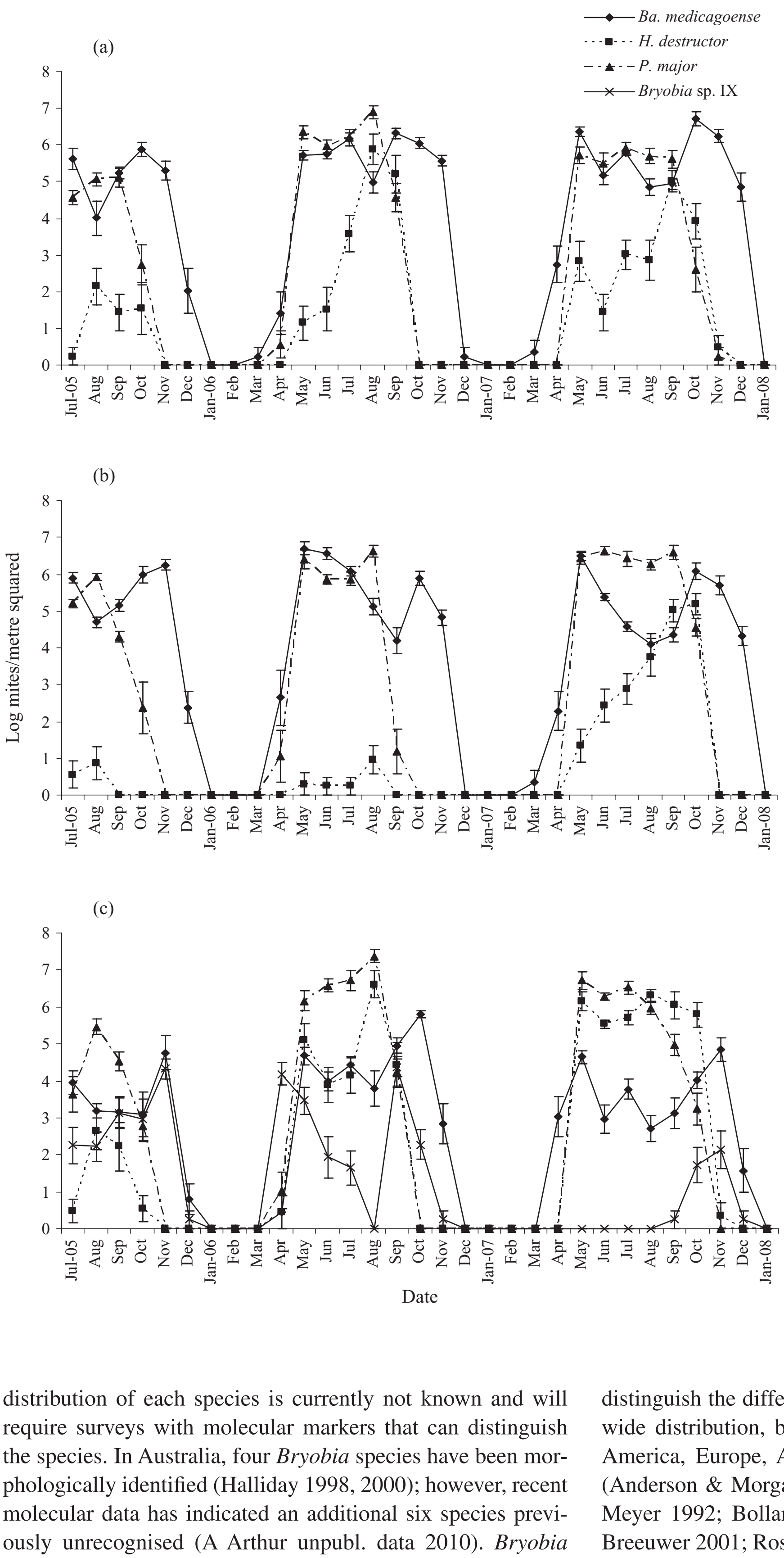

Fig. 9. Seasonal abundance patterns of *Balaustium medicagoense*, *Halotydeus destructor*, *Penthaleus major* and *Bryobia* sp. IX at Rokewood site 1 in plots (a) 1, (b) 2 and (c) 3.

distribution of each species is currently not known and will require surveys with molecular markers that can distinguish the species. In Australia, four *Bryobia* species have been morphologically identified (Halliday 1998, 2000); however, recent molecular data has indicated an additional six species previously unrecognised (A Arthur unpubl. data 2010). *Bryobia* mites are difficult to identify morphologically given their small size and limited number of suitable morphological characters (Ros *et al*. 2008); therefore, molecular markers are needed to distinguish the different species. *Bryobia* mites have a worldwide distribution, being known from North America, South America, Europe, Africa, New Zealand, Asia and Australia (Anderson & Morgan 1958; Pritchard & Keifer 1958; Smith Meyer 1992; Bolland *et al*. 1998; Halliday 1998; Weeks & Breeuwer 2001; Ros *et al*. 2008), but species are generally not distinguished in surveys. *Ba. medicagoense* has a more restricted distribution. *Ba. medicagoense* is thought to have been introduced in the early 1930s (Halliday 2001) and the

Table 1 Number of outbreaks recorded for each mite species on broad acre crops and pastures in the present study and surveys represented in Robinson and Hoffmann (2001)

Species	Faba beans	Canola	Lucerne	Field peas	Wheat	Triticale & lucerne	Pasture	Oats	Subclover	Oats & vetch	Lupins	Lucerne & oats	Total	Robinson & Hoffmann (2001)
H. destructor	2	3	1	1	4	1	6	1	2				21	25
P. major		1		1			1	2					5	44
P. tectus		1			4					1			6	24
P. falcatus							1						1	26
Ba. medicagoense		2			1		1				2	1	7	0
Bryobia spp.		2					1						3	0
Total	2	9	1	2	9	1	10	3	2	1	2	1	43	119

Table 2 List of control failures and the mite species responsible

Species	Location (nearest town)	Crop	Pesticide	Application rate
H. destructor	Nhill, VIC	Pasture	Dimethoate	100 ml/ha
H. destructor	Gibson, WA	Canola	Alpha-cypermethrin	300 ml/ha
H. destructor & P. major	Galong, NSW	Canola	Alpha-cypermethrin	100 ml/ha
H. destructor & P. major	Corinella, NSW	Oats	Dimethoate	100 ml/ha
P. falcatus	Marnoo, VIC	Canola	Methidathion	100 ml/ha
P. falcatus	Bedgerebong, NSW	Canola	Dimethoate	100 ml/ha
Ba. medicagoense	Cummins, SA	Canola	Alpha-cypermethrin	200 ml/ha
Ba. medicagoense	Tatyoon, VIC	Lupins	Methidathion	200 ml/ha
Ba. medicagoense	Cummins, SA	Lupins	Alpha-cypermethrin	250 ml/ha
Ba. medicagoense	Edillilie, SA	Lupins	Lorsban & alpha-cypermethrin	200 ml/ha (both)
Ba. medicagoense	New Norcia, WA	Oats	Alpha-cypermethrin	400 ml/ha
Bryobia spp.	Temora, NSW	Canola	Bifenthrin	100 ml/ha
Bryobia spp.	Williams, WA	Canola	Bifenthrin	200 ml/ha

Table 3 Number of control failures on broad acre crops and pastures from surveys represented in Umina and Hoffmann (1999), Robinson and Hoffmann (2001) and in the present study

Species	Umina & Hoffmann (1999)	Robinson & Hoffmann (2001)	Present study
H. destructor	4	5	4
P. major	0	3	2
P. falcatus	3	11	2
P. tectus	0	7	0
Ba. medicagoense	0	0	5
Bryobia spp.	0	0	2

species has presumably dispersed widely since this time. The MAXENT model suggests that *Ba. medicagoense* has reached the full potential of its distribution on mainland Australia. Areas such as Kangaroo Island, King Island and the north-eastern coast of Tasmania appear climatically suitable for *Ba. medicagoense*, but these areas have not yet been sampled. The MAXENT model suggests that summer and winter temperature variables and winter precipitation are the best predictors of the distribution of this species.

The distribution of *Ba. medicagoense* within Australia is more restricted than that of the other major earth mite pests *H. destructor*, *P. major* and *P. falcatus* (Wallace & Mahon 1971; Robinson & Hoffmann 2001; Weeks & Breeuwer 2001). These mites tend to occur further inland in all states and in the mallee region within Victoria where *Ba. medicagoense* was absent, suggesting that they can occur in relatively drier regions. *Ba. medicagoense* have also been found together with *H. destructor* in South Africa, around the western and eastern cape province coastal areas (Halliday 2001; Halliday & Paull 2004).

The seasonal abundance data show that *Ba. medicagoense* are winter pests and are active from March (early autumn) until December (early summer), although this period can be shorter depending on conditions. The inactive phase most likely is due to a period of diapause. Other pest mites tend to diapause as eggs throughout the harsh summer months, as in the case of *H. destructor* and the *Penthaleus* species (Wallace 1970; Ridsdill-Smith & Annells 1997; Umina & Hoffmann 2003; Umina *et al*. 2004). Species within the genus *Balaustium*, such as the predatory mite *Balaustium putmani*, also have a diapause stage; this species overwinters in the egg stage and diapausing eggs are laid by the second generation of mites (Putman 1970; Cadogan & Laing 1977). In *Ba. medicagoense*, the first generation in autumn is likely to develop from diapause eggs following exposure to favourable conditions, presumably triggered by rainfall and temperature as in the case of other earth mites (Wallace 1970; Jeppson *et al*. 1975). The second generation emerges in spring and also appears to be induced through favourable conditions as it appears to occur around the same time every year. Other species of the genus *Balaustium*, such as *Ba. putmani*, also have two generations a season (Putman 1970; Cadogan & Laing 1977, 1981; Childers & Rock 1981). The hatching and development of *Ba. putmani* eggs is induced through favourable conditions relating to moisture and temperature. The first generation emerges from overwintering eggs in early spring when there is adequate moisture in the field and temperatures increase. The second generation emerges in midsummer and is dependent on timely summer rains to provide adequate moisture for hatching of eggs, as the temperature at this time is already adequate for optimum development (Putman 1970; Cadogan & Laing 1977, 1981; Childers & Rock 1981). This may reflect the hatching of generations seen in *Ba. medicagoense* but in the opposite direction, as in *Ba. medicagoense* the first generation appears to hatch after adequate autumn rains when the temperature is still relatively warm, and the second generation appears to hatch when the temperature increases and there is adequate moisture in the field from the winter months.

Bryobia sp. IX and *Bryobia* sp. I have very different seasonal abundance patterns. *Bryobia* sp. IX is active from March (early autumn) until December (early summer), although this can be shorter depending on conditions at a site, and conditions also seem to influence the number of generations (one at both Rokewood sites in 2007, two on other occasions). *Bryobia* sp. I appears to have no diapause at all at least at the site monitored, and this species seems to complete a generation approximately every 3 months. Differences in life cycle and occurrence of diapause are common among *Bryobia* species from different parts of the world and for species from within the same geographical area (Venables 1943; Roosje & van Dinther 1953; Mathys 1957; Anderson & Morgan 1958; Snetsinger 1964; Jeppson *et al*. 1975; Helle & Sabelis 1985). Some species have no diapause stage (e.g. *B. kissophila* and *B. cristata*) with the succession of generations proceeding continuously throughout the year, while others have one to several generations a year, separated by a hibernal (e.g. *B. praetiosa*, *B. ribis*, *B. arborea* and *B. rubrioculus*) and/or an aestival (e.g. *B. praetiosa*) diapause. Some species diapause only in the egg stage, whereas others diapause independent of stage.

While all pests mites were active at the same time during much of their life cycle there were differences in activity patterns. *Ba. medicagoense* and *Bryobia* sp. IX were active for longer periods than both *H. destructor* and *P. major* and these mites were more abundant than both *H. destructor* and *P. major* in the autumn and spring months. This suggests that *Ba. medicagoense* and *Bryobia* sp. IX populations can tolerate and thrive in warmer temperatures than the other pest mites or perhaps persist on resources available at that time. *H. destructor* and *P. major* were active for similar periods from April (autumn) until November (late spring), consistent with previous studies (Ridsdill-Smith & Annells 1997; Weeks & Hoffmann 2000; Umina *et al*. 2004). The stable abundance patterns of *P. major* during their active period and the peak in abundance of *H. destructor* in late winter/spring and sometimes autumn/early winter was also consistent with patterns noted by Weeks and Hoffmann (2000). Changing abundance patterns throughout the season suggest that the mites have the potential to be pests at different times throughout the season, but we do not yet have sufficient data to test this.

The pest status survey shows that *Ba. medicagoense* and *Bryobia* spp. are capable of causing significant damage to broad acre crops and pasture and appear to be problematic to control through the use of chemicals. While *H. destructor* was responsible for the majority of outbreaks, *Ba. medicagoense* was reported as being problematic just as often as the *Penthaleus* species. A previous survey suggested that the pest status of *Penthaleus* species had been underestimated within south-eastern Australia and that these species were as important as *H. destructor* in many regions (Robinson & Hoffmann 2001). The current results suggest that *Ba. medicagoense* and *Bryobia* spp. should also be regarded as serious pests in this region. A collation of pest outbreak data from report bulletins in south-eastern and Western Australia suggests that there has been an increase in the incidence of outbreaks involving *Ba. medicagoense* and *Bryobia* spp. in the past decade (Hoffmann *et al*. 2008). The reason for the increasing importance of these mites is still unknown; however, misidentification, increased awareness, climate change, high pesticide usage and/or changing agricultural practices may all contribute (Arthur *et al*. 2008; Hoffmann *et al*. 2008).

All mite species with the exception of *P. tectus* were responsible for control failures in the surveys. Four of the failures involving *Ba. medicagoense* were associated with applications of alpha-cypermethrin and one involving methidathion. Laboratory tests show that *Ba. medicagoense* had a much greater natural level of tolerance to a range of pesticides, including alpha-cypermethrin and methidathion, than *H. destructor* (Arthur *et al*. 2008). For *Bryobia* spp. there were two cases of control failures involving bifenthrin, and laboratory tests have also shown one species of *Bryobia* to have a high level of tolerance to bifenthrin compared to *H. destructor* (Arthur *et al*. 2008). Previous studies have also found differences in the levels of tolerance of mites to pesticides that could be related to control failures. In particular, *P. falcatus* has a high level of tolerance to a range of registered pesticides compared to other earth mites, and has been responsible for many chemical control failures (Umina & Hoffmann 1999; Weeks & Hoffmann 1999; Robinson & Hoffmann 2000, 2001). Given the high tolerance levels present in *Ba. medicagoense* and *Bryobia* sp., these mites pose a serious problem for chemical control strategies, reinforcing the need for alternative strategies not reliant on chemicals.

In conclusion, the results show that *Ba. medicagoense* and *Bryobia* mites are established winter pests in southern Australia capable of causing damage and being responsible for control failures. These mites have the potential to be serious pests particularly given control failures, high levels of abundance, widespread distributions and a broad window of activity. These species appear to share strategies in common with other earth mites particularly around a period of summer inactivity most likely reflecting summer diapause. For *Bryobia* mites, the exact nature of species distributions and seasonal patterns remains to be determined because of the fact that this group represents a cryptic species complex.

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