Strategies for control of the redlegged earth mite in Australia

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Abstract. The redlegged earth mite, *Halotydeus destructor*, continues to be an intractable pest causing damage to most crop and pasture species in southern Australia. *H. destructor* feed on all stages of plants, but particularly damage seedlings in autumn. Research has aimed to develop new controls based on a better understanding of the biology and ecology of this pest. Chemicals remain the key tool to control *H. destructor*, despite the recent appearance of resistance to synthetic pyrethroids. A control package, Timerite, has been developed by which a single well-timed spray in spring can prevent *H. destructor* from developing diapause eggs. Field trials show this strategy provides effective control of *H. destructor* the following autumn, and protects plant seedlings, although mite populations build up again during winter. Non-chemical control strategies include grazing, the use of tolerant plants such as cereals, resistant legume cultivars and avoiding rotations where favourable host plants are available in the year before growing susceptible crops such as canola. Natural enemies can assist in mite control, and their numbers can be enhanced by methods including increasing landscape features like shelterbelts. Interspecific competition can occur between *H. destructor* and other pest mites, but the extent to which these interactions influence the structure of pest communities under different management regimes remains to be investigated.

Introduction

The redlegged earth mite, *Halotydeus destructor* (Acari: Penthaleidae), is arguably the most important and widely distributed pest in broadacre farming systems in southern Australia. A whole-farm bioeconomic model, MIDAS, showed that the potential productivity benefits of completely removing *H. destructor* through spraying on a 1000-ha mixed-enterprise sheep and cropping farm in south Western Australia amounted to $49/ha (Young *et al*. 1995).

A review of *H. destructor* biology, ecology and control was published in 1997 (Ridsdill-Smith 1997), and here we review published research since that time, placing it within the context of earlier studies. In addition, we describe current practices and strategies used by farmers for controlling *H. destructor*. Research is discussed within the context of integrated pest management for redlegged earth mite control in southern Australia agroecosystems.

Biology and distribution

H. destructor is a damaging pest, attacking most field crop and pasture species as well as many common weeds. Many plants are preferred hosts when seedlings but are unsuitable hosts when mature; this includes crops such lupins and lentils (McDonald *et al*. 1995; Umina and Hoffmann 2004). Others plants can support *H. destructor* at all stages and these include canola (*Brassica napus*), pasture legumes such as vetches and clovers, and weeds such as capeweed (*Arctotheca calendula*) and bristly ox-tongue (*Picris echioides*) (Umina and Hoffmann 2004). The soil surface microflora consisting of filamentous algae and mosses can also sustain *H. destructor* juvenile stages (Maclennan *et al*. 1998). *H. destructor* spend most of their time on the soil surface in pastures typically sheltering under the cooler, more humid tall patches that are often dominated by *A. calendula*, but they feed mostly on clover, which is usually in shorter patches (Ridsdill-Smith and Pavri 2000).

H. destructor is normally active from May to October, completing three generations a year (Ridsdill-Smith and Annells 1997). In the hotter, drier months of summer they survive as diapause eggs in the cadavers of adult females. The production of diapause eggs in spring at any locality can be predicted from daylength and duration of long-term plant growing season (Ridsdill-Smith *et al*. 2005). Mites emerge in autumn following cooler temperatures and adequate rainfall (Ridsdill-Smith and Annells 1997).

Population genetic data collected using allozyme markers (Weeks *et al*. 1995; Qin 1997) indicate that *H. destructor* is a sexual species. Weeks *et al*. (1995) showed that genotypes at allozyme loci are in Hardy–Weinberg equilibrium, as expected when only sexual reproduction is present in populations. In crosses between male and female mites, alleles are inherited

from both parents and heterozygotes of both sexes are detected, reflecting diploidy rather than a haplodiploid mode of reproduction (Weeks *et al.* 1995). This is in contrast to closely related species of earth mites, such as *Penthaleus* spp., which exhibit parthenogenesis (Weeks and Hoffmann 1998, 1999).

Wallace and Mahon (1971) defined the rainfall, temperatures and land use that predict the distribution of *H. destructor*. Since then the mite has been found further inland in drier areas in Western Australia and in south-eastern Australia (Qin 1997; Robinson and Hoffmann 2001; A. Arthur and S. McColl, pers. comm.) (Fig. 1). It is not clear if this reflects more intensive surveying of inland areas, or represents a response of *H. destructor* to climate change coupled with an evolutionary shift allowing mites to occupy new areas. Ridsdill-Smith (1997) suggested that long-distance wind dispersal of diapause eggs with soil particles during the summer could result in mites being transported to these isolated favourable habitat patches in inland sites otherwise unsuitable for their survival.

Ecology and competition

H. destructor populations are generally resource limited (Grimm *et al.* 1994; Ridsdill-Smith and Annells 1997). The ability of *H. destructor* to increase rapidly when conditions are favourable may be one reason it remains a persistent major pest (Mangano and Severtson 2008). The number of diapause eggs dramatically influences mite populations the following autumn. When there is a late end to the growing season, mites survive for longer and produce more diapause eggs. Conversely, when there is an early end to the growing season, mites die before producing a large number of diapause eggs. During the 27-week period of activity in south Western Australia each generation of *H. destructor* is marked by a peak in numbers (Ridsdill-Smith and Annells 1997).
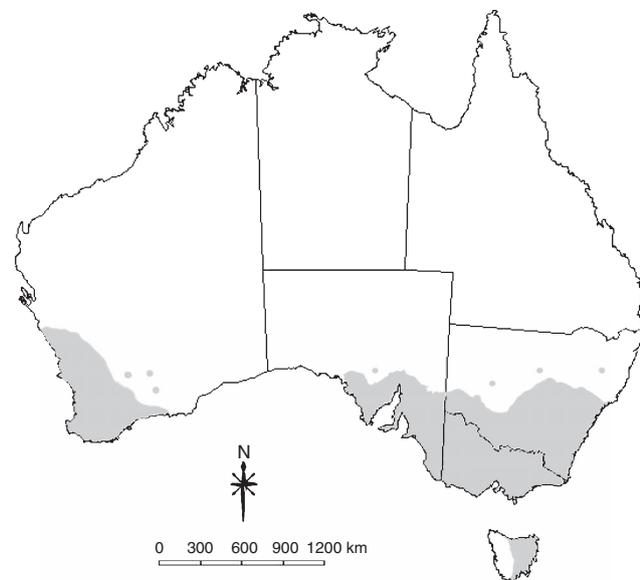

Fig. 1. Distribution of *Halotydeus destructor* across southern Australia. Data from western (Qin 1997; S. McColl, pers. comm.) and south-eastern (Robinson and Hoffmann 2001; A. Arthur, pers. comm.) Australia.

In weekly sampling at Keysbrook there was a mean population of 11 000 mites/m^2, but the numbers peaked at an average of 1.9 times the mean, with an absolute peak at this site of 38 000 mites/m^2 (Ridsdill-Smith and Annells 1997). Studies in Victoria also show strong fluctuations from 2200 mites/m^2 at the autumn break of season to 100 mites/m^2 at mid-season at Birregura, and from 18 000 to 600 mites/m^2 at Kilmore (Gower *et al.* 2008). Thus numbers given from one or two samples a year in other studies may not represent the average level of abundance for that site.

Weeks and Hoffmann (2000) established field enclosures in a pasture environment to study competition between *H. destructor* and the closely related species *Penthaleus major*, using mixed and pure populations. In 1 year, *H. destructor* had a negative impact on the numbers of *P. major*, but this was reversed in the ensuing year. A similar relative abundance of the mite species was seen in pastures outside the plots. Competitive interactions have also been reported between *H. destructor* and other pest *Penthaleus* species (Umina and Hoffmann 2005). In their study, Umina and Hoffmann (2005) found that *H. destructor* was a particularly effective competitor on canola and *P. echioides*, whereas some *Penthaleus* species had a competitive advantage over *H. destructor* on cereals. *H. destructor* and the lucerne flea *Sminthurus viridis* also compete for resources (Michael *et al.* 1997). These studies provide evidence for competitive displacement between *H. destructor* and other invertebrate pests, suggesting species have the capacity to fill a gap when control measures target a single pest. However, no studies have examined competitive interactions over an extended scale or time period, and the likely direction of competition under different cropping and environmental conditions remains unpredictable.

Feeding damage

H. destructor is particularly damaging at the establishment phase of crops and pastures in autumn. In years with a late 'break of season' or with late-sown crops and pastures, seedlings emerge in the presence of established populations of *H. destructor*. Intensive feeding at high population densities at this time can lead to entire crops needing resowing. In feeding trials, damage to grain legume seedlings from *H. destructor* is greatest to field peas and faba beans, and least to chickpea (Thackray *et al.* 1997*a*). Damage to cereals by *H. destructor* is sometimes greater around the borders of paddocks. More often *H. destructor* occurs on paddocks where the mites have previously occurred at high populations. Canola is particularly vulnerable to mite attack, whereas lupins and other pulse crops can tolerate more damage by *H. destructor*. However, Liu *et al.* (2000) showed that *H. destructor* feeding on lupin seedlings can reduce grain yield by up to 50%.

In spring in set-stocked pastures, Michael *et al.* (1997) measured a 2.1 t DM/ha (range of 0.2–4.0 t DM/ha) increase in production of pasture plants following repeated chemical sprays to control *H. destructor* during the growing season. In small plots *H. destructor* and *S. viridis* caused an 80% reduction in clover seed yield and a 77% reduction in herbage yield, compared with plots with chemical control (Michael 1995).

Legumes in Australian annual pastures are self-seeding, and *H. destructor* is one factor causing a decline in pasture legume content (Michael *et al.* 1997; Howieson *et al.* 2000). High numbers of aphids and *H. destructor* in a subterranean clover pasture in spring can result in a 50–90% reduction in seed production and up to a 34% reduction in dry matter production (Brennan and Grimm 1992). This leads to fewer seedlings the following year.

Chemical control

Chemicals will remain the major control tool against *H. destructor* and other earth mite species for the foreseeable future. Farmer reliance on pesticides has been increasing steadily over recent decades with the wider adoption of minimum and no-till farming systems and the lower cost of chemicals (Mangano and Micic 2008). The level of pest abundance at which control becomes cost effective is the action threshold (economic threshold). At the seedling stage, control of redlegged earth mites is recommended when there are 5000 mites/m^2 in cereals (Hopkins and McDonald 2007), but at first sign of mite activity in winter oilseeds (Berlandier and Baker 2007), in winter pulses (Miles *et al.* 2007), and in winter pasture legumes (Pavri 2007). Later in the season when the plants are larger, control may be warranted in legume pastures if feeding damage is observed to more than 20% of the leaf area, to protect spring pasture and seed production (Pavri 2007).

Seedlings of many crop and pasture species that are susceptible to mites can be protected by coating seed with systemic chemicals before seeding (e.g. imidacloprid and fipronil), by use of contact sprays applied to bare earth before the seeds emerge (e.g. bifenthrin), or by foliar sprays to emerging seedlings (e.g. chlorpyriphos, methidathon) (Berlandier and Baker 2007; Miles *et al.* 2007; Pavri 2007). Many farmers who sow susceptible crops such as canola apply pesticides mixed with herbicides in knockdown or after-sowing pre-emergence sprays, because they are cost-effective strategies to control pests before the vulnerable seedling stage occurs (Mangano and Micic 2008; R. Lewellyn, pers. comm.). During the growing season mites can be controlled in crops and pastures with a foliar spray about 2 weeks after the first rains and cool weather, which prompts mite hatching (Ridsdill-Smith and Annells 1997) but is before they lay their first generation of winter eggs (Miles *et al.* 2007). Alternatively, a perimeter spray of weedy fence lines and adjacent pasture can be used to prevent the invasion of mites into a susceptible crop (Berlandier and Baker 2007). Effective borders need to be more than 10 m wide based on dispersal rates of *H. destructor* (Weeks *et al.* 2000).

Development of resistance to pesticides

Chemicals are often used to target multiple pests, and individual farmers may apply up to four pesticide sprays on susceptible crops in a single season (Umina and Hoffmann 2003). The increasing application of pesticides places enormous selection pressure on species to develop resistance. Hoffmann *et al.* (1997) provided evidence of some tolerance in *H. destructor* populations in Victoria to an organophosphate chemical (Table 1). They predicted future problems with pesticide resistance in *H. destructor* and suggested that a reduction in the use of pesticides and dependence on this one control method was needed. The evolution of chemical resistance has been observed in hundreds of mite and insect pests (Penman and Chapman 1988; Georghiou 1990; Caprioa 1997).

The first demonstrated case of chemical resistance in *H. destructor* was reported in 2006 with very high levels of resistance to two synthetic pyrethroids, bifenthrin and α-cypermethrin (Umina 2007) (Table 1). For bifenthrin, LD_{50} estimates show a difference in resistance of greater than 240 000 fold, and resistance to α-cypermethrin is almost 60 000 fold (Umina 2007). This resistance is heritable, persisting after several generations of culturing. There is currently no recorded resistance to organophosphates. In view of the very high densities that *H. destructor* reach in the field (Ridsdill-Smith and Annells 1997) and the high selection pressure imposed on this species (Hoffmann *et al.* 1997; Ridsdill-Smith 1997) it is surprising that chemical resistance in *H. destructor* has not been demonstrated earlier.

The mechanism conferring pesticide resistance in *H. destructor* was not identified by Umina (2007), but evidence suggests that a target-site mechanism is likely to be involved. First, there is cross-resistance between multiple synthetic pyrethroids (Umina 2007; P. Umina and A. Weeks, pers. comm.). Second, very high levels of resistance have been detected (Umina 2007), and third, it appears that resistance has evolved rapidly in this species. The initial population where resistance was discovered had been sprayed routinely (one to two applications/year) with synthetic pyrethroids for only 5 years before resistance developed (Umina 2007), although the immigration of resistant individuals cannot be excluded. Resistance is probably more widespread than first thought and could be spreading in Western Australia (P. Umina and A. Weeks, pers. comm.). Intensive use of synthetic pyrethroids, which now

**Table 1.	Cases of insecticide tolerance and resistance in *Halotydeus destructor* populations in Australia determined using laboratory bioassays**

Date	Location	Crop	Chemical	Authors
		Tolerance		
1996	Mansfield, Victoria	Pasture	Omethoate	Hoffmann *et al.* (1997)
2002	North Woogenellup, Western Australia	Canola	Bifenthrin and cypermethrin	C. Pavri and J. Ridsdill-Smith, pers. comm.
		Resistance		
2006	Esperance, Western Australia	Canola	Bifenthrin and α-cypermethrin	Umina (2007)
2007	Wansbrough, Western Australia	Canola	Bifenthrin and α-cypermethrin	P. Umina and A. Weeks, pers. comm.
2007	Woogenellup, Western Australia	Canola	Bifenthrin	P. Umina and A. Weeks, pers. comm.

account for ~25% of the world pesticide market (Hemingway *et al*. 2004), has led to the development of resistance in many other insect pests (Georghiou 1990).

Timerite

Biological or chemical control of *H. destructor* in spring provides seed yield benefits in pastures, and increased seedling density in autumn. Controlling *H. destructor* in spring reduces over-summering eggs and thus damaging mite populations the following autumn (Ridsdill-Smith and Annells 1997). The package Timerite (www.timerite.com.au, verified 14 October 2008) has been developed for *H. destructor* control using a single spray whose timing is based on a model to predict the date of onset of diapause egg production (Ridsdill-Smith *et al*. 2005). The date remains constant for individual sites between years, but varies between sites. A single spring spray was applied to pastures at three trial sites on the recommended date (2 weeks before the appearance of 90% diapause eggs), and control averaged 99% 1 week later, and 99% the following autumn (Ridsdill-Smith *et al*. 2005). Subterranean clover seed yield in summer was 45% greater in the spayed treatments, and clover seedling densities were 36% higher at the initial break of season in autumn and 66% higher 1 month later (Ridsdill-Smith and Pavri 1998). In a separate study at five sites in Victoria, a spring spray on the recommended date provided between 70 and 90% control of *H. destructor* at the following autumn break (Gower *et al*. 2008).

Although most *H. destructor* diapause eggs are produced at the same time each year at a site (Ridsdill-Smith *et al*. 2005), Umina and Hoffmann (2003) demonstrated that a small number of mites are not controlled by Timerite. Ridsdill-Smith *et al*. (2005) recorded an average of 3 mites/sample emerging following 'spring-spray' treatments. Repeated spraying of *H. destructor* in the same paddock on the same date for multiple years should be avoided, as it could place strong selection pressure on *H. destructor* populations leading to a shift in the timing of the onset of diapause egg production. This has been demonstrated in the corn rootworm (*Diabrotica* spp.), which have circumvented control attempts by evolving different diapause strategies (Krysan *et al*. 1984; Levin *et al*. 2002). This risk could be avoided by monitoring populations and rotating Timerite with other control strategies, such as grazing management and crop rotations.

Although control of *H. destructor* is high in autumn (May and June) at sites in Victoria following a spring spray at the Timerite date, control is lost by mid-season (August) and can even result in a significant increase in numbers compared with unsprayed areas (Gower *et al*. 2008). In other studies, a spring spray produced an average of 95% control of *H. destructor* in autumn, but this had fallen to an average of 40% control after 12 months by the following spring (J. Ridsdill-Smith and C. Pavri, pers. comm.). The reason for the differences in levels of control in the season following a spring spray between these studies is unclear. Gower *et al*. (2008) suggest the rebound in numbers observed in some studies may be due to a reduction of natural predator numbers either directly by spraying or indirectly by the population 'crash' of their prey. Alternatively, *H. destructor* populations in other studies may respond to a pasture resource

relatively faster than the other mite species (J. Ridsdill-Smith and C. Pavri, pers. comm.). Timerite has little effect on other mite pests, including *Penthaleus* spp. (Umina and Hoffmann 2003; Gower *et al*. 2008), which lay diapause eggs earlier in the season and before the recommended Timerite date (Umina and Hoffmann 2003).

Cultural control

Many farming practices influence *H. destructor* populations and can be used to reduce populations in a more environmentally sustainable manner, although these are unlikely to be adopted rigidly while current chemical options remain cost effective. Methods available include grazing management in spring, crop rotations, the use of border crops to repel mites and improved weed management.

The potential benefits of careful grazing management have been demonstrated in Western Australia in set-stocked pastures in spring. *H. destructor* populations were reduced from $46\,000/m^2$ to $27/m^2$ following a four-fold increase in grazing days (total number of sheep multiplied by the number of days grazing) (Grimm *et al*. 1994). Much of the spring pasture production in set-stocked pastures is wasted, with only 10–40% of feed estimated to be utilised, allowing *H. destructor* populations to increase (Michael *et al*. 1997). The relative humidity is lower when vegetation is short and when plant density is low, which probably increases mite mortality (Ridsdill-Smith and Pavri 2000). In addition, young mites feed on the soil surface microflora, which is more abundant under dense crop and pasture vegetation (Maclennan *et al*. 1998). Heavily grazing pastures in spring is recommended when sowing a susceptible crop the following year (Berlandier and Baker 2007; Hopkins and McDonald 2007; Pavri 2007).

H. destructor respond differently to crop plants (Umina and Hoffmann 2004) and paddocks vary in their risk of sustaining mite damage depending on previous history. The risk is generally higher if paddocks have been in long-term pasture (with high densities of broad-leafed plants) and where mite populations have not been controlled (Umina and Hoffmann 2004). Strategies to minimise reliance on pesticides include planting crops such as lentils or lupins before cereals (Hopkins and McDonald 2007), cereals or chickpeas before winter pulses (Miles *et al*. 2007), and lentils or chickpeas before canola (Merton *et al*. 1995; Umina and Hoffmann 2004). Planting a border of wheat or oats can protect canola from mite invasion from neighbouring mite-infested paddocks (Merton *et al*. 1995), whereas a border of lupins can act as a trap crop.

Broad-leaved weeds are suitable food for *H. destructor*, including cat's ear (*Hypochoeris* spp.), *A. calendula* and *P. echioides* (Gaull and Ridsdill-Smith 1996; Weeks and Hoffmann 1999; Umina and Hoffmann 2003), and it is widely accepted that 'weed-free' paddocks typically harbour lower mite numbers. Weeds should be controlled along fence lines adjacent to the crop (Berlandier and Baker 2007; Miles *et al*. 2007). Weed management inside crops (Hopkins and McDonald 2007) and summer weed management in pastures (Pavri 2007) are also recommended cultural controls, typically by applying herbicides. Although cultivation and burning have in the past provided effective control of *H. destructor*

and other pests (Ridsdill-Smith 1997), vast areas of crops are now sown using direct drilling methods with minimal soil disturbance, aimed at minimising soil damage, conserving moisture and promoting sustainability. These practices can result in increased weed density and this will support higher *H. destructor* populations.

Natural enemies

Several natural enemies of *H. destructor* are already known from Australia. The mite *Anystis wallacei*, introduced to Australia from France, is an effective predator of *H. destructor*, *P. major* and *S. viridis* (Michael 1995). When *A. wallacei* and *Neomologus capillatus* were added to field enclosures containing *H. destructor* and *S. viridis* there was an 80% reduction in pest numbers, and losses to clover seed yield and herbage production were reduced by 30% (Michael 1995). *A. wallacei* spreads very slowly, and must be aided in its distribution if it is to be of any benefit to farmers (Michael 1995).

A recent search for predators of *H. destructor* in the Western Cape Province of South Africa for biological control led to the identification of 56 predatory mite species from 14 families (Halliday 2005). Of the 41 species that could be identified, nine are already in Australia. The most promising of the South African species, *Chaussieria capensis* (Acari, Anystidae), was assessed in more detail, but factors common to other Anystidae, such as slow reproductive rate, long generation time, cannibalism and a broad prey range, make it unlikely that this species would control *H. destructor* effectively in Australia (Halliday and Paull 2004).

Managing the landscape could enhance the impact of existing *H. destructor* natural enemies. Numbers of *H. destructor* are low in complex shelterbelts, consisting of trees, shrubs and small herbaceous plants with a dense understorey of grass (Tsitsilas *et al*. 2006), suggesting that these do not act as reservoirs for pest species. Moreover, numbers of *H. destructor* are relatively lower up to 50 m into pasture adjacent to these shelterbelts. Complex shelterbelts support high populations of predatory mites and other generalist predators like spiders, which may be effective in suppressing *H. destructor* populations, particularly as samples of these have been shown to decrease *H. destructor* numbers when added to containers with mites (Tsitsilas *et al*. 2006).

Host plant resistance

Alternative pasture legume species being considered for new pasture phases are small seeded, have high seed yield (both qualities that are likely to make seedlings more susceptible to *H. destructor*), and are deep rooted (Howieson *et al*. 2000). One alternative pasture legume species, *Trifolium glanduliferum* (CV Prima), has already been released in part because it has strong resistance, which prevents *H. destructor* feeding. This resistance results from the volatiles coumarin and β-ionone (Wang *et al*. 2005). Resistance to *H. destructor* has been found in seedlings of some wild lines of yellow lupins, *Lupinus luteus*, which is correlated with levels of different non-polar alkaloid components (Wang *et al*. 2000). Different responses of *H. destructor* are also evident on different canola cultivars (McDonald *et al*. 1995; H. Gu, pers. comm.), and on different grain legume species (Liu and Ridsdill-Smith 2001).

Lines of the annual *Medicago* spp. with reduced seedling susceptibility to *H. destructor* have been identified in glasshouse screening (Lake and Howie 1995). Several hundred introductions of subterranean clover, *Trifolium subterraneum*, have also been screened for seedling resistance, of which less than 3% show reduced susceptibility to *H. destructor*, and also to *P. major* (Ridsdill-Smith and Nichols 1998). The mechanisms causing *H. destructor* not to feed on subterranean clover cotyledons are a combination of a volatile, 1-octen-3-one, and increased cotyledon toughness (Jiang *et al*. 1996). Subterranean clover lines with the lowest seedling susceptibility to *H. destructor* have been crossed with well-adapted cultivars, and their progeny evaluated at sites across southern Australia. There are plans to make a commercial release of a small number of cultivars that have reduced susceptibility to *H. destructor* as a quality (P. Nichols, pers. comm.).

Integrated management

The elements of an integrated pest management plan for *H. destructor* are generally accepted to be the combined use of chemical control, cultural control, biological control and host plant resistance (Ridsdill-Smith 1997; McDonald *et al*. 1999; Gu *et al*. 2007; Mangano and Micic 2008). In the last 10 years most progress has been made in our understanding of the impact of these factors individually on mite populations. However, farmers are faced with combinations of factors and a suite of pest species, including the mites, *Penthaleus* spp., *Bryobia* spp., *Balaustium medicagoense*, lucerne flea, *S. viridis*, and aphids (Mangano and Severtson 2008). *H. destructor* has remained the major pest in Western Australia (Ridsdill-Smith 1997; Mangano and Severtson 2008) and sometimes in eastern Australia, but *Penthaleus* spp. are frequently more abundant and are responsible for many pest outbreaks (Robinson and Hoffmann 2001; Umina and Hoffmann 2004). It remains unclear why the relative abundance of species varies in different paddocks, regions and years. Two factors that influence abundance are soil type and host plant. Sandy soil is more beneficial to *H. destructor* multiplication than loam soil (Thackray *et al*. 1997*b*), whereas *S. viridis* occurs more commonly on heavier soils (Gu *et al*. 2007). Different host plants favour *Penthaleus* spp. and *S. viridis* (Thackray *et al*. 1997*a*; Umina and Hoffmann 2003; Umina and Hoffmann 2004).

Selection of chemicals for pest control is important because pest species vary in their tolerance to different pesticides (Umina and Hoffmann 1999; Robinson and Hoffmann 2000; Arthur *et al*. 2008; Roberts *et al*. in press). Dimethoate and omethoate are effective systemic chemicals against *H. destructor* and *S.viridis* with omethoate having longer residual activity. Of nine chemicals tested against *S. viridis*, omethoate and chlorpyrifos were most effective, whereas carbaryl was toxic to *S. viridis* and earth mites but not aphids, and fenvalerate was toxic to aphids but not *S. viridis* (Bishop *et al*. 1998). Roberts *et al*. (in press) also showed that the tolerance of *S. viridis* varies between chemicals. *B. medicagoense* and *Bryobia* spp. have a higher tolerance level against some registered chemicals compared with *H. destructor* (Arthur *et al*. 2008). Thus, over time a pesticide regime would control some pests but not others, potentially changing the suite of species present at a given site. Also, the timing of

application will influence which species is controlled. For example, a tool like Timerite provides effective control for *H. destructor* in autumn, but not for other species. It is desirable to select chemicals that kill pests but not their natural enemies. James *et al.* (1995) showed that the potential exists to use α-cypermethrin and to a lesser extent bifenthrin against *H. destructor* without major adverse effects on important mite predators. However, these are the two pesticides to which *H. destructor* has developed resistance, and so there is a potential trade-off from the prophylactic use of these chemicals.

Management strategies are required that optimise the economic benefits of using the chemicals but limit the development of resistance in *H. destructor*. Because gene flow is likely to occur between *H. destructor* populations (Weeks *et al.* 1995; Qin 1997), resistance alleles could be spreading throughout the range of this species without the resistance being expressed, and the resistance to synthetic pyrethroids may become a much broader problem. It is encouraging that, at this stage, resistance appears to be confined to synthetic pyrethroids (Umina 2007), although resistance to other commonly used chemical classes could arise in the future (Hoffmann *et al.* 1997). Integrated strategies for *H. destructor* should aim to reduce the risk of developing resistance.

Conclusions and future directions

The traditional ley farming system of southern Australia is being replaced by one with increased cropping, shorter lengths of the pasture phase, and an increased diversity of legumes in pastures (Howieson *et al.* 2000). The extent to which changing farming practices are influencing the abundance of invertebrate species is not yet understood. For farmers to have more confidence in the use of non-chemical approaches to *H. destructor* control the strategies need to be extrapolated from small plot studies and demonstrated on the whole farm.

Wallace and Mahon (1963) investigated the effect on the yield and botanical composition of legume-based pastures in Western Australia when pests are controlled with pesticides. Their findings are still relevant today. They recommended that pastures should only be treated when damage is evident. However, when pastures are growing vigorously, there will be sufficient feed available for animals even when high pest numbers are present. To be able to increase animal stocking rates on pastures it may be more economical to increase fertiliser rates rather than apply pesticide, especially for low-yielding pastures. Pesticide sprays are fully justified only on areas that are already highly productive. However, although adding fertiliser increases seed yield and pasture production, the losses caused by invertebrates are also greater (Brennan and Grimm 1992).

In their study of *H. destructor* ecology, Ridsdill-Smith and Annells (1997) conclude that the two factors chiefly responsible for regulating abundance are rate of oviposition and mortality of active mites. It should be possible to achieve lower mite abundance by avoiding plants that are favourable hosts for several years that would have allowed the populations to build up. Resistant plants as well as plants that are less-suitable hosts would prevent the increase in abundance. When the populations are controlled at a lower level in this way the impact of predators and other natural enemies should become greater. Evidence for positive interactions between plant favourability and biological control should be studied in paddocks and on farms.

A demonstration of population regulation of *H. destructor* is the reduction in numbers caused by heavy grazing with sheep (Grimm *et al.* 1994), which is consistent with data given by Ridsdill-Smith (1997) indicating that pastures have a carrying capacity for *H. destructor*. This also is evident where strong intraspecific and interspecific competition in *H. destructor* has been demonstrated in field enclosures. The direction of interspecific competition can be influenced by the host plant species (Umina and Hoffmann 2005). A negative interaction is evident when heavy grazing in spring or repeated crop rotations not only reduce *H. destructor* populations, but also significantly reduce the abundance of predators, limiting their effectiveness (Michael 1995). *H. destructor* has a patchy distribution within pastures, and we need to understand the scales at which competition is occurring, and how this might be utilised to improve management decisions.

The challenge for researchers is to reduce mite populations cumulatively by pyramiding options (McDonald *et al.* 1999). Insecticides are still the main tool used for *H. destructor* control, but the appearance of resistance in *H. destructor* to synthetic pyrethroids is a threat to future effective control. We need to monitor and map the distribution and frequency of resistance, to determine its genetic basis and mechanisms, so as to be able to reduce the risk of it developing further. The potential benefits of a resistance management strategy are highlighted by the successful approach used to control pyrethroid- and endosulfan-resistant *Helicoverpa armigera* in Australian cotton over several years (Forrester *et al.* 1993). A successful pesticide resistance management program relies on judicious chemical use, providing refuges for susceptible individuals and reducing reliance on chemicals through biological and cultural methods within an integrated pest management framework (Phillips *et al.* 1989; Denholm and Rowland 1992; Elzen and Hardee 2003). There is a need to use sprays only when required, and to avoid repeated use of the same chemical.

Accurate identification of mites before selection of a chemical is important as incorrect treatment could lead to control failures and place further selection on resistance development (Umina *et al.* 2004; Arthur *et al.* 2008). Timerite has proven a very effective tool where a single spring spray reduces populations the following autumn. Spraying in spring is undertaken when there is evidence that severe damage will occur, or more prophylactically to protect the cropping system from a range of pests. A risk calculator has been developed and placed on the Timerite website to help farmers decide whether a spray is justified by asking a set of questions about their farming system and mite abundance. Practices such as increased grazing density, the use of rotations and tillage practices, and the enhancement of natural enemies through 'softer' sprays and landscape-level changes, need to be tested in combination at demonstration sites on farms to deliver packages to farmers for *H. destructor* integrated management.

Acknowledgements

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