WWAPM: Integrated Management of Weevils, Woolly Aphid and Powdery Mildew

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FINAL REPORT

Compiled by: D.G. Williams

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Final Report

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This report was compiled by the Project Leader from material supplied by team members. The sub-project leaders were Stewart Learmonth (AgWA) weevils, Adrian Nicholas (NSW Ag, UWS) woolly aphid, and Bill Washington (AV) powdery mildew.

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Industry Summary

The apple industry and research organisations have invested heavily in the development of Integrated Pest Management (IPM) systems to reduce the industry reliance on broad-spectrum pesticides. A possible side effect of using more selective “IPM friendly” pesticides is that previously minor pests, that had been controlled by the broad-spectrum pesticides, may become more important. The AAPGA was concerned that Woolly Aphid, Weevils and Powdery Mildew could become major pests when growers reduced their spray programs by adoption of IPM programs for Codling Moth, Lightbrown Apple Moth, and Apple Scab. This concern led to HRDC commissioning research to determine if the concerns were justified, and to develop an integrated approach to control of these pests. The successful applicant was a team of entomologists, plant pathologists and extension specialists from State Departments of Agriculture in Victoria, New South Wales, Queensland, South Australia, Western Australia and Tasmania, as well as CSIRO, the University of Western Sydney, and Evergreen Marketing International. The project took the acronym WWAPM, which signified integrated management of Weevils, Woolly Aphid, and Powdery Mildew.

The project team found that woolly aphid may not develop as a major pest in orchards where the control of codling moth was based on using mating disruption or the insect growth regulator Fenoxycarb, so long as the choice of chemicals used for other pests such as Lightbrown apple moth (LBAM) and weevils takes account of effects on the parasitic wasp Aphelinus mali and European earwigs. The earwigs migrate quickly and can control woolly aphid in the first year of an integrated pest management program if sufficient numbers of earwigs are present in nearby vegetation or adjacent blocks. Earwigs can cause some fruit damage to short stemmed varieties or fruit in tight clusters. Weevils also shelter in such clusters. This is a good reason for having an effective thinning program. Carbaryl is toxic to earwigs and should not be used in the thinning program if woolly aphid is an issue. Other pesticides highly toxic to earwigs are alpha-cypermethrin, azinphos-methyl, chlorpyrifos, fenthion and parathion-methyl. Endosulfan, imidacloprid and tau-fluvalinate are moderately toxic. Tau-fluvinate is less toxic than chlorpyrifos to earwigs but it is more toxic to the predatory mite Typhlodromus occidentalis used for biological control of pest mites. Spraying only ‘hot spots’ or those varieties or trees in a block which are highly susceptible may allow predators to move back in from untreated areas.

A 3 year field trial comparing “conventional” numbers of fungicide applications against reduced applications and alternative “softer” chemicals found that all treatments reduced primary and secondary mildew compared to the untreated trees. There were no differences in yields between the different treatments.

New Jonagold and Pink Lady were the most susceptible to mildew. Lady William and Pink Lady were the most susceptible to scab. There was a high level of resistance to leaf scab in Florina-Querina, Redfree and Jonafree and to powdery mildew in Earlidel. Jonathan, Bonza and Red Elstar showed a useful level of resistance to scab while Red Fuji, High Early and Redfree all showed some resistance to powdery mildew.

Garden Weevil (GW) damaged up to 50% of fruit in some plots. Apple Weevil (AW) damaged up to 15% of fruit and reduced the weight of individual fruit by 20% as a result of girdling the fruit stalk. The relationship between weevil numbers and amount of damage was not linear and we were not able to determine an economic injury level based on weevil numbers. Where an orchardist experienced considerable damage in one season, control measures would be needed next season. The correct timing of control measures can only be determined by monitoring. No single monitoring system was suitable for all 3 species of weevils because they had different habits and were also distributed differently in the orchard. Cardboard trunk bands were the most efficient way of monitoring GW and AW. The bands are easy to make and use, and if made from waxed cardboard last the entire season. Limb jarring similar to the technique used for apple dimpling bug was the best method for monitoring FRW. It was more difficult to determine the effects of Fullers Rose Weevil (FRW) because it didn’t cause direct damage to the fruit. The main problem associated with FRW was blockage of drippers and minisprinklers as a result of eggs being laid in the orifices. These blockages required considerable labour to fix and if undetected caused drought stress to the trees.
GW and FRW do not start laying fertile eggs until about 3 weeks after emergence. AW takes about 6-8 weeks to start laying fertile eggs. This means that there is a reasonable time in which control measures can be applied before the weevils reproduce.

GW larvae appear to have a preference for tap rooted plants. Dandelion supported the highest number of weevil larvae. Capeweed and sow thistle were also important hosts. White clover had significantly lower numbers and appears to not be a favored host. One interesting observation was that ants took considerable numbers of weevil larvae in one of the trials.

Work overseas had indicated birds could give good control of beetles in orchards so we used an enclosure, similar to that used by low chill stone fruit growers to protect their crop from fruit bats, to compare turkeys, guinea fowl, and chickens as controls for weevils. Turkeys gave good results but tended to roost in the trees and their weight caused some limb damage. Chickens proved easier to train than guinea fowl, gave reasonable results and were the easiest to handle. Foxes were controlled by the use of a low 2-wire electric fence. In areas where hail, fruit bats or fruit feeding birds warrant the use of netting chickens may be a viable aid in control of weevils (and an additional source of income!).

The results of this project, in combination with those from other projects involving the team members, have been adopted to varying degrees throughout apple regions in Australia. Growers are more aware of the importance of their choice of fungicides early in the season and those who have reduced their program against scab have not had significant problems with powdery mildew provided they followed our guidelines. The use of earwigs to control woolly aphid has been accepted in some districts but not others. Districts where pome and stone fruit are grown on the same property are less likely to adopt the use of earwigs. Many growers have improved their management of woolly aphid simply by using the monitoring system developed in this project. Weevil management proved more difficult but at least one grower successfully implemented the use of birds to control weevils, and other growers have minimised problems by changing their micro-sprinklers to those less attractive to egg-laying weevils.
Technical Summary

This work was commissioned because of concerns that a side effect of fruitgrowers adopting Integrated Pest Management (IPM) programs for the key pest Codling moth (Cydia pomonella L.) and disease apple scab (Venturia inequalis) could be an increase in importance of pests and diseases that had been previously controlled by broad-spectrum pesticides. The project team consisted of entomologists, plant pathologists and extension specialists from State Departments of Agriculture in Victoria, New South Wales, Queensland, South Australia, Western Australia and Tasmania, as well as CSIRO, the University of Western Sydney, and Evergreen Marketing International.

Woolly aphid (Eriosoma lanigerum Hausmann) populations were monitored over the 1995/96 and 1996/97 growing seasons, completing a four year study of the pest’s status and management under several IPM programs at Bathurst in the Central Tablelands of NSW. Woolly aphid infestation in two IPM treatments, based on alternative control techniques for codling moth (namely mating disruption and fenoxycarb), were compared with a conventional insecticide (azinphos-methyl) program. No insecticides were applied for woolly aphid control. A minimal fungicide program was applied each season. In the azinphos-methyl treatment the level of woolly aphid infestation increased with each successive season. Biological control of woolly aphid was achieved in the IPM treatments during the 1995/96 season. Several natural enemies of woolly aphid were observed in the IPM treatments, including the parasitoid Aphelinus mali (Haldeman), lacewings, ladybirds and hoverflies. However the principal control agent was identified as the European earwig (Forficula auricularia L.). A pre-bloom application of chlorpyrifos applied for apple dimpling bug (Campylomma liebknechti (Girault)) control in the three seasons prior to this trial and subsequently withdrawn may have prevented biological control from occurring earlier.

Since European earwig is nocturnal it is more likely to come into contact with dry chemical residues than in direct contact at the time of spraying. A modified Petri dish and a Potter tower were used to test the toxicity of chemical residues against the European earwig. The chemicals tested were those commonly used in the management of apple orchards of eastern Australia. Based on the estimated LD_{50} relative to the recommended field rate the chemicals were classed, according to their potential to disrupt the biological control of woolly aphid, as low = LD_{50} > 10x field rate, moderate = LD_{50} 1-10x field rate and high = LD_{50} < 1x field rate. The insecticides: parathion-methyl, alpha-cypermethrin, chlorpyrifos, carbaryl, fenithion and azinphos-methyl were highly toxic; endosulfan, imidacloprid, and tau-fluvalinate were moderately toxic and endosulfan, imidacloprid, and tau-fluvalinate were of low toxicity to European earwigs. The fungicides bupirimate, dithianon, dodine, mancozeb, penconazole and thiram; the chemical thinners benzyladenine and ethephon and the weedicide glyphosate were all of low toxicity to European earwigs.

Laboratory, field cage (fruit, leaves and earwigs caged on the tree) and harvest assessments were used to identify and determine the extent to which European earwig would cause damage to apples. In the laboratory trial, in the absence of alternative food sources, most damage occurred on beside or close to the calyx. In the field cage trial, Jonathan apples incurred damage in December but not in January or February. Red Delicious and Granny Smiths were not damaged. At harvest serious fruit damage by other pests made identifying earwig damage difficult. However Jonathan, a variety that produces fruit in tight clusters and so provides excellent day-time refuges for earwigs, incurred more damage than the other varieties.

We demonstrated that when the broad-spectrum pesticides azinphos-methyl and chlorpyrifos were withdrawn from an apple orchard, European earwigs can migrate into blocks quickly and if in sufficient numbers can provide biological control of woolly aphid within one season. Earwigs are nocturnal feeding at night and returning to the orchard floor or taking refuge in cracks and crevices during the day. Provision of artificial refuges in the canopy, in an attempt to enhance populations within the tree, did not improve the control of woolly aphid.

The pesticide alpha-cypermethrin is highly toxic to weevils and is used by apple growers in Western Australia for their control. However it is also toxic to European earwig and could potentially disrupt the biological control of woolly aphid. Following a single application as a butt spray, alpha-
cypermethrin suppressed the number of European earwigs in apple trees for 14 weeks. This single application did not reduce earwigs numbers to the extent that the biological control of woolly aphid was lost, however a full season program with applications every 14 to 21 days to all trees, as recommended to control weevils, within an orchard is likely to be very disruptive.

A 3-year field spray trial was established to compare the efficacy of "conventional" numbers of fungicide applications against reduced applications and alternative "softer" chemicals against powdery mildew _Podosphaera leucotricha_. All treatments reduced primary and secondary mildew compared to the untreated trees. The trial did not produce the build up of powdery mildew that had been anticipated in the trees treated with fewer or softer treatments and there were no differences in yields between the different treatments. It should be stressed, however, that conditions were not favorable for mildew in the last 2 years of the trial. The mildew infection recorded in the unsprayed trees was 30.3%, 10.0%, and 10.4% in January 19996,1997, and 1998 respectively.

A cultivar susceptibility trial produced some interesting results regarding mildew and apple scab susceptibility of 20 cultivars. New Jonagold and Pink Lady were the most susceptible to mildew. Lady William and Pink Lady were the most susceptible to scab. There was a high level of resistance to leaf scab in Florina-Querina, Redfree and Jonasfree and to powdery mildew in Earlidel. Jonathan, Bonza and Red Elistar showed a useful level of resistance to scab while Red Fuji, High Early and Redfree all showed some resistance to powdery mildew.

The pest status of three weevil species (Garden Weevil _Phlyctinus callosus_, Apple Weevil _Otiorrhynchus cribricollis_, and Fullers Rose Weevil _Asynonychus cervinus_) was investigated. Garden Weevil (GW) damaged up to 50% of fruit in some plots. Apple Weevil (AW) damaged up to 15% of fruit and reduced the weight of individual fruit by 20% as a result of girdling the fruit stalk. The relationship between weevil numbers and amount of damage was not linear and we were not able to determine an economic injury level based on weevil numbers. Where an orchardist experienced considerable damage in one season, control measures would be needed next season. The issue is not whether control measures are needed but what is the correct timing. This can only be determined by monitoring. It was more difficult to determine the effects of Fullers Rose Weevil (FRW) because it didn’t cause direct damage to the fruit. The main problem associated with FRW was blockage of drippers and minisprinklers as a result of eggs being laid in the orifices. These blockages required considerable labour to fix and if undetected caused drought stress to the trees.

No single monitoring system was suitable for all 3 species of weevils because they had different habits and were also distributed differently in the orchard. The use of cardboard trunk bands was the most efficient way of monitoring GW and AW activity although AW managed to somehow avoid some bands. The bands are easy to make and use, and if made from waxed cardboard last the entire season. Limb jarring similar to the technique used for apple dimpling bug was the best method for monitoring FRW. The team also found that FRW larvae were more likely to be found in the inter-row area in both Vic and Qld (unlike citrus and stone fruit where they are found in large numbers amongst the tree roots). GW larvae also appeared more concentrated in the inter-row in Vic but in WA both GW and AW were more concentrated in the tree root zone.

Adult weevils do not lay eggs immediately after emerging. GW and FRW start laying fertile eggs about 3 weeks after emergence. AW takes about 6-8 weeks to start laying fertile eggs. This means that there is a reasonable time in which control measures can be applied before the weevils reproduce.

Since GW had the potential to cause the greatest amount of damage, and was easy to culture in the laboratory, the team set up a feeding trial to determine if any orchard floor plants would inhibit the weevil population. GW larvae appear to have a preference for tap rooted plants. Dandelion supported the highest number of weevil larvae. Capeweed and sow thistle were also important hosts. White clover had significantly lower numbers and appears to not be a favored host. One interesting observation was that ants took considerable numbers of weevil larvae in one of the trials.

Work overseas had indicated birds could give good control of beetles in orchards. Although it was a bit of a long shot we decided to investigate this further with a trial in WA to compare turkeys, guinea fowl, and chickens as controls for weevils. An enclosure similar to that used by low chill stone fruit
growers to protect their fruit from fruit bats was used to contain the birds. Turkeys gave good results but tended to roost in the trees and their weight caused some limb damage. Chickens proved easier to train than guinea fowl, gave reasonable results and were the easiest to handle. Foxes were a problem initially but this was overcome by the use of a low 2-wire electric fence. The local Pest Animals Advisor suggested that since foxes are territorial, if the foxes were removed by trapping or shooting it would be a short time before another fox took over the territory. Having a fox trained not to go near the electric fence kept other foxes out of the area. In areas where hail, fruit bats or fruit feeding birds warrant the use of netting chickens may be a viable aid in control of weevils (and an additional source of income!).
Introduction

The AAPGA, HRDC, State Departments of Agriculture, and CSIRO have invested heavily in R&D to develop Integrated Pest Management (IPM) systems to reduce the fruit industry reliance on broad spectrum pesticides. IPM recognises that biological and cultural control methods will not always give sufficient control for growers to produce large enough quantities of fruit that meets the consumer demand for strict quality (including appearance) standards. IPM uses selective pesticides that have a narrow range of activity to assist natural control agents and prevent pests and diseases from causing economic damage.

One possible side effect of using more selective pesticides is that previously minor pests that had been controlled by the broad-spectrum chemicals may become more important. The AAPGA was concerned that once the use of broad-spectrum pesticides against insects such as codling moth and lightbrown apple moth, and diseases such apple scab and pear scab was reduced, minor problems such as woolly aphid, powdery mildew and weevils may increase in importance. This concern led to HRDC commissioning R&D on integrated control of these pests.

The project team was led by David Williams from Agriculture Victoria, and comprised entomologists, plant pathologists and extension specialists from State Departments of Agriculture in Vic, NSW, SA, Qld, WA, and Tas as well as CSIRO, the University of Western Sydney, and Evergreen Marketing International. HRDC funding was provided from apple and pear levies and a voluntary contribution from Evergreen Marketing International. The project title took the acronym WWAPM (pronounced wop'em) which signified integrated management of Weevils, Woolly Aphid, and Powdery Mildew.

To capitalise on R&D that had already been completed the team decided to use some sites from previous projects where pesticide use had been reduced over a number of years and the changes in pest pressure were documented. The experimental orchard at Bathurst had been used for the HRDC funded project on integrated control of codling moth. It contained plots that had no insecticide applications over 3 years, which could be compared to plots that had been treated with either selective or broad-spectrum chemicals over the same period. Detailed observations of woolly aphid populations had been made at the site during the codling moth project.

Weevil field trial sites were established in 3 orchards in Qld and 7 in WA. In Victoria a range of vineyard and apple orchards in the Yarra Valley and Mornington Peninsula were used to study the distribution of weevil larvae in the orchard floor. This was done to take advantage of the different management techniques and orchard floor vegetation.

A commercial block of Jonathan apples was used to investigate if powdery mildew would become more severe as fungicide use was reduced. Jonathan was selected because of their known susceptibility to powdery mildew. At the same time a block of 20 apple cultivars was established at Knoxfield to monitor the relative susceptibility to powdery mildew.

This report presents the results of 3 years research conducted by the WWAPM team and reviews the world literature on Garden Weevil, Fullers Rose Weevil, Apple Weevil, Woolly Aphid and Powdery Mildew.
Literature Reviews

1. Weevils
The three species of weevil investigated in this project are Garden Weevil *Phylletinus callosus*, Apple Weevil *Otiorrhynchus cribicollis*, and Fullers Rose Weevil *Asynonychus cervinus*. Their known distribution around the world is shown in figure 1.

![Fig. 1. The current world distribution of the weevils (a) garden weevil, (b) apple weevil and (c) Fuller’s rose weevil and their origin.](image)

Disinfestation
Quarantine aspects, particularly a range of disinfestation treatments for Fullers rose weevil eggs on fruit (particularly citrus) have dominated the literature in recent years. A wide range of methods have
been evaluated. These included fumigation (Soderstrom et al 1991), gamma irradiation (Coats et al 1990, Johnson et al 1990), insecticide cover sprays such as azinphos-methyl, cryolite, carbaryl and methidathion in citrus orchards (Bullock 1988), trunk banding or trunk insecticide barrier plus skirt pruning (Morse et al 1988, Magarey et al 1992, Magarey et al 1993). The insect growth regulator fenoxycarb was tested against the eggs (Coats 1990). Various strains of fungal pathogens have been tested against the eggs (Coats 1990, larval and adults (McCoy et al 1989, Edwards 1994).

Edwards (1994) reviewed the literature concerning the use of entomopathogenic fungi and nematodes for the control of FRW, and she conducted trials in citrus orchards of Sunraysia (HRDC project CT115). None of these biological control methods reduced the weevil populations in the citrus orchards to a satisfactory level (Edwards 1994).

Biology

FRW is a short lived insect capable of surviving a wide range of temperatures and conditions. It is a prolific egg layer capable of laying up to 28 batches of eggs and over 1000 eggs in total (Masaki 1987, Masaki et al 1996). Day degree models have been developed for the eggs, larvae, pupae, and adult preoviposition. The development threshold temperatures and day degrees required for development of various stages have been calculated (Masaki 1996) and a day degree model was developed to predict egg hatch (Lakin 1989). These are listed in Table 1.

Table 1: Developmental threshold temperatures and day-degree requirements for FRW.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Eggs</th>
<th>Larvae</th>
<th>Pupae</th>
<th>Pre-oviposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developmental threshold °C</td>
<td>9.0</td>
<td>14.5</td>
<td>9.6</td>
<td>8.4</td>
</tr>
<tr>
<td>Day degrees required for development</td>
<td>275</td>
<td>1406</td>
<td>206</td>
<td>349</td>
</tr>
</tbody>
</table>

The distribution of the larvae in the orchard, as indicated by adult emergence traps, was studied by Kovach (1986). He showed that in a peach orchard 70 percent of the beetles emerged at the base of the tree, 28 percent at the drip line, and only one individual emerged in the middle of the sod inter-row. This is similar to our findings in apples where the larval population was concentrated near fine apple roots along the drip line.

Madge et al (1992) found the pattern of adult emergence to be temperature and rainfall dependent and reported a rapid increase in numbers of adults following rainfall in late December and early January. Our results showed a large emergence during December with numbers increasing in January. Madge (1992) reported that peak populations occurred from March to May in citrus at Mildura. The differences in peak weevil activity shown by our studies, where high numbers were recorded in late December-February with numbers declining by late March could be explained by the different climatic conditions in apple growing regions. Apple and peach trees also senesce in autumn whereas citrus are evergreen with food for adult FRW available year round.

Integrated Management

Fumigation has been the only satisfactory treatment to meet quarantine requirements for some commodities (Soderstrom 1991, Jessup 1993). However, since methyl bromide is being phased out and fumigants can be detrimental to fruit quality, there have been several studies of alternative treatments.

The use of heat treatment for fruit disinestation has been widely investigated. Studies by Jessup (1993) showed that hot water treatment of Valencia oranges at 46 °C for 75 minutes completely prevented egg hatch but severely damaged the fruit. Soderstrom et al (1993) modeled the temperature and exposure times necessary to kill eggs of FRW. There were no survivors from eggs infesting the calyces of lemons when immersed for eight minutes at 52 °C. FRW can lay egg masses in the calyces of apples, but this problem appears to be more prevalent in citrus where the fruit is the preferred site for oviposition (Coats 1989).

It is difficult to reduce weevil populations to the extent that oviposition into the calyces of fruit can be totally eliminated for quarantine purposes. A range of options is available so that quarantine
requirements can be met (Morse et al. 1988). Cover sprays with organophosphates, carbamates, and synthetic pyrethroids have been used to reduce weevil populations but there is always a danger that these may result in unacceptable residues in fruit (Bullock 1988, Prestige 1989). James (1991) showed that skirt pruning and trunk banding (polybutenes) could be useful as a management strategy based on non-chemical control options. Insecticide trunk banding with the synthetic pyrethroid lamda-cyhalothrin has proven to be highly effective in reducing the numbers of weevils reaching the canopy, and more importantly in reducing oviposition into citrus calyces (Magarey et al. 1992, Magarey et al. 1993, Sale 1997, Phillips et al. 1987). This chemical is not registered on apples for control of weevils in Australia and it is quite expensive to use. With any banding treatment there is a risk of weevils bridging the band by climbing up on prunings or weeds, or by crawling along dripper lines or trellis wires (Sale 1997). The 1997-98 edition of the New South Wales Orchard Plant Protection Guide recommended prevention of weevil access to citrus trees by skirt pruning, removing tall weeds and the use of polybutene bands. A carbaryl spray was recommended (permit required) when leaf damage became evident (Thwaite et al. 1997).

Defoliation by FRW is usually minor in apple orchards. With the change to softer IPM options for control of key pests in pomefruit and stonefruit, the number of FRW have increased (Bolitho 1993, Williams pers. com). The current research supports this. Chemicals are not registered for the control of FRW in apples in eastern Australia. If broad-spectrum cover sprays such as azinphos-methyl or chlorpyrifos are used regularly for control of other pests such as codling moth and light brown apple moth, the weevil population will usually be suppressed. Results from the current project, including grower surveys, support this. Growers will accept sub-economic damage to foliage, but their perception of what is acceptable will vary. The effects of larval damage to roots has not been thoroughly researched, although it is presumed to be minor (Hely et al. 1982).

2. Woolly Aphid

Woolly aphid (Eriosoma lanigerum (Hausmann)) (Hemiptera: Aphididae) is an important pest of apple Malus domestica (Borkh.) that has spread to apple growing regions throughout the world (Eastop 1966). In Australia woolly aphid occurs almost exclusively as a pest of apples, but can occasionally be found infesting Hawthorn, pears and the exposed roots of Liquidamber styraciflua (Hely et al. 1982).

Biology

The life cycle and ecology of this cosmopolitan pest species have been studied extensively and its occurrence under Australia conditions described (Nicholls 1919, 1932, Lloyd 1961, Hely et al. 1982, Thwaite and Bower 1983, 1986, Asante and Danthanarayana 1992, 1993, Fitzgibbon 1993, Asante 1994). Woolly aphid feed by piercing the bark and sucking the sap and once feeding has commenced remain sessile unless disturbed by a change in environmental conditions (Asante 1994). Woolly aphid feeding causes hypertrophy and gall formation, the smooth thinly barked galls frequently splitting open to provide further feeding sites (Weber and Brown 1988) and leaving the tree open to the invasion of fungi that cause perennial canker. Continued heavy infestation of woolly aphid causes the tree to become gnarled and lumpy and greatly reduces productive wood. Heavy infestations can reduce tree growth and vitality, completely destroy buds, reduce cropping and lower fruit quality. Severe root swellings can stunt tree growth, particularly on young trees, although this rarely affects the vigour of established trees (Thwaite and Bower 1986). Woolly aphid can cause some fruit damage when occupying the stem cavity. Feeding woolly aphid exude honey dew that supports a fungal growth of the Capnoidales group known as sooty mould. If excessive, this growth can reduce the light intercepted by leaves, suppressing plant growth and causing some fruit fall. Fruit soiled by sooty mould can become disfigured and the colour of red varieties severely affected (Bertus 1986, Hely et al. 1982). Brown et al. (1995) estimated that approximately 2.4 kg of fruit (13 fruit) per tree per season is lost as a direct result of woolly aphid root infestations.

Woolly aphid populations over-winter as adult females on both the aerial and subterranean parts of the tree. Adult females over-wintering below ground continue developing and reproducing at a slow rate while those over-wintering aerially remain for the most part dormant in cooler regions (Thwaite and Bower 1983). Nevertheless those over-wintering aerially are reported to be the major source of reinestation in the following spring (Hely et al. 1982). In late spring to early summer, young nymphs produced by over-wintering females move up from below ground to infest vulnerable and thinly
barked areas. Colonies frequently develop on those parts of the tree that have incurred physical damage. Common sites of colonisation include limbs damaged accidentally by farm machinery or split through heavy cropping. Pruning cuts are also vulnerable to infestation. As the season progresses new colonies develop and show a preference for the new season's young vigorous growth. The woolly aphid's life span is approximately one month with each female capable of producing up to 100 active young at a rate of between 2 and 20 nymphs per day (Thwaite and Bower 1983, Mueller et al. 1992). In summer, depending on temperature, most of these active young pass through four instars, reaching adulthood in 8 to 10 days. As a result, several generations are produced each growing season.

Natural enemies of woolly aphid

Woolly aphid has several natural enemies in Australia (Table 2) and while the native coccinellid Harmonia (Leis) conformis (Boisduval) has been described as the most effective of these (Asante 1995), none have previously matched the reported effectiveness of the introduced parasitoid Aphelinus mali (Haldeman) (Wilson 1960). Aphelinus mali, a minute parasitic wasp, was introduced into Australia, via New Zealand, in 1923 (Gurney 1926, Wilson 1960). The life history A. mali has been studied extensively (Mueller et al. 1992). Over-wintering as pupae in the dead parasitised aphid's body, the wasps begin to emerge in spring as the woolly aphid colonies become active. Some adults may survive the winter months, particularly in warmer areas or mild winters (Gurney 1926). The female wasp, capable of laying between 50 to 140 eggs, deposits one egg per host at a rate of 3 or 4 per day (Gurney 1926). The life cycle from point of egg laying through to adult eclosion is between 19 and 43 (mean of 24) days depending on temperature, and consequently six or more generations may occur in a summer (Gurney 1926, Dumbleton and Jeffreys 1938, Mueller et al. 1992). Studies have shown that A. mali development lags behind that of woolly aphid especially at low temperatures. Woolly aphid has a lower development threshold of 5°C requiring about 270 degree days for full development (birth to adult) compared with A. mali's lower development threshold of 8.5°C, requiring about 250 degree days. Aphelinus mali's higher temperature requirement ensures that woolly aphid colonies have become established and are available as hosts prior to its own spring emergence (Asante and Danthanarayana 1992). Normally a dark reddish purple and covered in 'wool' when feeding, parasitised woolly aphids become black as the A. mali develops. When fully developed the parasite exits the cadaver, leaving a small circular hole in the woolly aphid's abdominal tergum.

Following its introduction A. mali is recorded, in combination with other natural enemies and resistant rootstock, as successfully controlling woolly aphid (Gurney 1926, Wilson 1960). However, the persistent use of broad-spectrum pesticides significantly reduced the effectiveness of this biological control and specific targeting of woolly aphid with pesticides became necessary. For many years oil sprays, such as those used to control over-wintering phytophagous mites, were not thought to kill over-wintering A. mali (Dumbleton and Jeffreys 1938). However recent reports to the contrary indicate further research on this subject is required (Readshaw 1995).

The European earwig (Forficula auricularia L.) (Dermaptera: Forficulidae) is known to feed on woolly aphid (McLeod and Chant, 1952) and is capable of consuming, under laboratory conditions, up to 106 woolly aphids in a 24 hour period (Asante 1995). The European earwig is a polyphagous insect feeding on algae, mosses, fungi, arthropods and plant material including fruit (Phillips 1981), however it has not been recorded as a serious pest of apples in Australia. Field experiments in the Netherlands to assess the efficacy of earwigs against woolly aphid (Stap et al. 1987, and Mueller et al. 1988) all concluded that earwigs are an important biological control agent of woolly aphid with potential in integrated pest management (IPM) or integrated fruit production (IFP) programs. However they did not record the orchard conditions or pesticide regimes under which the trials were conducted.

Earwigs are also known to feed on codling moth eggs (A. H. Nicholas unpublished data) and occasionally leaves, particularly new growth, infested with powdery mildew (Podosphaera leucotricha Ellis and Everhart) (Carroll et al. 1985).

Other natural enemies, such as lacewings, ladybirds and hoverflies, known to be present at the Bathurst trial site (Nicholas et al. 1999), were not considered good candidates for effective control of woolly aphid. Lacewings were discounted because they only occurred in high numbers early in the season, ladybirds and hoverflies because their numbers were very low throughout the season.
IPM programs

The broad-spectrum organophosphate insecticide azinphos-methyl used to control codling moth (*Cydia pomonella* L.) is highly toxic to many of the woolly aphid’s natural enemies, including ladybirds, lacewings, earwigs, (Nicholas et al. 1999) and adult *A. mali* (Nicholas unpublished data). Through its persistent use the potential for biological control of woolly aphid is lost. However in the absence of azinphos-methyl and other broad spectrum insecticides for codling moth control, for example where they have been replaced by less toxic chemicals, such as Ryania (Lloyd et al. 1970) and fenoxycarb (Readshaw and Cambourne 1991) woolly aphid infestation is reported to decline. Both reports attribute the reductions to increasing numbers of natural enemies. Earwigs were identified as playing an important role in controlling woolly aphid in an IPM program where the insect growth regulator diflubenzuron was used to manage codling moth, leafrollers and the apple blossom weevil (*Anthonomus pomorum* L.) (Ravensberg 1981). In plots treated with diflubenzuron earwigs were absent and the infestation of woolly aphid high, whereas in untreated plots where earwigs were present, woolly aphid infestation was low.

In New Zealand an experimental integrated fruit production (IFP) program, based on the insect growth regulator tebufenozide (Mimic®) for leafroller and codling moth control, allowed *A. mali* populations to increase and provide effective biological control of woolly aphid over a two year period (Shaw and Walker 1996). However in cooler climates such as those occurring on the Northern Tablelands of New South Wales, *A. mali* was considered incapable of providing effective control of woolly aphid due to its higher temperature development threshold (Asante and Danthanarayana 1993).

As part of the Horticultural Research and Development Corporation codling moth IPM program (Project AP 201), three alternative codling moth control strategies; mating disruption (MD), MD plus early season applications of fenoxycarb (an insect growth regulator) (MD+F) and MD plus early season applications of azinphos-methyl (MD+A) were trialed at Bathurst on the Central Tablelands of New South Wales. The MD and MD+F treatments were IPM strategies capable of replacing the conventional azinphos-methyl spray program for codling moth control (Vickers et al. 1998, Nicholas et al. 1999). As part of this program, during the 1993/94 and 1994/95 seasons, the level of woolly aphid infestation was monitored.

In the absence of azinphos-methyl, i.e. in the MD and MD+F treatments, woolly aphid infestation was reduced. This finding supported those of Lloyd et al. (1970) and Readshaw and Cambourne (1991), when again the reduction in woolly aphid infestation was attributed to increased numbers of *A. mali*, lacewings ladybirds and earwigs. However, in the findings of Nicholas et al. (1999), none of these natural enemies were identified as being directly responsible for the lower levels of woolly aphid observed. Parasitism of woolly aphid by *A. mali* reached 35% during this trial but this did not provide effective or sufficient to control for commercial growers. This suggested that either the Bathurst climate was too cool, as reported by Asante and Danthanarayana (1993), or that pesticides used to control other pests adversely affected the *A. mali* population.

### Table 2. Natural enemies of woolly aphid (*Eriosoma lanigerum* Hausm) in Australian apple orchards.

<table>
<thead>
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<th>Order</th>
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<th>Species</th>
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<td>Diptera: Syrphidae</td>
<td>Macrosyphus confrator (Weid.)</td>
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<td></td>
<td>Cryptoleaemus montrouzieri (Mulsant)</td>
<td>Melangyna viridiceps (Macq.)</td>
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<td></td>
<td>Dionus notescens (Blackburn)</td>
<td>Syrphus pusillus Frog.</td>
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<td></td>
<td>Harmonia conformis (Boisdulval)</td>
<td>Neuroptera: Hemerobiidae</td>
<td>Micromus tasmaniae (Walker)</td>
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<tr>
<td></td>
<td>Parapriaps Australasiae (Boisdulval)</td>
<td>Dermaptera: Forficulidae</td>
<td>Forficula auricularia L.</td>
</tr>
<tr>
<td></td>
<td>Rhyzobius spp</td>
<td>Fungal pathogen</td>
<td>Verticillum lecanii (Zimm.) Viégas</td>
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</table>
3. Powdery Mildew

Powdery mildew, caused by the fungal pathogen *Podosphaera leucotricha*, occurs wherever apples are grown (Agrios 1997). The disease occurs throughout all Australian pome fruit growing areas. Economic losses from powdery mildew vary with climatic conditions (Jeger & Butt 1983), cultivar susceptibility and orchard or nursery management practice (Jones & Aldwinkle 1990). The disease is common and, while usually less important than apple scab (caused by *Venturia inaequalis*), is capable of reducing yields dramatically in infected trees. Reports on yield reductions vary, with Agrios (1997) indicating reductions from 20-40%, while Ruess and Blatter (1990) reported yield reductions up to 700% when unsprayed trees were compared with trees treated with an EBI fungicide. The disease has also been reported on pears, but in Australia such infection is rarely, if ever, seen (Washington 1994).

Lifecycle
The powdery mildew fungus overwinters on apple as mycelium in dormant leaf or fruit buds infected during the previous growing season. Conidia produced on overwintering mycelium cause primary infections on young leaves, shoots and fruit that develop from these overwintered infected buds. Infections on these structures provide the inoculum for secondary infections. Leaves are susceptible for only a few days after they emerge. As infected buds usually emerge after non-infected buds there is susceptible tissue available for the released conidia. Conidia germinate readily over the range 10-26°C (optimum at 20-22°C) and at relative humidities as low as 70%. No germination takes place in free water or at temperatures over 30°C (Jones & Aldwinkle 1990). Infections only take a few days to become visible. Thus, the disease flourishes under different conditions to apple scab, which requires leaf wetness for infection and takes over a week to develop into visible infection.

Infection of laterals, shoots and fruit buds generally occurs within a month of formation. Terminal shoots are the main sites of over-wintering inoculum. Infections on leaves appear as whitish mycelium most commonly on the underside of the leaf. Severely infected leaves tend to fold along the longitudinal axis, desiccate, become brittle and may abscise. Infected terminal shoots appear silver-grey and often the terminal bud is shrivelled. Flower buds infected with primary mildew often develop into stunted fruit. Fruit infected during the bloom often exhibit a characteristic network of fine russetting across the fruit surface.
Control
Mildew may be controlled by a combination of the following practices. 1). Pruning out infected terminal buds in winter and spring is important as these buds can be an abundant source of spores for infecting new leaves and buds. 2). Modification of the environment by maintaining good air movement throughout the tree canopy and the orchard to reduce the relative humidity on the leaf surface is important as it will reduce the germination of spores on leaf surfaces. Pruning, tree training, and management of windbreaks in the orchard are all important in reducing humidity and therefore mildew. 3). Spraying fungicides during spring and summer can protect new buds from infection. Sprays from the pink bud stage through to the end of petal fall are most important, but on highly susceptible cultivars further sprays may be required until the end of lateral extension to protect fruit, leaf and terminal buds. Cultivars vary considerably in their susceptibility to mildew, and selection of more resistant cultivars is important in planning new plantings that will require less fungicide spraying.

Fungicides
The control of powdery mildew in commercial orchards currently depends mainly on the use of chemical fungicides. Control of mildew was achieved in the early part of the century by way of elemental sulphur (Groves et al. 1958), in combination with detailed pruning to remove infected buds and shoots. It is important in orchard management of powdery mildew to consider the need for simultaneous control of apple scab (*Venturia inaequalis*), a fungus which has different environmental requirements. Ideally the control of this pathogen should occur without duplication of spray regimes. After the introduction of organic fungicides, orchard management of the two pathogens was obtained by way of the non-systemic, substituted dinitrophenol fungicides dinocap and binapacryl (Locke and Andrews 1986; Hickey and Yoder 1981). Mildew control was appreciably improved in the 1970’s with the introduction of benomyl. The unrestricted use of benomyl within commercial orchards quickly led to resistant isolates of the apple scab fungus (Dekker 1976). This reduced the usefulness of benomyl and related compounds for powdery mildew control (Jones 1981) as growers found the new ergosterol biosynthesis inhibiting (EBI) fungicides were effective against both scab and mildew (Siegel 1981; Szolnoki 1981; Hickey and Yoder 1981; Yoder 1982). Contemporary community concern in relation to pesticides in the environment and considerable evidence for EBI resistance in apple scab (Koller & Scheinpflug 1987; Hildebrand et al. 1988), has led to increased efforts for alternative control methods for both diseases.

Non- Fungicidal Agents
Use of high pH material (Calcium Hydroxide Ca(OH)₂) to prevent germination of fungal spores on susceptible host tissue has proved effective for apple scab but has limited effect on powdery mildew incidence or severity (Wong et al. 1993; Beresford et al. 1995; Beresford et al. 1996). Baking soda (Sodium Bicarbonate NaHCO₃) has been reported to control powdery mildew on varieties of varying susceptibility (Horst et al. 1992). Trials in New Zealand using baking soda demonstrated limited control of apple scab and only slight control for *Podosphaera leucotricha* in commercial apple orchards (Beresford et al. 1996). The addition of mineral oil to baking soda increased the rate of control for mildew but not apple scab. Cupric hydroxide (Cu(OH)₂) has been shown to be effective against powdery mildew but results in severe russetting of fruit. Sulphur results in reduced russetting of fruit but has less efficacy against mildew than Cupric hydroxide. (Beresford 1995).

Surfactants and oils
Surfactants and film forming polymers have been reported to control powdery mildew to varying degrees and usually with some associated phytotoxicity (Hislop et al. 1978; Elad et al. 1989; Northover and Schneider 1993). Application of surfactants during the dormant season eradicated over-wintering mycelium from infected buds (Frick and Burchill. 1972; Hislop and Clifford. 1976; Burchill et al. 1979). Difficulties have been experienced with these dormant sprays mainly in relation to tree damage. Damage has included bud death, fruit russet and reductions in yield and fruit set (Hislop and Clifford. 1976; Burchill et al. 1979). The dormant season use of surfactants alone and combined with mildew fungicides was evaluated in Victoria (Washington 1987) but these treatments have not been commercialised due partly to the cost of surfactant and partly due to the fact that some of these treatments were found to be phytotoxic. A further difficulty associated with relying on only the dormant spray application is the opportunity for cross infection from adjacent untreated areas where over-wintering inoculum is high. Reduced spring/summer sprays after dormant treatment can result in considerable secondary infections from transported spores (Burchill et al. 1979). Investigations
conducted over the past two decades have demonstrated the capacity of both plant and mineral oils for mildew control. Mineral oils have been reported to be fungicidal against various powdery mildews (Calpouzos 1966) but activity appears most pronounced when used as an adjuvant as opposed to discrete application (Beresford et al. 1996). The mode of action of the oils against mildew is not well understood and may involve protective, suppressive or curative effects. Use of mineral or plant oils against mildew appears to be relatively unrelated to chemical structure. Plant oils including sunflower, olive, canola, corn, soybean and grapeseed oils were effective in providing over 99% control of powdery mildew when applied to apple foliage 1 day before or one day after inoculation (Northover and Schneider 1993). Both Mineral and plant oils have demonstrated limited effect against the apple scab fungus.

**Disease modeling**

Powdery mildew epidemiology has been demonstrated to be one of a relatively constant inoculum development making the pathogen suitable for mathematical modeling. The major determinants of the levels of daily mildew infections are the amounts of inoculum (Butt 1978) and availability of susceptible host tissue. Decision based disease management (Butt & Jeger 1982), requires the monitoring of both the crop and its physical environment. Trapping of airborne conidia has been used to estimate orchard disease levels (Jeger 1984), based on the relationship between cumulative number of trapped spores and mildew incidence. Similarly, disease severity within an orchard is capable of being predicted on the basis of collected incidence data with consistency exhibited within climatically similar areas and with specific cultivars (Seem et al. 1980, 1981). A strong mathematical relationship has been demonstrated between marketable yield and mid season secondary mildew incidence on foliage (Locke & Andrews 1986). Models have been derived which estimate the concentration of fungicide necessary to manage secondary mildew infections at a desired level, given the estimated amount of primary mildew (Lalancette & Hickey 1986). Adem®, an integrated disease warning system developed in the UK, is now commercially available for apple growers. This software incorporates a model for predicting apple powdery mildew (Butt and Xu 1996).

**Conclusion**

Currently, fungicides provide economic control of powdery mildew in apples. The development of apple scab resistance for the current generation of fungicides will necessitate new control strategies for this disease and impact upon orchard mildew control. Environmental issues and consumer perceptions of chemical residues may result in lowered community tolerance for the application of chemical pesticides in apple orchards. These considerations compel the industry to develop alternative methods for managing powdery mildew. Previous research undertaken over the last 2 decades indicates that there is some immediate opportunity in the areas of alternative and innocuous chemicals and disease modeling forecast. Longer term investigations may support biological control programs for the disease.
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5. Research trials
The project team had the following general objectives:

- To determine the interaction between reduction in use of pesticides and each pest or disease.
- To identify and evaluate potential biological control agents
- To develop monitoring methods and economic thresholds for applying control measures
- To develop cost effective integrated control methods.

The project was divided into 3 sub-projects for ease of management of the research trials required to solve aspects of the problem related to each pest or disease. Each sub-project was further divided into a number of smaller trials to answer particular questions before the team was able to provide an integrated management system. These trials are reported below.

5.1. Will powdery mildew increase if fungicide spraying is reduced?

Introduction
Powdery mildew caused by *Podosphaera leucotricha* is an important disease of apples (and less commonly pears) which occurs in all Australian pome fruit growing regions. The disease affects some varieties such as Jonathan, Granny Smith, Lady William and Pink Lady more than others, and it can cause loss through stunting of trees, reduced cropping and downgrading of russetted fruit. Overseas, apple powdery mildew has been shown to reduce tree growth and fruit yields and quality (Ruess and Blatter, 1990, Locke and Andrews, 1986).

Powdery mildew is normally controlled through the application of suitable fungicides during spring and summer. Many of the current scab fungicides (EBIs such as fenarimol, penconazole and flusilazole) are also effective against powdery mildew and consequently these two diseases can be controlled with the one chemical. There is currently an emphasis on reducing fungicide inputs in fruit production. In Australia there is the possibility of replacement of some scab fungicides with alternative materials such as calcium hydroxide (Wong, pers. comm., Washington, 1998). This material apparently has little or no activity against mildew, and consequently specific control measures may be required for mildew control on apples. In addition, the introduction of new varieties such as Lady William, Pink Lady, Fuji and Gala, which appear to be more susceptible to mildew than varieties such as Red Delicious, may require a greater emphasis on mildew control measures. This work aimed to identify the relation between a reduction in fungicide use and the level of mildew.

Materials and Methods
To determine the interaction between disease and fungicide reduction a field trial was established in a commercial block of Jonathan apples at Strathewen in southern Victoria. Three different schedules of a commercial mildew fungicide (penconazole or Topas®, an EBI fungicide) were applied from pink bud through to cover stage of tree development over three seasons. Disease in these trees was compared with that in trees treated with six sprays of wettable sulphur, or another simple chemical compound (hydrated lime) or in unsprayed trees. Five single tree replicates of each of the six treatments were established in two rows of 16 year old Jonathan apple trees. The only other fungicides applied to the trial area in the first year were two applications by the grower. The first of these was Topas® combined with a protectant fungicide at the 2.5cm green stage, and the second was a protectant scab fungicide in summer. Mildew levels were monitored for three years over winter and during the growing season, and other diseases and insect pests were also recorded when present. Crop yields were determined at harvest each year to quantify the effects of reduced fungicide programs on mildew levels and crop yields.

Results and Discussion
1995/96 Results at the end of the first year indicate that two, four or six sprays of Topas® during the pink bud, bloom and petal fall stages gave significant control of primary and secondary mildew (Table 3). The lower number of sprays were generally less effective. Six sprays of Kumulus® (wettable
sulphur) or hydrated lime also gave some control although chemical hydrated lime was less effective than the sulphur. Topas® sprays showed a strong eradicative effect on primary mildew. None of the treatments had a significant effect on total fruit yield, fruit size or incidence of russet on fruit at harvest. These results are consistent with the effect of powdery mildew, that is, damage to the tree and crop is cumulative and likely to be more obvious in the season following disease buildup.

Scab infection on fruit at harvest showed that all treatments gave significant reduction of scab. Calcium hydroxide was less effective than other treatments. It is interesting to note that on this cultivar, which is known to be relatively scab resistant, two sprays of Topas® gave control of fruit scab equivalent to that on trees treated with six sprays of Topas®. However, leaf scab levels were higher in the trees treated with two sprays of Topas®, indicating that scab infection pressure is likely to build up under such a program.

1996/97 The effect of spray treatments applied to trees in the previous seasons on overwintering mildew was clear. Winter assessment of terminal shoots (a major source of primary mildew infections in the following growing season) showed mildew levels of about 22% in trees which were unsprayed in the previous season, about 11% in trees previously sprayed with Limil, while levels in trees sprayed with Topas or sulphur were around 3-6% (Table 3).

Mildew levels in 1996/97 were lower than occurred 1995/96, indicating unfavourable conditions for mildew development had occurred. For example, secondary mildew assessed in January 1996 showed 30% leaf infection on unsprayed trees, while at the same time in 1997 only 10% of leaves were infected. All spray treatments reduced mildew levels when compared with the unsprayed control trees. The more effective mildew treatments (six or four sprays of Topas, or six sprays of sulphur) prevented an increase of secondary leaf infection. By contrast, trees treated with two sprays of Topas, six of Limil or no treatment all showed increases in leaf mildew during the late spring and summer.

Fruit russet, which can be an indicator of mildew infection, was rated at harvest. Sulphur treated fruit showed the highest levels of russet in 1997, significantly more than any of the Topas treated fruit (Table 4) but there was no relationship between fruit russet and levels of leaf mildew. Thus russet was unlikely to have been caused by mildew infection, and may have been associated with effects of spray treatments and/or weather conditions on fruit finish.

Crop yields were about three times higher than those from last season indicating that trees were in a biennial bearing pattern, and that some significant factor has affected fruit set and/or fruit size. There was no significant yield difference between treatments in either year, with average crop weight per tree varying from 49 to 76 kg in 1997, and from 21 to 32 kg in 1996 (Table 4).

Scab infection levels on fruit were much lower in 1996/97 than in 1995/96 (Table 5). In year two, only six or four treatments of Topas or six treatments of sulphur reduced fruit scab levels when compared with the untreated control.

1997/98 Primary mildew levels were lower than those in the previous year. All treatments reduced levels compared to untreated trees. Similarly, secondary mildew levels were reduced by all treatments, but there were no differences between treatments. There was a tendency for calcium hydroxide treated trees to have more mildew than the other treatments.

Crop yields were similar to the previous year, and there was no significant difference between treatments. There was a consistent trend for lower yields with more sprays of the EBI fungicide in each of the three years, but differences were not significant. Hydrated lime treated fruit had lower levels of russet than the untreated fruit and most other treatments. This contrasted with results from 1996-97, although in 1995-96 there was some indication that hydrated lime treated fruit was less russetted than untreated fruit.

No scab was observed on any tree in 1997-98.
Summary
These results show that from 2-6 sprays of penconazole during spring (from pink bud to first cover) can significantly reduce powdery mildew on leaves and in buds when compared with levels in unsprayed trees. Six sprays of wettable sulphur gave a similar result but tended to be less effective than penconazole. Calcium hydroxide reduced mildew significantly in some assessments but was clearly less effective than penconazole.

This trial failed to produce the build up of powdery mildew that was anticipated in the trees treated with fewer or softer treatments for mildew control. As a consequence, there were no differences between yields from trees treated with different spray schedules, which would have been expected if mildew developed to a high level in this trial. It demonstrates some of the difficulties of doing trials that are dependent on seasonal conditions.

No clear treatment effects were noted for fruit russet, insect infestation or fruit yields, although there was a non-significant trend to increasing yields in treatments with fewer penconazole sprays.

All treatments reduced leaf and fruit scab when compared with the control trees. Six or four sprays of penconazole gave better control than two, and were generally better than six sprays of sulphur or calcium hydroxide, when scab pressure was high. In a season of low scab pressure most treatments were better than the unsprayed control, but not different from each other.
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<td>5.2</td>
<td>2.5</td>
<td>1.0</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>6. calcium hydroxide x6, 2kg product/100L</td>
<td>14.3</td>
<td>13.9</td>
<td>9.2</td>
<td>11.0</td>
<td>11.0</td>
<td>5.3</td>
<td>1.1</td>
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<tr>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
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Table 4. Effect of field sprays on fruit russet, crop yield and insect damage on cultivar Jonathan, 1995-98, Strathewen, Victoria.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fruit russet (%)</th>
<th>Crop yield (kg/tree)</th>
<th>Insect damage (% woolly aphid)</th>
<th>Fruit russet (%)</th>
<th>Crop yield (kg/tree)</th>
<th>Insect damage (% codling moth)</th>
<th>Fruit russet (%)</th>
<th>Crop yield (kg/tree)</th>
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<td>1. control</td>
<td>66.3</td>
<td>21.3</td>
<td>6.4</td>
<td>20.4</td>
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<tr>
<td>2. penconazole x6, 25ml product/100L</td>
<td>64.0</td>
<td>21.1</td>
<td>7.0</td>
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<td>1.3</td>
<td>5.2</td>
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<td>3. penconazole x4, 25ml product/100L</td>
<td>69.6</td>
<td>24.5</td>
<td>9.1</td>
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<td>66.6</td>
<td>0.5</td>
<td>6.2</td>
<td>63.9</td>
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<td>4. penconazole x2, 25ml product/100L</td>
<td>61.5</td>
<td>25.0</td>
<td>5.2</td>
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<td>75.7</td>
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<tr>
<td>5. sulphur x6, 200g product/100L</td>
<td>60.4</td>
<td>31.6</td>
<td>2.1</td>
<td>26.3</td>
<td>49.1</td>
<td>0.2</td>
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<tr>
<td>6. calcium hydroxide x6, 2kg product/100L</td>
<td>56.5</td>
<td>24.2</td>
<td>11.9</td>
<td>20.3</td>
<td>66.2</td>
<td>0.5</td>
<td>2.2</td>
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<tr>
<td>LSD P=0.05</td>
<td>(11.0)</td>
<td>(14.9)</td>
<td>(8.5)</td>
<td>7.7</td>
<td>(31.7)</td>
<td>1.1</td>
<td>3.2</td>
<td>(26.1)</td>
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<td>0.682</td>
<td>0.031</td>
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<tr>
<td></td>
<td>% leaf scab</td>
<td>% fruit scab</td>
<td>% fruit scab</td>
<td>% fruit scab</td>
<td>% fruit scab</td>
<td>% fruit scab</td>
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<td>35.0</td>
<td>1.3</td>
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<tr>
<td>2. penconazole x6, 25ml</td>
<td>5.1</td>
<td>4.7</td>
<td>1.3</td>
<td>0.2</td>
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<td>product/100L</td>
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<td></td>
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<tr>
<td>3. penconazole x4, 25ml</td>
<td>6.2</td>
<td>8.3</td>
<td>4.2</td>
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<tr>
<td>product/100L</td>
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<td></td>
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<tr>
<td>4. penconazole x2, 25ml</td>
<td>14.7</td>
<td>14.2</td>
<td>3.4</td>
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<td>product/100L</td>
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<tr>
<td>5. sulphur x6, 200g</td>
<td>12.7</td>
<td>9.0</td>
<td>3.7</td>
<td>0.3</td>
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<td>product/100L</td>
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<tr>
<td>6. calcium hydroxide x6, 2kg</td>
<td>17.9</td>
<td>21.7</td>
<td>12.3</td>
<td>0.5</td>
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<tr>
<td>product/100L</td>
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<tr>
<td>LSD P=0.05</td>
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<td>6.7</td>
<td>11.2</td>
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<tr>
<td>F prob</td>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.042</td>
<td></td>
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5.2. Which cultivars are susceptible to powdery mildew and how do you monitor the disease?

Introduction
Integrated Pest and Disease Management generally relies on affordable monitoring techniques which allow pest and disease populations to be assessed with a reasonable degree of accuracy. Monitoring methods have been developed overseas (Butt and Barlow, 1979, Butt and Xiang-Ming Xu 1996) but field trials in Australia were needed to adapt the sampling methodology, and thresholds for timing of spray controls, for use in Australian orchards.

Breeding programs in the USA and elsewhere have led to the release of many cultivars with resistance to apple scab (Crosby et al 1992) and some of these cultivars also show reduced susceptibility to powdery mildew. In Australia, there is little information on the susceptibility of apple cultivars to scab and mildew, including those cultivars which have been developed in Australia (Tancred et al, 1994). Information about the relative susceptibility of current commercial cultivars is essential for planning mildew monitoring and integrated pest management approaches to mildew control.

Materials and Methods
Mildew monitoring. Primary mildew was assessed in the field spray trial during winter or spring by counting all terminal shoots with a mildewed terminal bud out of 50-100 shoots on each tree. Symptoms of mildewed terminal buds included whitish growth over the shoot and terminal bud (dormant); a shrivelled appearance of the terminal bud (dormant); and by completely mildewed leaves which had developed from the terminal bud (spring). Other buds (leaf and flower) can be affected by primary mildew, resulting in completely mildewed leaves or flowers in spring. Secondary mildew was assessed during late spring and summer by examining all leaves on 5-10 shoots per tree, recording the proportion of leaves with mildew. Mildew symptoms include whitish patches (more commonly on the underside of leaves) which are often associated with leaf curling or crinkling.

Cultivar trial. A cultivar susceptibility trial involved planting 20 cultivars of apple in a replicated layout at IHD Knoxfield in spring 1995. Trees were obtained from a commercial nursery and were planted in a randomised block design in five rows, with each row containing one single tree replicate of each cultivar. No pest or disease control measures were applied to this block for the duration of the trial. In each season, the incidence of apple scab and powdery mildew on leaves was recorded in summer. All leaves on each of five shoots per tree were examined and scored for the presence of scab or powdery mildew. In the last two years, all fruit on each tree was counted and examined for presence of scab.

Results and Discussion
Mildew monitoring. Primary mildew levels in unsprayed plots of the field spray trial ranged from 6.7% terminal shoots mildewed in 1997/98 to 22% in 1996/97. Levels in the dormant period of one year (1996/97) were higher than levels in the spring after budburst. This may have been due to the death of a proportion of mildewed terminal buds, which consequently did not grow and were not counted in later primary mildew assessments. Primary mildew levels recorded in October each year indicated a decline in mildew with time, from 19% in 1995/96 to 12.7% in 1996/97 and 6.7% in 1997/98. Secondary mildew assessments also showed higher mildew levels in the first year (20.3-30.3% leaves infected) compared with 2.6-10% in 1996/97 and 10.4-11.8% in 1997/98.

Cultivar trial. 1995/96 Summer disease assessments indicate that leaf mildew levels after one season were highest on the cultivars Pink Lady, New Jonagold and Smoothee (>10% leaves infected), and lowest on Earlidel, Fuji, Jonafree, Querina Fiorina and HiEarly (<2% leaves infected). 1996/97 In the unsprayed cultivar block at IHD Knoxfield, leaf mildew infection in late November of the second season was highest in varieties Pink Lady, Red Elstar, Golden Delicious, Imperial Gala, Braeburn and Smoothee (more than 10% leaves infected), and lowest on Earlidel, Red Fuji and HiEarly (less than 2% leaves infected). By February mildew levels were highest in New Jonagold, Red Elstar, Braeburn, Mutsu, Imperial Gala, Pink Lady, Jonathan and Golden Delicious (more than 10% leaves infected), and lowest in Earlidel, Fuji and Querina Fiorina (less than 2% leaves infected). These results are generally consistent with observations from the first season and show that some newer cultivars are
quite susceptible to mildew infection. Scab infection on leaves showed that Pink Lady, Lady William, Braeburn, Firmgold, Jonagold and Mutsu are all quite susceptible to scab (from 55-25% infection). Several cultivars show little or no leaf scab; these were the scab resistant cultivars Jonafree, Querina Florina and Redfree.

1997/98. The third seasons results generally confirmed the previous results for both mildew and scab susceptibility (Tables 6 and 7).

Over all results showed that a number of important commercial cultivars are highly susceptible to leaf scab. The average leaf scab incidence over three years was: Pink Lady, 40.2% of leaves; Lady William, 37.1%; Braeburn, 20.0%; New Jonagold, 18.7% and Mutsu, 18.1%. For powdery mildew the average leaf mildew incidence over three years was: New Jonagold, 23.0%; Pink Lady, 17.8%. There was a high level of resistance to leaf scab in the cultivars Florina-Querina, Redfree and Jonafree (all less than 1% incidence on leaves) and to powdery mildew in the cultivar Earlidel (no infection observed). The cultivars Jonathan, Bonza and Red Elstar showed a useful level of resistance to scab (average incidence of leaf scab between 1.6 and 3.2%), while the cultivars Red Fuji, Florina-Querina and High Early all showed some resistance to powdery mildew (average incidence of mildew between 2.6 and 5.9%).

Observations made on the low and variable numbers of fruit produced by some trees in their third year after planting showed that Pink Lady and Lady William were highly susceptible to fruit scab (67.6% or 57.6% infected fruit, respectively). Twig infection by scab was also observed on shoots of the current season's growth of Pink Lady.

Summary

Mildewed terminal buds could be readily detected during the dormant period but primary mildew was most easily detected in early spring around flowering or petal fall. Secondary mildew was also readily detected in spring and early summer, especially on the underside of leaves. As leaves aged in summer it was harder to detect slightly mildewed leaves, and the mildewed areas became yellowish and less obvious.

Ranking of cultivars for susceptibility to mildew indicates the following:

Highly susceptible:
New Jonagold, Pink Lady

Susceptible:
Mutsu, Bonza, Red Elstar, Braeburn, Imperial Gala, Jonathan, Lady William, Firmgold, Jonafree, Golden Delicious, Smoothee, Granny Smith, Summer Red, Redfree

Resistant:
High Early, Florina-Querina, Earlidel

Ranking of cultivars for susceptibility to scab indicates the following:

Highly susceptible:
Pink Lady, Lady William, Braeburn, New Jonagold, Mutsu

Susceptible:
Imperial Gala, Golden Delicious, Granny Smith, Red Fuji, High Early, Firmgold, Summer Red, Earlidel, Smoothee

Resistant:
Red Elstar, Bonza, Jonathan

Highly resistant:
Redfree, Jonafree, Florina-Querina

This information will be important when planning monitoring schedules in mixed blocks, as monitoring should take into account the most susceptible cultivar. It will also be useful when growers who want to minimise fungicide sprays plan new plantings.
Table 6. Incidence of leaf and fruit scab (%) on 20 cultivars of apples over three seasons, Knoxfield, Victoria

<table>
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</thead>
<tbody>
<tr>
<td>Pink Lady</td>
<td>37.9 (3.29)</td>
<td>56.4 (3.98)</td>
<td>32.4 (2.77)</td>
<td>40.2 (3.66)</td>
<td>25.0</td>
<td>67.6 (3.73)</td>
</tr>
<tr>
<td>Lady William</td>
<td>38.3 (3.51)</td>
<td>53.7 (2.88)</td>
<td>23.6 (2.94)</td>
<td>37.1 (3.54)</td>
<td>100</td>
<td>57.6 (3.71)</td>
</tr>
<tr>
<td>Braeburn</td>
<td>16.9 (2.76)</td>
<td>39.7 (3.50)</td>
<td>6.0 (1.74)</td>
<td>20.0 (2.90)</td>
<td>4.8</td>
<td>5.6 (0.64)</td>
</tr>
<tr>
<td>New Jonagold</td>
<td>35.0 (2.67)</td>
<td>29.8 (3.45)</td>
<td>5.2 (0.89)</td>
<td>18.7 (2.75)</td>
<td>15.7</td>
<td>-</td>
</tr>
<tr>
<td>Mutsu</td>
<td>26.5 (2.94)</td>
<td>25.6 (3.14)</td>
<td>5.6 (0.40)</td>
<td>18.1 (2.79)</td>
<td>18.1</td>
<td>-</td>
</tr>
<tr>
<td>Imperial Gala</td>
<td>8.1 (1.12)</td>
<td>23.7 (2.87)</td>
<td>4.9 (1.22)</td>
<td>10.8 (2.22)</td>
<td>2.3</td>
<td>2.3 (-0.21)</td>
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<tr>
<td>Golden Delicious</td>
<td>13.6 (2.21)</td>
<td>17.0 (2.68)</td>
<td>2.5 (-0.69)</td>
<td>10.2 (2.18)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Granny Smith</td>
<td>16.0 (1.50)</td>
<td>11.0 (1.23)</td>
<td>2.6 (-1.33)</td>
<td>9.8 (2.02)</td>
<td>NF*</td>
<td>2.3 (-1.19)</td>
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<tr>
<td>Red Fuji (=Naga Fu. No. 2)</td>
<td>15.9 (2.32)</td>
<td>11.9 (2.38)</td>
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<td>9.4 (2.03)</td>
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<tr>
<td>High Early</td>
<td>6.7 (1.92)</td>
<td>20.1 (2.68)</td>
<td>1.6 (0.07)</td>
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<td>Firmgold</td>
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<td>30.9 (3.12)</td>
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<td>9.1 (2.20)</td>
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<td>Summer Red</td>
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<td>1.7 (-0.76)</td>
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<td>Earlibel</td>
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<td>0.7 (-0.79)</td>
<td>5.7 (1.19)</td>
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<td>Smoothee</td>
<td>7.9 (1.94)</td>
<td>6.9 (1.07)</td>
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<td>5.3 (1.67)</td>
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<td>Red Elstar</td>
<td>4.4 (0.12)</td>
<td>4.2 (0.14)</td>
<td>0.8 (-1.10)</td>
<td>3.2 (0.69)</td>
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<td>Bonza</td>
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<td>9.1 (0.36)</td>
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<td>2.6 (-0.22)</td>
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<tr>
<td>Jonathan</td>
<td>1.8 (-1.40)</td>
<td>1.9 (-0.37)</td>
<td>1.0 (-0.61)</td>
<td>1.6 (0.13)</td>
<td>7.3</td>
<td>1.7 (-1.51)</td>
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<td>2.3 (-0.96)</td>
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<td>0</td>
<td>0.6 (-1.33)</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Jonafree</td>
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<td>0</td>
<td>0</td>
<td>0.4 (-1.32)</td>
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<td>0</td>
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<tr>
<td>Florina-Quérina</td>
<td>1.8 (-1.78)</td>
<td>0</td>
<td>0</td>
<td>0.1 (-1.97)</td>
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<tr>
<td>overall mean</td>
<td>12.9</td>
<td>17.1</td>
<td>4.8</td>
<td>10.9</td>
<td>-</td>
<td>7.6</td>
</tr>
<tr>
<td>LSD (p=0.05)</td>
<td>(1.90)</td>
<td>(1.97)</td>
<td>(2.08)</td>
<td>(1.18)</td>
<td>-</td>
<td>(2.26)</td>
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* Figures in parentheses are means of the log (x + 0.1) transformed percentages

* No fruit

* not included in analysis
Table 7. Incidence of powdery mildew (%) on leaves of 20 cultivars of apples over three seasons, Knoxfield, Victoria

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>1995-96</th>
<th>1996-97</th>
<th>1997-98</th>
<th>3 year mean</th>
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<td>New Jonagold</td>
<td>14.0 (2.62)</td>
<td>25.4 (3.21)</td>
<td>28.0 (3.29)</td>
<td>23.0 (3.12)</td>
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<tr>
<td>Pink Lady</td>
<td>16.4 (2.75)</td>
<td>13.4 (0.83)</td>
<td>22.0 (2.67)</td>
<td>17.8 (2.56)</td>
</tr>
<tr>
<td>Mutsu</td>
<td>3.1 (0.56)</td>
<td>18.7 (2.65)</td>
<td>17.0 (1.86)</td>
<td>13.3 (2.47)</td>
</tr>
<tr>
<td>Bonza</td>
<td>3.4 (0.02)</td>
<td>8.3 (1.93)</td>
<td>22.0 (2.56)</td>
<td>12.4 (2.32)</td>
</tr>
<tr>
<td>Red Elstar</td>
<td>7.8 (1.71)</td>
<td>22.5 (2.94)</td>
<td>9.4 (2.24)</td>
<td>12.3 (2.46)</td>
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<tr>
<td>Braeburn</td>
<td>9.1 (2.07)</td>
<td>19.7 (1.63)</td>
<td>9.6 (1.65)</td>
<td>12.3 (2.11)</td>
</tr>
<tr>
<td>Imperial Gala</td>
<td>7.3 (0.56)</td>
<td>18.0 (2.59)</td>
<td>11.5 (1.21)</td>
<td>12.0 (2.28)</td>
</tr>
<tr>
<td>Jonathan</td>
<td>4.4 (0.86)</td>
<td>12.3 (2.26)</td>
<td>17.4 (0.59)</td>
<td>11.7 (2.21)</td>
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<td>Lady William</td>
<td>3.5 (0.58)</td>
<td>4.1 (0.75)</td>
<td>24.3 (2.80)</td>
<td>11.2 (2.28)</td>
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<td>Firmgold</td>
<td>5.4 (1.49)</td>
<td>9.9 (2.01)</td>
<td>10.2 (0.48)</td>
<td>10.4 (2.04)</td>
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<td>Jonafree</td>
<td>1.0 (-1.07)</td>
<td>5.1 (1.40)</td>
<td>23.8 (2.61)</td>
<td>9.9 (2.12)</td>
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<tr>
<td>Golden Delicious</td>
<td>6.9 (1.75)</td>
<td>10.2 (1.41)</td>
<td>11.7 (1.89)</td>
<td>9.6 (2.12)</td>
</tr>
<tr>
<td>Smoothee</td>
<td>10.7 (2.10)</td>
<td>7.6 (1.22)</td>
<td>8.2 (1.89)</td>
<td>8.9 (2.08)</td>
</tr>
<tr>
<td>Granny Smith</td>
<td>10.4 (1.87)</td>
<td>9.9 (1.21)</td>
<td>4.9 (0.67)</td>
<td>7.7 (1.61)</td>
</tr>
<tr>
<td>Summer Red</td>
<td>7.3 (1.32)</td>
<td>6.2 (0.97)</td>
<td>9.1 (1.29)</td>
<td>7.6 (1.54)</td>
</tr>
<tr>
<td>Redfree</td>
<td>3.6 (-0.86)</td>
<td>7.7 (1.17)</td>
<td>9.9 (0.65)</td>
<td>5.9 (0.88)</td>
</tr>
<tr>
<td>High Early</td>
<td>1.5 (0.07)</td>
<td>3.9 (0.08)</td>
<td>4.0 (-0.42)</td>
<td>3.1 (0.44)</td>
</tr>
<tr>
<td>Florina-Quérina</td>
<td>1.7 (0.54)</td>
<td>1.4 (-0.87)</td>
<td>4.0 (0.21)</td>
<td>3.1 (1.07)</td>
</tr>
<tr>
<td>Red Fuji (=Naga Fu. No. 2)</td>
<td>0.3 (-0.37)</td>
<td>1.2 (-0.57)</td>
<td>2.5 (-0.52)</td>
<td>2.6 (0.14)</td>
</tr>
<tr>
<td>Earlidel</td>
<td>0 a</td>
<td>0 -</td>
<td>0 -</td>
<td>0 -</td>
</tr>
<tr>
<td>overall mean</td>
<td>6.2</td>
<td>10.1</td>
<td>12.6</td>
<td>9.8</td>
</tr>
</tbody>
</table>

LSD (P=0.05) | (1.96) | (2.23) | (2.40) | (1.25)

\(^a^\) Figures in parentheses are means of the log (x + 0.1) transformed percentages

\(^b^\) not included in analysis
5.3. **What is the potential for alternatives to conventional fungicides as part of a cost effective, integrated disease management system for powdery mildew?**

**Introduction**
Currently, fungicides provide economic control of powdery mildew in apples. The development of apple scab resistance for the current generation of fungicides will necessitate new control strategies for this disease and impact upon orchard mildew control. Environmental issues and consumer perceptions of chemical residues may result in lowered community tolerance for the application of chemical pesticides in apple orchards. These considerations compel the industry to develop alternative methods for managing powdery mildew. Previous research undertaken over the last 2 decades indicates that there is some immediate opportunity in the areas of alternative and innocuous chemicals and disease modeling forecast. Longer term investigations may support biological control programs for the disease.

This section reports work on a range of potential alternatives to conventional fungicides, and an attempt at biological control of powdery mildew.

**Materials and Methods**

**Glasshouse tests**
Glasshouse and field trials were established to test alternatives to conventional fungicides as part of an integrated control approach for mildew. The range of chemicals tested on potted apples in the glasshouse included Codacide (vegetable oil), Synertrol (vegetable oil), DCTron Plus (mineral oil), sodium and potassium bicarbonate, Powdown (phosphorous acid and spraying oil), Limil® (calcium hydroxide), Kumulus® (wettable sulphur) and Topas® (penconazole). Promising materials were evaluated further in field trials in later years of the project.

**Biocontrol with Sporodex**
As part of the project aims to develop alternative control strategies for mildew attempted some small scale studies with a biocontrol agent shown to be effective against powdery mildew in glasshouse studies in Canada. In 1995 an application was made to import the biocontrol agent *Sporothrix flocculosa* through contacts with the company Evergreen Marketing. The application needed approval by AQIS and the Australian Nature Conservation Agency. At the same time contacts were made with the Canadian researchers (Dr R. Belanger of the University of Quebec) and the company commercialising the product. Approvals were eventually granted by the relevant bodies, and in January 1998 5 kg of dried product Sporodex was received. All attempts to grow the organism in culture failed. Contact with the Canadian researchers revealed that they had similar problems in other attempts to supply cooperators around the world. We are therefore unable to produce any data to show the benefit of this biocontrol agent against apple powdery mildew.

**Field trials in Victoria and Interstate**
See Section 5.1. "Will powdery mildew increase if fungicide spraying is reduced?" for Victorian studies on this aspect. Interstate co-operators in Tasmania, Queensland and South Australia established replicated field trials in 1996-97 to evaluate DCTron Plus mineral oil and other treatments for mildew control. These trials were on the cultivars Jonathan, Sturmer and Royal Gala.

**Queensland.** DCTron Plus was compared at two rates with bupirimate, myclobutanil and an untreated control treatment. Five sprays were applied between 7/11 and the 6/1/97 to four single tree plots per treatment.

**Tasmania.** DCTron Plus was compared at two rates with calcium hydroxide, wettable sulphur and an untreated control. Six sprays were applied between 7/10 and the 26/11/96 to four single tree plots per treatment. Trees were assessed for mildewed shoots by examining 20 shoots per tree on the 29/11/96.

**South Australia.** DCTron oil at 0.5 and 1.0% were compared with Topas and Polyram treatments on mature Jonathan trees. Five sprays were applied between 14/10 and 23/12/96. Treatments were applied by airblast sprayer to plots 10 trees long.
Results and Discussion

Glasshouse tests

1995-96 Results from one trial showed that one spray of any of the two registered fungicides Topas® and Kumulus®, along with the unregistered fungicide Powdown and sodium and potassium bicarbonate all reduced powdery mildew on leaves of naturally infected Golden Delicious apples for up to 30 days. Sodium and potassium bicarbonate showed good activity against mildew but caused severe leaf burn at the rates tested. By contrast one spray of the oils Synertrol and DCTron Plus, and calcium hydroxide had no effect on mildew levels when compared with the controls under the conditions of this test. Higher rates and/or testing over a period of time with a number of sprays may result in higher efficacy, as oils materials are reported to be effective against some other mildew diseases.

1996-97 Combinations of oils and other treatments including bicarbonates and fungicides were tested with the aim of finding less phytotoxic or more effective treatments. Results from one trial showed that sprays of Topas combined with oils, or bicarbonates combined with oil gave good control of mildew incidence on seedlings after three sprays. Unfortunately, bicarbonates combined with oil were still highly phytotoxic (see results from 1995-96 where bicarbonates were tested alone). Topas, sulphur, oils including DCTron plus, Codacide and Synertrol and Powdown gave control of mildew and showed little or no phytotoxicity to apple seedlings. Calcium hydroxide (Limil) was less effective in this trial but still gave significant control of mildew.

1997-98 Trials tested a similar range of treatments as previous years. Best control was achieved with Topas at full rate. All treatments except hydrated lime significantly reduced mildew when compared with mildew in untreated plants (Table 8). Sodium bicarbonate at 0.5% plus Synertrol gave good control of mildew, and showed no tendency to cause the phytotoxicity observed in previous tests using 1% bicarbonate alone. Topas, sulphur, oils including DCTron plus, Codacide and Synertrol and Powdown gave control of mildew and showed little or no phytotoxicity to apple seedlings. Calcium hydroxide (Limil) was less effective in this trial but still gave significant control of mildew.

Field trials in Victoria and Interstate

See Section 5.1. "Will powdery mildew increase if fungicide spraying is reduced?" for Victorian studies on this aspect. Myclobutanil gave best control of powdery mildew (assessed in summer) in Queensland with bupirimate and DCTron oil at 1 and 0.5% also being better than the untreated control (Table 9). Some trees showed leaf spotting and marginal scorching in summer. These symptoms were worst in the trees sprayed with 1% DCTron, and only appeared to be associated with trees which were water stressed. Myclobutanil gave best scab control. DCTron oil sprays gave less control but better than unsprayed trees on the scab susceptible cultivar Granny Smith.

In Tasmania wettable sulphur gave the best control of leaf mildew (Table 10). DCTron Plus oil at 0.5 and 1% gave significant control but less than sulphur, while hydrated lime gave no control of leaf mildew. At harvest sulphur sprays were associated with a large increase in fruit weight and fruit number. Both rates of DCTron Plus significantly reduced fruit yield, while hydrated lime sprays had no effect on mildew or fruit weight or number when compared with the control fruit. Leaf spotting and browning were noted on leaves sprayed with 1% DCTron Plus.

So little mildew developed in the South Australian trial that no results are available.

Results from the other trials indicate that 5-6 sprays of DCTron Plus at 1% and 0.5% give a moderate level of mildew control but have caused some leaf damage including scorching, spotting and browning. This damage appears to be associated with sprays during periods of hot weather, when trees are under some water stress. Calcium hydroxide showed a weak effect against mildew. Wettable sulphur showed reasonable control of mildew, but inferior to conventional mildew fungicides such as bupirimate, penconazole and myclobutanil.

Summary

DCTron Plus mineral oil can reduce mildew but not as well as conventional mildew fungicides including wettable sulphur, myclobutanil or bupirimate. Phytotoxicity was observed in both field trials.
associated with DCTron Plus sprays (reduced yields, spotting and scorching of leaves). This appears to be associated with hot weather close to spraying and/or water stressed trees.

Calcium hydroxide reduced mildew significantly in some assessments in one field trial but was clearly less effective than penconazole (Victoria), while it gave no effect on mildew in the other field trial (Tasmania).

No clear treatment effects were noted for fruit russet, insect infestation or fruit yields, although there was a non-significant trend to increasing yields in treatments with fewer penconazole sprays.
Table 8. Effect of spray treatments on incidence of powdery mildew on potted Golden Delicious apples in the glasshouse (spring 1997).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate</th>
<th>Incidence of mildew at assessment #3</th>
<th>Average incidence of mildew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td></td>
<td>27</td>
<td>14.9</td>
</tr>
<tr>
<td>Topas</td>
<td>20ml</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Topas</td>
<td>10ml</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Sulphur</td>
<td>300g</td>
<td>9.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Na bicarbonate &amp; Synertrol</td>
<td>0.5 &amp; 1%</td>
<td>3.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Topas &amp; Synertrol</td>
<td>10ml &amp; 1%</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Synertrol</td>
<td>1%</td>
<td>12.1</td>
<td>8.0</td>
</tr>
<tr>
<td>DCTron Plus</td>
<td>0.5%</td>
<td>34</td>
<td>25.3</td>
</tr>
<tr>
<td>bupirimate 60 ml/100L</td>
<td>25</td>
<td>16.8</td>
<td>13</td>
</tr>
<tr>
<td>myclobutanil 12 g/100L</td>
<td>0</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Hydrated lime</td>
<td>2%</td>
<td>22.6</td>
<td>16.9</td>
</tr>
<tr>
<td>LSD</td>
<td></td>
<td>10.8</td>
<td></td>
</tr>
<tr>
<td>Fpr</td>
<td></td>
<td>&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

Table 9. Effect of field sprays on mildewed shoots and leaves assessed on 28 January 1997 for cultivars Jonathan and Royal Gala, Queensland, 1996-97

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Jonathan % mildewed shoots</th>
<th>Jonathan % mildewed leaves</th>
<th>Royal Gala % mildewed shoots</th>
<th>Royal Gala % mildewed leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>75</td>
<td>65</td>
<td>88</td>
<td>68</td>
</tr>
<tr>
<td>DCTron Plus 0.5%</td>
<td>34</td>
<td>19.3</td>
<td>36</td>
<td>25.3</td>
</tr>
<tr>
<td>DCTron Plus 1%</td>
<td>25</td>
<td>16.8</td>
<td>33</td>
<td>13</td>
</tr>
<tr>
<td>bupirinate 60 ml/100L</td>
<td>0</td>
<td>6</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>myclobutanil 12 g/100L</td>
<td>7</td>
<td>16.3</td>
<td>0</td>
<td>20.3</td>
</tr>
<tr>
<td>LSD</td>
<td>33</td>
<td>14.0</td>
<td>21</td>
<td>15.3</td>
</tr>
</tbody>
</table>
Table 10. Effect of field sprays on mildewed shoots in November, and fruit scab, fruit weight, fruit number and yield at harvest, cv Sturmer, Tasmania, 1996-97

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% mildewed shoots 29/11/96</th>
<th>% fruit scab</th>
<th>Fruit weight kg</th>
<th>Fruit number</th>
<th>Mean fruit weight g</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>25</td>
<td>73.1</td>
<td>60.9</td>
<td>622</td>
<td>97.5</td>
</tr>
<tr>
<td>DCTron Plus 0.5%</td>
<td>12.5</td>
<td>56.3</td>
<td>24.6</td>
<td>241</td>
<td>93</td>
</tr>
<tr>
<td>DCTron Plus 1%</td>
<td>11.3</td>
<td>53.2</td>
<td>21.5</td>
<td>236</td>
<td>90.7</td>
</tr>
<tr>
<td>Sulphur 250 g/100L</td>
<td>3.8</td>
<td>6.8</td>
<td>116.5</td>
<td>1193</td>
<td>97.7</td>
</tr>
<tr>
<td>Calcium hydroxide 2 kg/100L</td>
<td>27.5</td>
<td>22.6</td>
<td>61.6</td>
<td>592</td>
<td>104.2</td>
</tr>
<tr>
<td>LSD</td>
<td></td>
<td>32.1</td>
<td>304</td>
<td>11.9</td>
<td></td>
</tr>
</tbody>
</table>

Future directions
Growers should monitor for mildew during winter and the growing season to help decisions about mildew control. The level of mildewed terminals in winter can be used to help plan mildew control strategies for the coming spring. Shoots with infected terminal buds can be assessed immediately after flowering using a minimum of 10 trees per block. In the UK more than 2% primary mildewed shoots is considered high. For assessment of secondary mildew, label 15 trees per ha and assess 4 extension shoots per tree. Assess the top 5 unfolded leaves per shoot for mildew, and record the incidence of mildewed shoots. Assess the same trees at intervals during the growing season. If mildew levels increase over time then control measures may need to be improved. Methods to assess mildew are important and mild symptoms are easily overlooked, therefore training is important.

More work is needed to define threshold levels of mildew that, if exceeded, will require increased control measures eg. more frequent sprays, use of more active fungicides.

The ranking of cultivars for susceptibility to mildew (and scab) is useful when planning monitoring schedules in mixed blocks, as monitoring should take into account the most susceptible cultivar. Growers can also use it when planning new plantings, to minimise fungicide spraying.

Biocontrol agents and compounds including sodium bicarbonate at low rates combined with oil sprays should be considered for further testing. The bicarbonates showed good efficacy against mildew in glasshouse tests and, if safe to use on apples, could have good potential as alternative protectant mildew fungicides. Biocontrol agents have been shown to be effective in other crops against mildews, and may be a useful supplement to field control of mildew. Unfortunately, the DCTron Plus treatments showed relatively low efficacy against mildew in field trials, and caused significant phytotoxicity including reduced crop and leaf damage. They may have a place in reduced pesticide control of mildew, but more work is required to define conditions for their safe use.
5.4 Is there a difference in importance of weevil species between the states?

Introduction

There is more than one weevil species that attacks apples in Australia. Little is known about the relative importance of the different species, or if their importance varies between states. This background information was essential for planning the type of research needed to better understand the weevil problem, and to determine where the work would be conducted. Preliminary discussions had indicated that there were three main species causing the most concern for growers. These were Garden Weevil, Apple Weevil and Fuller's Rose Weevil. This section reports the importance of the three species of weevil in the various states where pome fruit is grown.

Materials and Methods

In Western Australia, a survey of orchardists in each of the main fruit growing districts was conducted. In the other states, the assessments were based on telephone interviews with government workers and private consultants involved with the industry.

Results and Discussion

For Western Australia, Table 11 shows the response of orchardists when asked whether each of the species of weevil is present in their orchard and, if present, if it is regarded as a pest. Apple weevil is considered a pest by the greatest proportion of orchardists, followed by garden weevil. The proportion of orchardists who rated a particular species of weevil as being important, varied among the districts. All three species are important in the Perth Hills orchards, apple weevil is the most important species in Donnybrook, while both apple weevil and garden weevil are important in the most southerly district, Manjimup.

Table 11. The number of orchardists surveyed in the main fruit growing districts of WA, and the percentage who regarded weevils as a pest, non-pest or absent from their orchard.

<table>
<thead>
<tr>
<th>District</th>
<th>No.</th>
<th>Garden weevil</th>
<th>Apple weevil</th>
<th>Fuller's rose weevil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Absent</td>
</tr>
<tr>
<td>Perth</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Donnybrook</td>
<td>35</td>
<td>34</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Manjimup</td>
<td>12</td>
<td>75</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>67</td>
<td>45</td>
<td>29</td>
<td>26</td>
</tr>
</tbody>
</table>

The relative importance of the three species of weevils considered in this project in other pome fruit regions of Australia is indicated in Fig. 2. This information is a summary of the views held by entomologists, other pome fruit workers and orchardists in eastern Australia. Garden weevil is most important in Western Australia, but also occurs as a pest in South Australia, Victoria and Tasmania. Apple weevil is primarily a pest in the Mediterranean climate regions of Western Australia and South Australia. Fuller's rose weevil is most important in Queensland, but also occurs as a pest in Western Australia, South Australia and Victoria. More recently, apple weevil is becoming a more important pest of summer fruit in the Sunraysia area of Victoria (Andrew Simes, pers. comm.).
Fig. 2. The pome fruit growing regions of Australia and the relative importance of the fruit tree weevils garden weevil (GW), apple weevil (AW) and Fuller's rose weevil (FRW) as indicated from discussions with entomologists.
5.5 How do you monitor weevil abundance?

Introduction
There are many methods used around the world to monitor insect populations. Not many are practical enough for commercial use. Where more than one species is present it is preferable to have a single method that performs adequately for all species of interest. This section reports attempts to determine the most efficient method(s) for monitoring the abundance of weevil pests in pomefruit orchards.

Materials and Methods
Orchards that were well-infested with weevils were selected. Such orchards were identified during surveys of weevil importance and/or by consulting other orchardists or fruit industry advisers and consultants. Incidence of reasonable populations of the insects was confirmed by soil sampling for the more easily seen mature larvae in early to mid spring.

Five different methods were assessed for monitoring the abundance of adult weevils:

(a) **Emergence trap** - consisting of 150 mm square and 150 mm long section of galvanised iron air conditioning duct was sunk into the orchard floor to a depth of about 30 mm. A slippery coating (teflon or fluon) was painted on the outer and inner upper walls of the metal and a grooved timber block was placed in the trap to facilitate counting the weevils. A metal frame with metal gauze window was placed over the duct. The timber block was examined weekly to fortnightly.

(b) **Tree band** - consisting of single faced cardboard attached to the butt or leader of a tree. Bands were 150 mm wide and wax coated to increase their field life. Velcro was attached at each end of the band to save time placing them onto the tree on each sampling occasion. A light coloured cotton cloth was placed on the ground under the band before it was removed from the tree to facilitate both catching weevils that fell to the ground as the band was removed and also to count weevils.

(c) **Grooved timber block** - placed on the ground at the base of a tree. The blocks were 150 mm by 110 mm by 25 mm and the grooves were approximately 6 mm deep by 4 mm wide. Trees at which the grooved blocks were placed did not have a butt or leader band attached, as this may have interfered with the natural distribution of some of the weevil species.

(d) **Sticky post** - based on the type used for monitoring Fuller's rose weevil in New Zealand (see Fig. 3) and consisting of a timber stake, 600 mm above ground level. The top 100 mm was coated with a polybutene sticky material. A length of black 12.5 mm black PVC trickle pipe was attached to the top of the post such that 20 mm protruded below the sticky band. A screw cap vial was attached to the top of the trickle pipe, with the lid also attached to the top of the wooden stake. The outer surface of the trickle pipe protruding into the vial was coated with teflon or fluon to prevent any weevils that enter the vial from escaping via the trickle pipe. It was expected that Fuller's rose weevil and possibly apple weevil adults might be caught in the sticky band, while garden weevil adults and possibly apple weevil adults, which are repelled by the sticky material, may climb through the trickle pipe and enter the vial.

(e) **Canopy sampling/limb jarring** - involved counts of adult weevils *in situ* in the tree canopy, based on using a “scratch” tray to define the length of limb that is inspected per sampling unit. By holding the tray under the limb during sampling, weevils that both remain on the limb and those dislodged during examination are recorded. The “scratch” tray is a Nally product part no. H 009 - 456 mm x 312 mm x 55 mm deep.
Results
The abundance and timing of collections of garden weevil, apple weevil and Fuller's rose weevil adults recorded from the different monitoring methods are given in Fig. 4 (a) to (e). Except for Fuller's rose weevil, more weevil adults were present in the cardboard trunk monitoring bands and, with the exception of the emergence trap at Yates orchard, the trunk bands recorded garden weevil and apple weevil presence at least at the equivalent time to other monitoring methods. Only for garden weevil at the Yates orchard did the emergence trap record weevils earlier that the trunk bands.

Fuller's rose weevil was recorded in low numbers only in the WA orchards, but none were found in trunk bands and ground blocks and limb jarring produced the greatest number of weevils. Garden weevil were recorded in low numbers from the limb jarring method of sampling at the Yates orchard, and only one apple weevil adult was recovered from limb jarring at the Maslin orchard from three sampling occasions. Some loss of fruit occurred during the limb jarring procedure.

Sticky poles trapped both apple weevil and Fuller's rose weevil in the sticky material, rather than the tube at the top of the trap.
Fig. 4 (a). Number of garden weevil adults obtained using different monitoring methods - Yates orchard, Donnybrook. Arrow on tree band graph indicates the time of insecticide application.
Fig. 4 (b). Number of apple weevil adults obtained using different monitoring methods - Maslin orchard, Manjimup.
Fig. 4 (c). Number of apple weevil adults obtained using different monitoring methods - Martin orchard, Pemberton.
Fig. 4 (d). Number of garden weevil adults obtained using different monitoring methods - Martin orchard, Pemberton.
Fig. 4 (e). Number of Fuller's rose weevil adults obtained using different monitoring methods - Martin orchard, Pemberton.
Discussion
The aim of these studies was to compare different monitoring methods for their efficiency and practicability for commercial use by orchardists or pest consultant scouts. For garden weevil and apple weevil, the use of cardboard trunk bands is recommended. These bands are easy to construct and use, and if made of waxed cardboard last the entire season. The bands were good indicators of the abundance and timing of weevil presence compared to other monitoring methods.

Sticky poles trapped Fuller’s rose weevil and apple weevil, but the numbers were low and inconsistent.

The emergence traps and ground blocks caught weevils as they emerged from the soil, but the numbers caught were low and too inconsistent to be reliable indicators of weevil presence.

The trunk bands were inefficient in detecting Fuller’s rose weevil. The most practical monitoring method for this weevil was limb jarring. Numbers detected with this method were low, but higher than for other methods. This weevil was not present in numbers high enough to be considered a pest in the Martin orchard, so it is possible limb jarring is a good technique in more heavily infested orchards.

Summary
No single monitoring method was suitable for all three weevil species because they had different habits and were distributed differently in the orchard. Cardboard trunk bands were the most efficient way of monitoring Garden Weevil and Apple Weevil. Limb jarring similar to that used for Apple Dimpling Bug was the most effective way of monitoring Fuller’s Rose Weevil.
5.6 Pest status and Economic Injury Level for weevils

Aims

Introduction

Part of the overall project aims was to quantify the pest status of the three species of weevils in pome fruit crops in terms of reduced fruit quality and yield. We also wanted to determine the relationship between pest abundance and damage levels and define an economic injury level (EIL) so that better informed decisions could be made about the need to take action against the weevils.

Adults of all three species cause damage that includes defoliation and possible associated effects on fruit quality. Apple weevil causes pedicel girdling and associated effects on fruit size. Fruit scaring by garden weevil leads to rejection of fruit on a quality basis and, in extreme cases, the loss of severely chewed fruit. Fuller's rose weevil excrement fouls the pedicel end of fruit and hence reduces fruit quality. The nuisance aspect of Fuller's rose weevil oviposition resulting in blocked sprinklers is considered elsewhere in this report.

There were no plans to examine the pest status of the larval stage of these weevils. Larvae certainly feed on the roots of fruit trees. Some orchardists have reported tree decline in the presence of high populations of adult weevils and when some orchards have been replanted, the root systems of the old trees showed signs of severe scalloping that was most likely the result of feeding by weevil larvae.

Materials and Methods

The pest status and EIL of the three species of weevil was examined concurrently in orchards selected for assessment of monitoring techniques described in the previous section. These orchards were selected on the basis of being reasonably heavily infested, which was determined from the abundance of larvae.

To examine the aspect of pest status, the natural variation in weevil abundance among trees within orchards was relied upon to "generate" the range of weevil infestation levels necessary to quantify the pest status and EIL of the weevils. Some trees in each orchard were treated to prevent infestation by weevils thereby resulting in some trees having a near zero infestation level. The exclusion treatments were (a) for apple weevil, a butt drench of 1 L of an insecticide solution per tree of the synthetic pyrethroid alpha-cypermethrin @ 100 ml 10% product / 100 L water; (b) for garden weevil, use of a sticky band (Enviroband) around the tree butt; and (c) for Fuller's rose weevil, application of both exclusion treatments on separate trees to investigate the dual aims of assessing their relative effectiveness in excluding this weevil from trees and measuring the pest status of this weevil.

For all three species of weevil, assessments included visual scoring of defoliation. For apple weevil, additional assessments on the incidence and severity of pedicel girdling and fruit scaring were made. At crop maturity, the pedicel girdling was assessed in relation to fruit size. For garden weevil, an additional assessment of fruit scaring was made at both sampling times. For Fuller's rose weevil, an additional assessment was made at crop maturity on the incidence of fouling of fruit by insect frass (excrement) at the pedicel end of the fruit. Damage to fruit trees was based on whole tree assessment at two times per season - the first in mid December to early January and the second at crop maturity.

Results:

Garden weevil

The Yates orchard near Donnybrook, WA with old Granny Smith apple trees was chosen for this study. The abundance of garden weevil adults during the season in apple trees to which a sticky trunk band was attached, untreated trees, and part of the commercial orchard where an insecticide butt drench was applied, is shown in Fig. 5. Unfortunately, a butt drench was accidentally applied to untreated and sticky band treated trees in November.
Fig. 5. Abundance of garden weevil adults in apple trees that were either unprotected, or protected with a sticky trunk band or an insecticide butt drench treatment in the rest of the orchard (commercial). A butt drench, indicated by the arrow on the right was inadvertently applied to untreated trees and trees protected with the sticky band in November. Yates orchard, near Donnybrook, WA.

The abundance of weevil adults was held in check by the sticky bands and the butt drench, both in the rest of the orchard and the later accidental butt drench application to trees in the area where the damage study was being undertaken reduced weevil abundance. The peak in garden weevil numbers in the trees receiving the sticky trunk band was the result of weevils breaching the band on one of the trees on one sampling occasion in late October during peak weevil emergence. This is shown in Fig. 6 where the weevil abundance on individual trees is shown, for both sticky band trees and untreated trees. This range of weevil numbers across the trial area was utilised in an examination of the EIL for garden weevil - see Discussion section below.
Damage to fruit from garden weevil in the Yates orchard was measured on two occasions - 7 Dec 1995 when fruit was approximately 30 mm diameter, and on 17 April 1996 at crop maturity, when treatment trees were strip harvested. Damage was categorised as light or severe, the difference between these categories being that light damage may have been saleable as a second grade fresh fruit on the local market, and severe being saleable as juice grade fruit only. Total damage to fruit on individual trees for the two sampling occasions is shown in Fig. 7. The sticky bands and butt drenching reduced the average level of fruit damaged by garden weevil adults compared to unprotected trees, but damage in trees protected with sticky bands was still at unacceptable levels. There was a range in the level of fruit damage, in both protected and unprotected trees, which was useful in examining the EIL of garden weevil. This is discussed in detail in the Discussion section below.
Apple weevil

(a) Maslin orchard, Manjimup
Soil sampling in November, 1995 indicated that the Maslin Orchard in Manjimup was infested with fruit tree weevils, primarily apple weevil. Weevil abundance and damage was monitored in a block of Golden Delicious trees, where sticky bands and a butt drench of insecticide were used on some of the trees to prevent weevils from entering the canopy. The abundance of apple weevil in monitoring bands in the trees is given in Fig. 8.

Previous experience with the sticky trunk bands has shown that they are less effective in excluding apple weevil adults than garden weevil adults from entering the tree canopy. This effect can be seen in Fig. 8 where weevil abundance in trees with the sticky trunk band was similar to that in untreated trees until the insecticide butt drench was applied in early December.

Garden weevil adults were recorded in very low numbers only during the season and consequently the fruit damage assessment in March revealed the weevil damage to fruit was fruit pedicel feeding only, characteristic of apple weevil. The average number and weight of fruit that sustained pedicel damage, categorised as either slight or ringbarked (where the entire circumference of the pedicel is chewed) for untreated and protected trees, are given in Table 12.

Damage to fruit in unprotected trees was relatively low at only 6% pedicels ringbarked. This resulted in a reduction in average fruit weight of about 20%, which was about twice the loss in weight for fruit with slight pedicel feeding. Damage to fruit in protected trees was very low at less than 1% fruit pedicels ringbarked. There were too few fruit damaged in protected trees to make a meaningful comparison of average fruit weight reduction as a result of damage to pedicels.
Fig. 8. The average number of apple weevil adults in monitoring bands on apple trees that were either untreated or received a sticky trunk band and a butt drench as indicated by the arrow, in the Maslin orchard, Manjimup, WA.

Table 12. The average number and weight of apple fruit divided into categories of damage to the pedicel from attack by apple weevil. Apples were harvested from trees either unprotected or treated with sticky trunk bands and insecticide butt drench to protect from apple weevil adults, Maslin Orchard, Manjimup, WA.

<table>
<thead>
<tr>
<th>Average number of fruit</th>
<th>Weevil Pedicel Feeding</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Undamaged</td>
<td>Slightly Chewed</td>
</tr>
<tr>
<td>Untreated</td>
<td>average</td>
<td>431</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>83</td>
</tr>
<tr>
<td>Excluded</td>
<td>average</td>
<td>591</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average weight of fruit</th>
<th>Weevil Pedicel Feeding</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Undamaged</td>
<td>Slightly Chewed</td>
</tr>
<tr>
<td>Untreated</td>
<td>151</td>
<td>137</td>
</tr>
<tr>
<td>% of undamaged</td>
<td>100</td>
<td>91</td>
</tr>
<tr>
<td>Excluded</td>
<td>150</td>
<td>112</td>
</tr>
<tr>
<td>% of undamaged</td>
<td>100</td>
<td>75</td>
</tr>
</tbody>
</table>

The variation in abundance of apple weevil adults among individual trees in the Maslin orchard is shown in Fig. 9. This variation in weevil abundance across the trial area was utilised in an examination of the EIL for apple weevil that is examined in more detail in the Discussion section below.
Fig. 9. The abundance of apple weevil adults on individual apple trees for both (a) sticky band and butt drenched trees and (b) untreated trees - Maslin orchard, Manjimup, WA.

(b) Kammann Orchard, Manjimup
Reports of a heavy infestation of apple weevil in a Manjimup apple orchard late in the 1995/96 season were investigated and, based on the situation, sampling of fruit was undertaken. Along a row of Pink Lady apple trees, the infestation of weevil varied for light through heavy. Ten apple trees in each section were strip harvested on 9 May 1996 and the fruit categorised to level of pedicel feeding, counted and weighed individually.

The results of this are given in Table 13. The proportion of fruit with ringbarked pedicels was much higher in the area of heavy infestation, and much higher than was recorded at the Maslin orchard (see Table 12). However, while the weight loss per fruit with a ringbarked pedicel compared to undamaged fruit in the Kammann orchard was around 8%, a weight loss of 20% was recorded at the Maslin orchard. Where the fruit pedicel was slightly chewed, weight losses of around 3% and 9% were recorded for the Kammann and Maslin orchards respectively.

Two orchards in the Perth Hills were also included in the study on pest status.
Table 13. The average number and weight of apple fruit divided into categories of apple weevil damage to the pedicel. Apples were harvested from trees along parts of a row that was infested either at low levels or high levels with apple weevil adults, Kammann Orchard, Manjimup, WA.

<table>
<thead>
<tr>
<th>Average number of fruit / tree</th>
<th>Weevil Pedicle Feeding</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Undamaged</td>
<td>Slightly Chewed</td>
</tr>
<tr>
<td>low infestation area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average no.</td>
<td>30</td>
<td>4</td>
</tr>
<tr>
<td>% of fruit</td>
<td>81</td>
<td>10</td>
</tr>
<tr>
<td>high infestation area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>average no.</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>% of fruit</td>
<td>34</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average weight of fruit</th>
<th>Weevil Pedicle Feeding</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Undamaged</td>
<td>Slightly Chewed</td>
</tr>
<tr>
<td>low infestation area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>av. weight</td>
<td>174</td>
<td>169</td>
</tr>
<tr>
<td>% of undam'd.</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>high infestation area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>av. weight</td>
<td>171</td>
<td>167</td>
</tr>
<tr>
<td>% of undam'd.</td>
<td>100</td>
<td>98</td>
</tr>
</tbody>
</table>

(c) Littlely Orchard, Perth Hills
The results of monitoring for apple weevils in both unprotected and protected Golden Delicious apple trees in the Littlely orchard are given in Fig. 10. The treatments to prevent weevils entering the tree canopy and the natural spread of infestation in the monitored area of fruit trees resulted in a good range of weevil abundance levels. Surprisingly, the proportion of apple pedicels that were ringbarked in unprotected trees was quite low - with the greatest level being just over 1%. The aspect of damage and EIL is considered in more detail in the Discussion section below.

(d) Owen Orchard, Perth Hills
The results of monitoring for apple weevils in both unprotected and protected Hi Early apple trees in the Owen orchard are given in Fig. 11. The treatment to prevent weevils entering the tree canopy resulted in a reduction in weevil abundance. The proportion of fruit with ringbarked pedicels in untreated ranged up to 10%, which was surprisingly higher than in the Littlely Orchard where the abundance of apple weevil was greater. This aspect is considered in more detail in the Discussion section below.
Fig. 10. The average number of apple weevil adults in monitoring bands on apple trees that were either untreated or received a sticky trunk band and a butt drench as indicated by the arrow, in the Littlely Orchard, Perth Hills, WA.

Fig. 11. The average number of apple weevil adults in monitoring bands on apple trees that were either untreated or received a sticky trunk band and a butt drench as indicated by the arrow, in the Owen Orchard, Perth Hills, WA.
Discussion:

Garden weevil

To assess EIL for garden weevil adults, the relationship between weevil abundance in the monitoring bands and fruit damage was examined. Before this, it is necessary to consider the most appropriate measurement of weevil abundance that would be of greatest value to an orchardist or crop scout in preventing economic loss.

Damage to apples is caused by the continued presence of weevils during the season. Unfortunately in the Yates orchard, an early inadvertent application of insecticide reduced the abundance of garden weevil prematurely. So, the following consideration may represent an underestimation, because for a given number of weevils, more damage would have occurred had the insecticide not been applied early.

The first aspect considered is the level of fruit damage per tree based on the sampling occasion on which garden weevil abundance was at its maximum. This relationship is given in Fig. 12. Linear regression analysis indicated that the relationship was not a linear one. It is apparent from this data that very low numbers of garden weevil adults results in high levels of damage to fruit. With this situation, it is not appropriate to continue with the next step in assigning an EIL. This would have meant examining a relationship between the abundance of garden weevil earlier in the emergence phase to maximum weevil abundance. Such a consideration is academic given the apparent very low EIL for garden weevil.

![Fig. 12. The number of garden weevil adults per monitoring band at maximum weevil abundance during the season for individual apple trees plotted against the level of fruit damage in that tree, Yates Orchard, Donnybrook.](image)

Where an orchardist has had the experience of damage by garden weevil in one season, treatment to protect trees in the following season becomes mandatory. Rather than approaching the issue of weevil control using a philosophy of whether control measures are required, the important consideration is the correct timing of implementation of control. This should be based on soil sampling for pupae to gain an early indication of insect development stages and monitoring for signs of adult presence such as leaf scalloping or using monitoring bands to measure weevil abundance directly. This aspect is considered in more detail in the section on Chemicals.

Apple weevil

The pest status of apple weevil is less clear compared to that for garden weevil. Pedicel feeding can at least be classified as cosmetic damage, with that part of the pedicel that is chewed apparent as a discolouration to the stalk. At worst, fruit weight loss and even fruit fall can result if ringbarking.
occurs. The aspect of fruit fall was not considered in this project. The other aspect not considered here was that of the effect of feeding by larvae.

The following discussion is restricted to a consideration of adult apple weevils ringbarking fruit and consequent reduced fruit weight.

From the data on abundance of apple weevil in individual trees and associated pedicel damage, the concept of EIL for apple weevil was examined. As for garden weevil, weevil abundance in individual trees and pedicel feeding were examined.

The level of pedicel ringbarking by apple weevil in individual apple trees in the Maslin orchard, Manjimup plotted against the maximum weevil abundance in monitoring bands is given in Fig. 13. Regression analysis showed the relationship was not a linear one. The variation in this data set was obviously too large to define what should be a direct and linear relationship between weevil numbers and proportion of fruit pedicels ringbarked.

![Fig. 13. Percent fruit with pedicels ringbarked by apple weevil adults in individual trees plotted against the maximum abundance of adults, Maslin Orchard, Manjimup.](image)

Regression analysis of the data on weevil abundance in the early stages of weevil emergence when most bands had around 10 weevils each and maximum weevil abundance did show a linear relationship (see Fig. 14). The fact that this relationship exists gives some hope to the possibility of introducing the concept of an EIL for apple weevil. It remains a challenge to determine the relationship between weevil abundance later in the emergence cycle and damage.
Fig. 14. The number of apple weevil adults per monitoring band for individual trees on 12 Dec. 1995 plotted against the number of weevils in monitoring bands in the same trees at maximum weevil abundance on 2 Jan. 1996, Maslin Orchard, Manjimup. Regression analysis showed the relationship was linear, with 25.3% of the variance accounted for (P = 0.014).

The relationship between maximum weevil abundance and fruit pedicel damage in the Owen Orchard in the Perth Hills is shown in Fig. 15. Regression analysis showed the relationship was not adequately defined as linear.

Fig. 15. Percent fruit with pedicels ringbarked by apple weevil adults in individual trees plotted against the maximum abundance of adults, Owen Orchard, Perth Hills. Regression analysis showed the relationship was weakly linear, with only 10.6% of the variance accounted for (P = 0.225).

Examination of the relationship between the abundance of weevils per band in the earlier stages of weevil emergence and when weevils were at maximum abundance on 18 December 1995 in the Owen Orchard, showed the best fit linear relationship existed with weevil abundance on 4 December 1995 (see Fig. 16).
These results provide further evidence to support the possibility of using weevil abundance in monitoring bands early in the emergence cycle to make decisions on the need to control the weevils. With the collection of further data on weevil abundance and fruit pedicel damage, the definition of an EIL for apple weevil should be possible.

Summary
Garden Weevil damaged up to 50% of the fruit in some plots. Apple Weevil damaged up to 15% of fruit and reduced the weight of individual fruit by 20% as a result of girdling the fruit stalk. Fullers Rose Weevil did not cause direct damage to the fruit. The relationship between weevil numbers and amount of damage was not linear and we were not able to determine an economic injury level based on weevil numbers.

5.7 What factors in the biology of weevils affect their distribution within orchards?

Introduction
The work reported in previous sections highlighted the importance of the pattern of distribution of the weevils throughout an orchard. A better understanding of the factors affecting the distribution of weevils could yield important leads for monitoring and control of the pests. The aims of the work presented in this section were
(i) To clarify the horizontal distribution of weevil larvae across the orchard floor and the number of generations of weevils per year based on seasonal abundance of mature larvae.
(ii) To clarify the role of some plants on larval growth and survival.
(iii) To relate adult weevil numbers with the number of generations occurring per year
(iv) To quantify the seasonal fertility status of females and to examine the potential effects of food plant on adult fecundity.

Materials and Methods
The horizontal distribution of larvae on the orchard floor was described on the basis of a sampling grid along tree rows and across tree rows i.e. in the tree inter-rows. This sampling was undertaken from late winter to late spring, when weevil larvae were large enough to be easily seen in field examination of soil. This sampling was conducted for the process of selecting orchard sites for other studies described in this report. The sampling unit was a square spade of soil, 0.04m², to a depth of about 15 cm. A consistent sampling pattern was followed on each orchard of alternately examining soil near the base of a fruit tree and half way across the inter-row.
The number of generations of weevils per year was determined by soil sampling from winter 1996 to autumn 1997 in a cherry orchard heavily infested by apple weevil. From autumn to spring, soil samples were examined intensively using the method described by Matthiessen and Ridsdill-Smith (1991). The process involves washing and sieving the soil samples, followed by flotation in soda ash to collect insects. Resultant samples were examined under a microscope to detect very small weevil larvae. Soil samples later in the season consisted of a square spade of soil to a depth of about 15 cm, which was examined in the field. At this time, only large larvae were expected to occur. The abundance of apple weevil adults in trunk monitoring bands on the fruit trees over the duration of the soil sampling was also measured.

The role of food plants on growth and survival of larvae of garden weevil was undertaken as pot trials in Victoria and Western Australia using plant species considered to be the most likely that larvae of the weevils would encounter, including apple and orchard floor plants. Selection of plants included in this food plant study, was based on surveys of orchards in Western Australia and Victoria, as well as previous field observations on weevil abundance under certain species of weeds. Newly emerged larvae from a laboratory culture of adult weevils were seeded into pots that had been sown to the target plant species about six weeks earlier. Pots were checked for larvae after infestation periods varying in duration from 3 days to ten weeks. The number of larvae, pupae and adults were scored to calculate percent survival. Head capsule widths of larvae were measured. For a full description of the trial conducted in WA, see Bowden (1997) and for Victoria see Endersby et al (1998).

The plants selected for testing in these experiments were:

- Dutch carrot: Daucus carota cv Topweight
- Apple: Malus sp
- Strawberry clover: Trifolium fragiferum
- Sub-clover: Trifolium subterraneum cv Dalkeith
- White clover: Trifolium repens
- Canola: Brassica napus cv Narendra
- Capeweed: Arctotheca calendula
- Common sowthistle: Sonchus oleraceus
- Dandelion: Taraxacum officinale
- Sorrel: Rumex acetosella
- Perennial ryegrass: Lolium perenne
- Oats: Avena sativa cv Mortlock

While some data was collected on garden weevil abundance during this study, the actual abundance of the weevil during the season in the single orchard where the weevil was most abundant was inadvertently sprayed just after peak weevil occurrence. Data on garden weevil seasonal abundance is available from other studies and is reported elsewhere.

No data is presented on seasonal abundance of Fuller's rose weevil adults due to relatively low numbers of weevils present in infested orchards studied. Other studies in Australia and overseas provide information on the number of generations per year for this species.

In determining the number of generations per year for apple weevil, the seasonal abundance of adults for other studies in this project was examined.

The fertility status of females was quantified in conjunction with the assessments on adult monitoring mentioned above. Sampling was undertaken approximately fortnightly, with 20 females being collected from across the sampling site and returned to the laboratory for dissection to ascertain reproductive status. The reproductive status of females was categorised as:

- **non-egg-laying** - these females were either young and immature, with soft exoskeletons, light colour and may not have fed and/or had no well developed eggs; or were old, occurred later in the season and had hard, dark exoskeletons, and may or may not have fed. Usually the body contents of these old weevils were dark and sometimes appeared dried-up.
- **mature and egg-laying:** these weevils had well developed eggs, had hard dark exoskeletons and usually had fed.

As more information comes to hand, these categories may be further refined. Eggs were counted also as each weevil was dissected.

The role of food plants on adult female fecundity is dependent on plants to which adults have access. Therefore, before work on adult fecundity in relation to food plant could be undertaken, a survey of orchard floor plants was conducted. This was achieved by mail questionnaire to orchardists in WA and a field assessment of orchard and vineyard floor plants in Victoria.

**Results:**
The horizontal distribution of larvae across the orchard floor is shown in Fig. 17. Sampling was conducted at the base of the fruit tree or halfway across the inter-row. There was no consistent trend in occurrence of larvae. In most cases weevil larvae occurred near the base of the fruit tree at least in equal abundance to that in the inter-row. Only two orchards had a much greater number of larvae in the inter-row than near the tree.

![Graph showing the abundance of weevil larvae per square metre of soil either near the base of the tree or halfway across the inter-row in apple orchards.](image)

**Fig. 17.** The abundance of weevil larvae per square metre of soil either near the base of the tree or halfway across the inter-row in apple orchards.

The abundance and relative proportions of the soil dwelling stages of apple weevil from winter to the following autumn is shown in Fig. 18 (a) and (b) respectively. The abundance of small larvae was roughly constant until spring. With the onset of warmer weather, the rate of larval development increased together with an apparent very large mortality level. The subsequent abundance of more mature larvae and pupae was much lower than that of young larvae. No young larvae were found on the last two sampling occasions when in-field sampling only was undertaken, so they could have been missed. On the last sampling occasion in early March, almost all weevils found were adults.

Although apple weevil adults have a nocturnal activity and do burrow into the upper soil surface, the abundance of adults indicated in Fig. 18 (a) and (b) would be a gross underestimate of the abundance of adults because many would be present on trees during the day. The abundance of apple weevil adults in the fruit trees while the soil sampling was conducted is indicated by the results from trunk
monitoring bands and is shown in Fig. 18 (c). Adults were first recorded in early December, which is consistent with finding some adult weevils during the soil sampling. The decline in adult numbers in the trunk band monitoring is to some extent an artifact resulting from a combination of greater weevil activity in the canopy of the fruit trees and some probable mortality of adults.
Fig. 18. (a) The abundance and (b) relative proportion of the different soil dwelling stages of apple
weevil in a cherry orchard in 1996/97, small, medium and large refer to larvae; and (c) the abundance of apple weevil adults in trunk monitoring band on trees where the soil sampling was undertaken.

The results of the pot trials examining the suitability of a range of plants for survival and growth of garden weevil larvae are shown in Figs. 19 to 23.

Fig. 19. The survival and growth of garden weevil larvae after nine weeks in pots sown to sorrel, canola, oats, carrot and subterranean clover. First instar larvae were placed in the pots. (a) % survival, (b) average dry weight in mg and (c) average head capsule width in mm.
Fig. 20. The survival and growth of garden weevil larvae after seven weeks in pots sown to carrot, sowthistle, capeweed, dandelion and white clover. First instar larvae were placed in the pots. (a) percent survival 14, 28 and 49 days after infesting pots, (b) average weight in mg and (c) average head capsule width in mm, 49 days after infesting pots.
Fig. 21. The survival and growth of garden weevil larvae eight to ten weeks after first instar larvae were placed in pots sown to carrot, apple, white clover, strawberry clover and perennial ryegrass. (a) percent survival and (b) average weight in mg.

Fig. 22. The survival and growth of garden weevil larvae 8 weeks after first instar larvae were placed in pots sown to carrot, apple, white clover, strawberry clover and perennial ryegrass. (a) percent survival and (b) average weight in mg.
The most favourable food plants for survival and growth of larvae of garden weevil were the weeds sorrel, sowthistle, capeweed and dandelion (see Figs. 19 and 20), carrot (see Figs. 19, 20, 21, 22 and 23), apple (see Figs. 21, 22 and 23), canola and oats (see Fig. 19). Clovers gave a slightly inconsistent result, but on average were poor food plants for garden weevil larvae in this series of experiments.

Also, in general, plants that were favourable in terms of a high survival rate resulted in the larger, more mature larvae. Garden weevil reached the pupal stage on carrot and apple within the duration of the individual experiments.

The seasonal abundance of adult apple weevil in apple orchards in the Perth Hills and Manjimup/Pemberton that were recorded in conjunction with other studies in this project, are shown Fig. 24. With the exception of the MHRC orchard in Manjimup/Pemberton, the data shows only one peak in weevil occurrence, indicating univoltinism.
Fig. 24. The abundance of apple weevil adults in trunk monitoring bands in orchards in the Perth Hills (broken lines) and in the Manjimup/Pemberton area (solid line), in 1995/96 and 1996/97 seasons.

The seasonal level of adult fertility, indicated by the presence of mature eggs in the oviduct, is shown in Fig. 25 (a) and (b) for apple weevil and Fig. 26 for garden weevil in the 1995/96 and 96/97 seasons, respectively. For apple weevil, 8 to 10 weeks elapsed between peak weevil abundance in the trunk monitoring bands and the maximum proportion of weevils with mature eggs. This situation was in contrast to that for garden weevil where the duration between peak weevil numbers and maximum proportion of weevils with mature eggs was around 5 weeks.

For Fuller's rose weevil, dissections of weevils in one orchard monitored in the Pemberton region in the 1995/96 season, indicated that 70 and 90% of weevils had mature eggs on 5 January 1996 and 16 January 1996 respectively. This was about 2 to 3 weeks after the peak in weevil occurrence of around mid to late December 1995 (Fig. 4 (d)).
Fig. 25. Seasonal abundance of apple weevil, and % adults with mature eggs, in two orchards during the 1995/96 season; (a) Perth Hills orchard, (b) Manjimup Orchard.

Fig. 26. Seasonal abundance of garden weevil, and % adults with mature eggs, in a Donnybrook Orchard 1996/97 season.
Surveys for plant species occurring on the orchard floor identified the following as being most common in Western Australia (20 most common shown, see Appendix 1 for complete list and relative abundance in the three main fruit growing regions in WA) and Victoria:

**WESTERN AUSTRALIA:**
- Clover
- Couch (water & summer)
- Fat hen
- Soursob
- Paspalum
- Wild radish
- Capeweed
- Guildford grass
- Kikuyu
- Blackberry nightshade
- Ryegrass
- Wireweed
- Milk thistle
- Prince (of Wales) feather
- Dock
- Portulaca
- Sorrel
- Barley grass
- Chickweed
- Marshmallow

**VICTORIA:**
- barley grass
- brown top bent, bent grass
- capeweed
- common sowthistle
- dandelion
- flatweed
- lesser canary grass
- perennial ryegrass
- strawberry clover
- white clover
- wild oat

**Discussion:**
The horizontal distribution of larvae in an orchard was found to be inconsistent for at least apple weevil and garden weevil, the species for which most data were available. This result is in some contrast to that found by Home et al (1997), where around 97% of garden weevil larvae were found in the inter-rows in a vineyard. More information is required to clarify the situation for Fuller's rose weevil. No attempt was made to determine whether the inconsistency of results in the present study was related to the distribution and type of plants present in orchards. This aspect is discussed in more detail below concerning the role of food plants on larval survival and development.

Soil sampling to determine the number of generations of apple weevil indicated that only one generation occurs per year. The soil sampling was not extensive but was spread over the season and the almost complete absence of larvae in the last sample in early March was considered to be good evidence in support of the conclusion of univoltinism. This result is further supported by the reproductive status of adults during the season (see Figs. 25 and 26). The situation regarding numbers of generations per year for the other two species of weevil was not examined in sufficient detail in this project to draw any conclusions.

The results of the pot trials assessing different plant species and types for their suitability as food plants for garden weevil larvae represents the early stages of this type of investigation. Recovery of larvae in some of the experiments was low and this was considered to not always be a reflection of the
unsuitability of that plant as a food source. Rearing methods need close attention such that consistent survival rates of larvae on what are considered to be acceptable food plants, can be achieved so that low recoveries relate to food source acceptability.

Nevertheless, results obtained produced some surprising differences. From previous field experience, it was expected that sorrel and capeweed would be suitable food plants, but it was a surprise that the grass, represented by oats, proved to be a reasonable food source. Also, the poor survival of larvae on the pots containing clover was unexpected.

These results have implications for weevil abundance and distribution of larvae in orchards. Both are important issues in relation to weevil management. By manipulating the type of plants in orchard inter-rows, it may be possible to reduce the reproductive and survival potential for weevils in orchards.

This series of experiments must be regarded as preliminary. The results obtained here require confirmation with further experimentation. This should involve testing the same range of plants with more mature larvae, in contrast to the method adopted here of using first instars. Such work could identify the very unfavourable plants for weevil survival.

The studies also need to be extended both in terms of the two other species of weevil - apple weevil and Fuller's rose weevil - and the type of plants tested.

The seasonal abundance of adults of apple weevil in tree trunk bands was consistent with this species having only one generation per season. This conclusion is supported by the data on larval abundance and maturity, and adult maturity. Apple weevil adults undergo a relatively long period prior to becoming capable of laying fertile eggs. This has implications for more sustained reduction in reducing the abundance of apple weevil in orchards. If good control of weevils can be achieved during the period of weevil emergence, then the effect on weevil abundance in the following season at least could be such that control measures may not be required.

More information is required on both garden weevil and Fuller's rose weevil seasonal abundance and adult maturity before firm conclusions about the number of generations per year can be clarified. Both species seem to reach reproductive maturity much sooner than apple weevil. If this is confirmed, the possibility of a second generation occurring in some seasons at least when temperatures are high. Also, sustained control of these species will be achieved only if control measures are adopted in a concerted effort in the early stages of weevil emergence.

The role of food plants on the fecundity of weevils was not investigated during this study. The main species of plants found on the orchard floor, and the fruit crop itself, should be included in any such studies.

Summary

Garden Weevil larvae seem to have a preference for tap-rooted plants. Dandelions supported the highest population but Capeweed and Sow Thistle were also important hosts. White Clover did not appear to be a favoured host. More work is required before recommendations can be made regarding choice of orchard floor species.
5.8 Can we reduce reliance on pesticides for management of weevils?

Introduction
Primary producers are under considerable pressure to reduce their use of pesticides, or at least to move towards “softer” chemicals. The aim of work in this section was to assess the effectiveness of a range of control methods, detailed below, for their ability to reduce weevil abundance in orchards. The emphasis was placed on methods that would reduce the reliance on pesticides.

Materials and Methods

(i) Exclusion bands
Polybutene sticky bands are successfully used in South Africa to prevent garden weevil from accessing the canopy of fruit trees and grapevines. Trials in WA confirmed this (Learmonth, unpbl. data), however early trials using sticky bands did not seem to prevent apple weevil adults from entering the tree canopy. They have not been tried against Fuller’s rose weevil.

To confirm whether sticky exclusion bands were unsuitable for preventing apple weevil from entering the tree canopy, a trial was undertaken in two commercial apple orchards infested with this weevil. Sticky bands were placed on some trees before weevil emergence. Nearby trees did not receive a sticky band and other trees in the same block were treated with insecticide according to commercial practice.

(ii) Baits
Because the adult weevils of all three species are flightless, the possibility for control through the application of a toxic bait on the orchard floor at weevil emergence provides another avenue for management. Compared to successful baits developed for other pests, bait for these weevils may have to take into account that all the weevils consume living plant tissue. Therefore as well as the usual problems of identifying suitable attractants and toxicants that will not repel the target pest, the identification of a suitable food base and its moisture content are a major requirement. This investigation concentrated on the aspect of comparing attractants for garden weevil that might be a component of a bait.

The method used was to record the presence of weevils at various compounds placed on carrot discs that were equidistant from a central release point for weevils on aluminium trays 53 cm square. The inner sidewalls of the trays were coated with Fluon to prevent weevils escaping. Recordings were made in a laboratory at 25 °C with the photophase reversed and set at long days (L:D = 14:10) to simulate summer. Experiments were set up in the morning and run during the day (darkness in the laboratory), recording the occurrence of weevils at 2 hour intervals from 1000 until 1600, with the final assessment being 0800 the next day.

(iii) Biological control.
The possible role of microbiological organisms and egg parasites was investigated.

The studies on microbiological organisms included screening a range of strains of the bacterium *Bacillus thuringiensis* and entomopathogenic nematodes. These agents were screened against the larval and adult stages of the weevils by entomologists at CSIRO, Canberra, using field-collected larvae and adults from WA during the season and laboratory held adults through autumn and winter where necessary. For *B. thuringiensis* tests, apple weevil adults were fed treated apple leaf discs for two days before transferring them to untreated carrot. In a second trial, treated carrot was used to administer the bacterium. There was only one trial involving Fuller’s rose weevil. In this trial weevil adults were fed treated carrot discs.

Three strains of entomopathogenic nematodes were assessed for efficacy in a laboratory bioassay using field-collected garden weevil larvae.

The occurrence of egg parasites for Fuller’s rose weevil and garden weevil is known. Egg parasites for Fuller’s rose weevil have been reported both overseas and in Australia and for garden weevil, they have only been reported from South Africa, the country of origin for this species. Therefore it is likely that egg parasites occur for apple weevil also, but this is yet to be confirmed in the area of origin of this
species. A survey to detect egg parasites of the three species of weevil at various locations in the southwest of Western Australia was undertaken, using fresh eggs collected from laboratory reared populations of weevils.

(iv) Birds.
There has been evidence that guinea fowl have some impact on the abundance of garden weevil in South Africa, and in WA in commercial vineyards. The role of insectivorous ground birds on weevil survival was studied.

These studies were restricted to field cage trials in research station orchard plots infested by either garden weevil or apple weevil. Areas of fruit trees under bird netting to protect fruit from attack by pest species of birds were used. In one trial involving garden weevil, the area under bird netting was subdivided into three compartments. Each of these was stocked with one species of bird – turkeys, chickens or guinea fowl - with the stocking rate of 50 to 70 birds / ha. In a second trial involving apple weevil, the entire caged area was stocked with guinea fowl at a stocking rate of 100 birds / ha. Plots for measuring any effects of the birds on weevil abundance were either single trees or 3 rows with 5 trees each row. These were caged with chicken wire 1 to 1.8 m high to exclude the birds. A paired adjacent plot, of the same dimensions, where birds had free access was used for comparison. There were 6 replications of each paired plot.

To measure the effect of the birds on weevil abundance, monitoring bands were placed on tree trunks both where the birds had access and on trees that were caged. In order to interfere with weevil movement as little as possible, the monitoring bands were placed on the trees for 3 to 4 days only, checked for weevils then removed until the next sampling occasion which were at approximately fortnightly intervals.

Weevil damage to the trees was recorded. For leaf damage a ranking system was used: 0 = none/little <5%; 1 = noticeable 5-25%; 2 = obvious 25-50%; 3 = severe >50%. For fruit damage, 100 apples or all apples if there were fewer than 100, in each plot were examined for signs of weevil feeding.

In the trial involving garden weevil, the trial was run for a second season. The trial design was modified to include a second series of cages and associated paired plots in each of the three partitions.

(v) Insecticides.
Currently, apple weevil and garden weevil are controlled commercially by application of insecticide solution to the crotch and butt of fruit trees. This is termed a butt drench and is only registered for use in WA. Azinphos-methyl is registered as a foliar application against Fuller's rose weevil in WA only. It is only the first two weevils that routinely require treatment. Situations where Fuller's rose weevil populations require control appear to be less frequent.

The disadvantages of the butt drench for weevil control are that they are very time consuming, need to be applied at the correct time for best control and sometimes a second application is required within a season to achieve control. Such disadvantages prompted the recent construction of an automatic butt drenching machine by a company in WA. The effectiveness of insecticide application by this machine to control both apple weevil and garden weevil was assessed in commercial orchards. The comparison included untreated trees and trees receiving a butt drench by the traditional hand lance method.

The effectiveness of the butt drench method for control of Fuller’s rose was not assessed.

Because of the disadvantages of the butt drench method for weevil control and where the butt drench may have been applied too late and weevils have already entered the fruit tree canopy, some investigations on foliar chemicals for weevil control were also undertaken.

Results:
(i) Exclusion bands
The abundance of apple weevil adults in trunk monitoring bands in the apple orchard where sticky bands were assessed is shown in Figs. 27 and 28. Peak weevil emergence in untreated trees occurred in mid December in both orchards. The use of sticky bands at best delayed slightly the occurrence of apple weevil adults in the monitoring bands. In both orchards, the commercial butt drench was applied earlier than peak weevil emergence resulting in fewer weevils in those trees. The trees receiving the
sticky bands were butt drenched after it was apparent the sticky bands were ineffective in preventing weevils accessing the tree canopy.

Fig. 27. The average number of apple weevil adults in monitoring bands on apple trees in the Owen Orchard, Perth Hills, WA in the 1995/96 season. The trees were either untreated, or received a sticky trunk band and a butt drench (as indicated by the dashed arrow), compared to commercial treatment for apple weevil using a butt drench (indicated by the solid arrow).

Fig. 28. The average number of apple weevil adults in monitoring bands on apple trees in the Littlely Orchard, Perth Hills, WA in the 1995/96 season. The trees were either untreated, or received a sticky trunk band and a butt drench (indicated by the dashed arrow), compared to commercial treatment for apple weevil using a butt drench (indicated by the solid arrow).
(ii) Baits
The results of the laboratory tests on various attractants, fresh foods and pellets, both commercial and prototype pellets with dried apple or dried carrot as the attractant base, are shown in Tables 14 and 15 and Fig. 29.

The ranking of attractants given in Table 14 is a broad, initial indication as to whether the candidate material is of any value as a bait component. The degree of variability in the attractiveness of particular materials is not presented in this report because of the preliminary nature of this investigation. Also, some materials that appeared to be attractive for garden weevil appeared to lose attractiveness when applied to grain pellets. For example apple cider vinegar ranked highly in Table 14 but poorly in Table 15 when applied to pellets.

There were also some unexpected results such as the effect of potato flour as a mid range attractant material (Table 14) and fresh potato tuber as the most attractive of the fresh food products (Fig. 29). Also, pollen was a mid range attractive material in the early tests (Table 14) and the most attractive of the pellets (Fig. 30, Table 15).

While carrot was reasonably consistently attractive to garden weevil in all tests, a suitable bait would need to have carrot or another suitable material incorporated in a some type of pellet for ease of application in an orchard. For this reason the apple and carrot pellets were formulated based on dried apple and carrot using an experimental pelleting machine. Good levels of attractiveness were achieved to these pellets, especially for the pellets with the higher concentration of apple or carrot.

Table 14. The attractants tested and the number of tests with each, for their potential use in a bait for garden weevil adults. Attractants are ranked according to the average number of weevils present on them over five replications and five readings per test in the laboratory.

<table>
<thead>
<tr>
<th>Attractant</th>
<th>Rank</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple cider vinegar</td>
<td>11.6</td>
<td>3</td>
</tr>
<tr>
<td>Lemon juice</td>
<td>8.9</td>
<td>5</td>
</tr>
<tr>
<td>Vanilla essence</td>
<td>8.9</td>
<td>1</td>
</tr>
<tr>
<td>Apricot nectar</td>
<td>8.7</td>
<td>3</td>
</tr>
<tr>
<td>Pollen</td>
<td>8.6</td>
<td>3</td>
</tr>
<tr>
<td>Carrot (no attractant)</td>
<td>8.0</td>
<td>4</td>
</tr>
<tr>
<td>Crushed garlic</td>
<td>7.5</td>
<td>8</td>
</tr>
<tr>
<td>Rice flower</td>
<td>7.0</td>
<td>2</td>
</tr>
<tr>
<td>Orange juice concentrate</td>
<td>6.6</td>
<td>4</td>
</tr>
<tr>
<td>Molasses</td>
<td>5.3</td>
<td>6</td>
</tr>
<tr>
<td>Liquid malt</td>
<td>5.1</td>
<td>3</td>
</tr>
<tr>
<td>Vegemite</td>
<td>5.1</td>
<td>3</td>
</tr>
<tr>
<td>Egg yolk</td>
<td>5.1</td>
<td>2</td>
</tr>
<tr>
<td>Potato flour</td>
<td>5.0</td>
<td>3</td>
</tr>
<tr>
<td>Sugar</td>
<td>4.6</td>
<td>3</td>
</tr>
<tr>
<td>Coffee powder</td>
<td>4.5</td>
<td>2</td>
</tr>
<tr>
<td>Honey</td>
<td>4.3</td>
<td>2</td>
</tr>
<tr>
<td>Crushed garlic</td>
<td>4.2</td>
<td>3</td>
</tr>
<tr>
<td>Peppermint essence</td>
<td>4.0</td>
<td>3</td>
</tr>
<tr>
<td>Crushed grains</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>Soybean oil</td>
<td>3.9</td>
<td>3</td>
</tr>
<tr>
<td>Peanut oil</td>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>Canola oil</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>Fructose</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>Apple juice</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>Sunflower oil</td>
<td>1.4</td>
<td>3</td>
</tr>
</tbody>
</table>
Fig. 29. Number of garden weevil adults at various fresh foods and crushed grain at varying intervals after placement.

Table 15. The attractants and grain based pellets tested and the number of tests with each, for their potential as a bait for garden weevil adults. Attractants are ranked according to the average number of weevils present on them over five replications and five readings per test in the laboratory.

<table>
<thead>
<tr>
<th>Attractant/Pellet</th>
<th>Rank</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot - fresh</td>
<td>21.0</td>
<td>8</td>
</tr>
<tr>
<td>Pollen pellets</td>
<td>18.7</td>
<td>2</td>
</tr>
<tr>
<td>Apple pellets 10%</td>
<td>17.3</td>
<td>3</td>
</tr>
<tr>
<td>Carrot pellets 20%</td>
<td>14.9</td>
<td>5</td>
</tr>
<tr>
<td>Apple pellets 20%</td>
<td>14.2</td>
<td>7</td>
</tr>
<tr>
<td>Carrot pellets 10%</td>
<td>11.8</td>
<td>1</td>
</tr>
<tr>
<td>Apple pellets 5%</td>
<td>11.6</td>
<td>3</td>
</tr>
<tr>
<td>Carrot pellets 5%</td>
<td>9.6</td>
<td>1</td>
</tr>
<tr>
<td>Grain pellets</td>
<td>5.8</td>
<td>8</td>
</tr>
<tr>
<td>Apple cider vinegar pellets</td>
<td>4.7</td>
<td>2</td>
</tr>
<tr>
<td>Apple juice pellets</td>
<td>4.6</td>
<td>2</td>
</tr>
<tr>
<td>Molasses pellets</td>
<td>4.5</td>
<td>2</td>
</tr>
</tbody>
</table>

The results of the single test that was run on apple weevil adults are given in Fig. 30. As was the case for garden weevil, pollen and apple cider concentrate were the most attractive materials tested.
(iii) Biological control.

46 strains of *B. thuringiensis* were tested against apple weevil. Results of the testing indicated that no strain currently available provides sufficient mortality to be considered worthwhile to proceed with more advanced trials such as a field test. The same result occurred in the Fuller’s rose weevil testing. Mortality levels in untreated controls were high, confounding any possible bacterium-related mortality effects.

The results of the laboratory bioassay on mortality of garden weevil larvae are given in Fig. 31. All three strains exhibited a dose response and strain JB1/X1 gave 100% mortality at the highest rate tested.

![Fig. 30. Number of apple weevil adults at various fresh foods at varying intervals after placement.](image)

Fig. 30. Number of apple weevil adults at various fresh foods at varying intervals after placement.

![Fig. 31. Mortality of garden weevil larvae exposed to three strains of entomopathogenic nematodes at a range of doses (IJs/ml) in a laboratory bioassay by R. Bedding, CSIRO, Canberra, ACT.](image)

Fig. 31. Mortality of garden weevil larvae exposed to three strains of entomopathogenic nematodes at a range of doses (IJs/ml) in a laboratory bioassay by R. Bedding, CSIRO, Canberra, ACT.

The locations within the southwest of WA where weevil eggs were placed to determine if egg parasites occur, are shown in Table 16. Also shown is the number of egg cards distributed in each area and, upon retrieval of them, the number of weevil larvae that emerged from the eggs when incubated in the laboratory. No egg parasites were found.
The duration between placing eggs in the field and recovering them ranged from 8 to 10 days. Eggs were placed in the field between late February and mid April. Because only fresh eggs were placed in the field and temperatures were falling, few eggs would have hatched in the field. Barnes (1987) describes the duration of the egg stage for garden weevil as being 7 days at 25 °C. Therefore the number of larvae that were recorded from the egg cards in the laboratory was a good indication of the viability of eggs placed in the field. As can be seen from Table 16, there was a poor egg viability of apple weevil eggs. There was a reasonable level of egg viability for the other two weevil species.

Table 16. The locations for field placement of cards containing eggs of three weevil species, the number of egg cards and the number of larvae reared from the eggs when returned to the laboratory in a survey for the presence of egg parasites in WA.

<table>
<thead>
<tr>
<th>Location</th>
<th>No. eggs cards distributed</th>
<th>No. larvae</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GW</td>
<td>AW</td>
</tr>
<tr>
<td>Perth Hills</td>
<td>40</td>
<td>63</td>
</tr>
<tr>
<td>Harvey</td>
<td>31</td>
<td>10</td>
</tr>
<tr>
<td>Donnybrook</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td>Bridgetown</td>
<td>34</td>
<td>21</td>
</tr>
<tr>
<td>Manjimup/Pemberton</td>
<td>113</td>
<td>27</td>
</tr>
<tr>
<td>Kendenup</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Albany</td>
<td>29</td>
<td>12</td>
</tr>
<tr>
<td>WA total</td>
<td>298</td>
<td>163</td>
</tr>
</tbody>
</table>

(iv) Birds.

The abundance of garden weevil in trunk monitoring bands on trees where the birds either had access or not in the 1996/97 season is shown in Fig. 32. Unfortunately the abundance of garden weevil was not uniform over the trial area - more weevils were present in the portion of the orchard stocked with turkeys, with successively fewer weevils in the area stocked with chickens and guinea fowl. Nevertheless, each of the three bird types reduced the abundance of weevils recorded in the monitoring bands. The effect was less noticeable in the area stocked with guinea fowl because the weevil was least abundant in that area.

The differences in weevil abundance in the caged and open areas was reflected in the level of damage by garden weevil adults to leaves and fruit for each of the three types of birds (see Figs. 33 and 34, respectively).
Fig. 32. The abundance of garden weevil adults in trunk monitoring bands on trees either excluded from birds by cages or uncaged (open) in an orchard stocked with turkeys, chickens or guinea fowl in separate partitions; at Stoneville Research Station, Perth Hills, 1996/97 season.

Fig. 33. The average number of trees with garden weevil leaf damage in four ratings categories (see text for definitions) in plots where trees were either excluded from three different bird types or where the birds had access to the trees; at Stoneville Research Station, Perth Hills, 1996/97 season.
Fig. 34. Percent fruit damaged by garden weevil adults in plots where trees were either excluded from three different bird types or where the birds had access to the trees; at Stoneville Research Station, Perth Hills, 1996/97 season.

Fig. 35. The abundance of garden weevil adults during the 1997/98 season in trunk monitoring bands on trees either excluded from birds by cages or uncaged (open) in one or two successive seasons in an orchard stocked with turkeys, chickens or guinea fowl in separate partitions; at Stoneville Research Station, Perth Hills.
In the areas stocked with turkeys and chickens, trees where the birds had access had leaf damage in category 1 only, compared with some of the trees in cages where the birds were excluded having leaf damage in category 2. Because of the low abundance of garden weevil in the portion of the orchard stocked with guinea fowl, only a low proportion of trees there had any damage and this was all in category 1. All trees in this area where the guinea fowl had access were rated in category zero leaf damage (see Fig. 33).

Damage to fruit was greatest in caged trees in the area stocked with turkeys where garden weevil abundance was highest. Lower levels of damage were recorded in trees stocked with chickens or guinea fowl where weevil abundance was lower. In all three areas, fruit on trees where birds had access had lower levels of damaged fruit (see Fig. 34).

Measurements made on weevil abundance and leaf and fruit damage in the second year of the trial at Stoneville Research Station are given in Figs. 35, 36, 37 respectively.
Fig. 37. Percent fruit damaged by garden weevil adults during the 1997/98 season in plots where trees were either excluded from birds by cages or uncaged (open) in one or two successive seasons in an orchard stocked with turkeys, chickens or guinea fowl in separate partitions; at Stoneville Research Station, Perth Hills.

In general, the abundance of garden weevil was similar in the 2 seasons, with the possible exception of a slightly greater number of garden weevils in the area stocked with guinea fowl. The trend in weevil abundance in each of the three partitions was similar to that for measurements made in the 1996/97 season (Fig. 35). The greatest number of weevils were recorded in the area stocked with turkeys, followed by the area with chickens and then the guinea fowl area. The variability in the abundance of garden weevil within a partition is reflected in the counts in the "open" areas for the two sets of areas – 1996/98 and 1997/98.

The abundance of garden weevil was greatest on trees excluded from the birds (Fig. 35). With the exception of the area stocked with guinea fowl, there appeared to be a cumulative effect of excluding birds from trees over 2 seasons. The abundance of weevils in the excluded trees for the 1996/98 seasons was greater than that for trees where cages were erected for the 1997/98 season for both the turkey and chicken stocked areas. The abundance of garden weevil was lowest in the open areas, with this effect being less apparent in the area stocked with guinea fowl where the abundance of the weevil was lowest, as was the case in the previous season.

Leaf damage was minor across the trial area in the 197/98 season but the trees with some leaf damage consistently came from those areas where birds were excluded (Fig. 36).

Differences in fruit damage between excluded and open areas were more apparent in trees where birds had been excluded for 2 successive seasons. The slightly lower numbers of weevils in the open areas in the 1997/98 series of trees was not reflected in reduced fruit damage (Fig. 37).

The abundance of apple weevil adults in trunk monitoring bands in a cherry orchard at Manjimup Horticultural research Centre where the role of guinea fowl was investigated in the 1997/98 season is shown in Fig. 38. There was no difference in weevil numbers on trees that had been excluded from the birds and those where the birds had access.
The results of the insecticide trial for control of garden weevil at an apple orchard near Capel are given in Tables 17 and 18, for weevil abundance and fruit damage for some of the treatments, respectively. As can be seen from Table 17 the distribution of weevils across the trial site was very uneven to the extent that the low numbers of weevils in the early butt drench treatment were not significantly different to untreated trees, despite the numerical difference. After the foliar treatments were applied in late November, all treatments gave a significant reduction in weevil numbers. For the data on proportion of fruit damaged by garden weevil, there was no significant difference among treatments selected for comparison (see Table 18). Considering the low numbers of weevils recorded in the trees receiving the early butt drench, this result is very surprising.
Table 17. The abundance of garden weevil adults in trunk monitoring bands in an insecticide screening trial near Capel, WA in the 1996/97 season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Date and mean number of weevils</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-Nov</td>
<td>13-Nov</td>
<td>18-Nov</td>
<td>25-Nov</td>
<td>9-Dec</td>
<td>23-Dec</td>
<td>20-Jan</td>
</tr>
<tr>
<td>1 Untreated</td>
<td>7.6</td>
<td>16.4</td>
<td>15.6</td>
<td>7.0</td>
<td>2.2</td>
<td>3.2</td>
<td>4.6</td>
</tr>
<tr>
<td>2 Butt drench; Dominex @ 100ml/100L</td>
<td>7.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>3 Foliar Regent @ 2.5ml/100L</td>
<td>13.8</td>
<td>12.2</td>
<td>6.6</td>
<td>3.4</td>
<td>1.0</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>4 Foliar Regent @ 5ml/100L</td>
<td>5.4</td>
<td>11.4</td>
<td>11.8</td>
<td>8.6</td>
<td>1.2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>5 Foliar Regent @ 10ml/100L</td>
<td>3.2</td>
<td>7.4</td>
<td>9.0</td>
<td>8.4</td>
<td>0.6</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>6 Foliar Regent @ 20ml/100L</td>
<td>3.4</td>
<td>4.8</td>
<td>6.6</td>
<td>6.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>7 Foliar Regent @ 10ml/100L - night</td>
<td>3.6</td>
<td>9.2</td>
<td>2.6</td>
<td>4.0</td>
<td>0.2</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>8 Foliar Dominex @ 50ml/100L</td>
<td>5.2</td>
<td>20.8</td>
<td>13.8</td>
<td>8.4</td>
<td>0.2</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

LSD ns ns ns ns 1.3 1.7 2.5 ns

*Treatments: Trt. 2 applied 7.Nov.96; Trts. 3 – 6 applied during the day on 27.Nov.96; Trts. 7 & 8 applied at night on 27.Nov.96

Table 18. The proportion of apples damaged in some of the treatments in an insecticide screening trial for the control of garden weevil in an orchard near Capel, WA in the 1996/97 season. Weevil damage was graded as slight if it could be sold as fresh fruit on the local market and severe if it was saleable as juice grade only.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% Slight Damage</th>
<th>% Severe Damage</th>
<th>% Total Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Untreated</td>
<td>7.9</td>
<td>11.2</td>
<td>19.1</td>
</tr>
<tr>
<td>2 Butt drench; Dominex @ 100ml/100L</td>
<td>7.7</td>
<td>12.9</td>
<td>20.7</td>
</tr>
<tr>
<td>6 Foliar Regent @ 20ml/100L</td>
<td>7.4</td>
<td>12.0</td>
<td>19.3</td>
</tr>
<tr>
<td>8 Foliar Dominex @ 50ml/100L</td>
<td>6.5</td>
<td>20.0</td>
<td>26.5</td>
</tr>
</tbody>
</table>

The results for the insecticide screening trials on apple weevil at Manjimup Horticultural Research Centre are given in Tables 19 and 20 for the 1995/96 and 1996/97 seasons respectively.

In the 1995/96 trial (Table 19), significantly lower numbers of weevils compared to for untreated trees were recorded on four occasions only. The best level of weevil control was achieved in the trees treated with the higher rate of Fastac. The other two treatments demonstrating some level of control were Talstar and Neem. Other insecticides performed poorly. There was a marked increase in weevil abundance in all trees in late summer to autumn.

In the 1996/97 trial (Table 20), significant differences in weevil abundance between untreated trees and treated trees were recorded on 7 occasions. Up to mid summer, all insecticide treatments significantly reduced weevil abundance. The treatments resulting in the greatest numerical reduction were the higher rates of Dominex and Talstar at the higher rates and Regent. There appeared to be better control of apple weevil as the rate of insecticide for the three insecticides used, although the differences between rates were not significant. During autumn, the only treatments with significantly lower numbers of weevils were the highest rates of Dominex and Regent.
Table 19. The abundance of apple weevil adults in trunk monitoring bands in an insecticide screening trial using foliar applications at Manjimup Horticultural Research Centre, WA in the 1995/96 season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Date and mean number of weevils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21-Dec</td>
</tr>
<tr>
<td>1. Untreated</td>
<td>57.0</td>
</tr>
<tr>
<td>2. Water only</td>
<td>39.4</td>
</tr>
<tr>
<td>3. Fastac 10ml/100L</td>
<td>62.4</td>
</tr>
<tr>
<td>4. Fastac 50ml/100L</td>
<td>71.2</td>
</tr>
<tr>
<td>5. Kluartan 40ml/100L</td>
<td>55.0</td>
</tr>
<tr>
<td>6. Talstar 20ml/100L</td>
<td>61.2</td>
</tr>
<tr>
<td>7. Confidor 15ml/100L</td>
<td>63.8</td>
</tr>
<tr>
<td>8. Guathion 490ml/100L</td>
<td>63.6</td>
</tr>
<tr>
<td>9. Neem oil 7.14l/100L</td>
<td>28.6</td>
</tr>
<tr>
<td>LSD</td>
<td>ns</td>
</tr>
</tbody>
</table>

Treatments 2 – 8 applied 21-Dec, 1995; Trt. 9 applied 22-Dec, 1995.

Table 20. The abundance of apple weevil adults in trunk monitoring bands in an insecticide screening trial using foliar applications at Manjimup Horticultural Research Centre, WA in the 1996/97 season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Date and **mean number of weevils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-Dec</td>
</tr>
<tr>
<td>1. Untreated</td>
<td>19.1</td>
</tr>
<tr>
<td>2. Butt drench Dominex</td>
<td>20.3</td>
</tr>
<tr>
<td>3. F Dominex 25ml N</td>
<td>21.5</td>
</tr>
<tr>
<td>4. F Dominex 50ml N</td>
<td>17.3</td>
</tr>
<tr>
<td>5. F Dominex 100ml N</td>
<td>14.8</td>
</tr>
<tr>
<td>6. F Dominex 50ml D</td>
<td>14.8</td>
</tr>
<tr>
<td>7. F Talstar 25ml N</td>
<td>5.3</td>
</tr>
<tr>
<td>8. F Talstar 50ml N</td>
<td>33.0</td>
</tr>
<tr>
<td>9. F Talstar 100ml N</td>
<td>14.9</td>
</tr>
<tr>
<td>10. F Regent 10ml D</td>
<td>19.0</td>
</tr>
<tr>
<td>11. F Regent 20ml D</td>
<td>22.6</td>
</tr>
<tr>
<td>12. F Regent 30ml D</td>
<td>13.7</td>
</tr>
<tr>
<td>LSD</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Treatment 2 applied 3 Dec, 1996; Trt. 6 & 10 - 12 applied 19 Dec, 1996; Trt. 3 - 5 & 7 - 9 applied 20 Dec, 1996. Butt drench rate in Trt. 2 was 100 ml Dominex/100L water @ 1L/tree. F = foliar; N = night spray; D = daytime spray. **Data that required transformation for analysis is shown as two series of figures within a column – the first is a square root transformation, the second number in italics is the back-transformed figure.
Discussion:
(i) Exclusion methods
The sticky band used to exclude garden weevil from fruit trees was not effective in excluding apple weevil. Given the laborious task involved in applying the sticky bands, they would only be practical to use in intensive crop situations and where garden weevil is the dominant pest species of weevil.

Further testing is required to assess any role these bands may have in managing Fuller’s rose weevil.

Alternative non-chemical exclusion methods such as use of Fluon slippery bands could be considered where apple weevil is a problem.

(ii) Baits
The range of attractants tested enabled a ranking of them for responses by garden weevil and, with a limited number of tests, also for apple weevil. The preliminary laboratory studies on pellet type baits indicated that such baits are worth considering for field experiments.

The next stage of development is to undertake field trials with prototype baits with additives such as pollen and a toxic component.

(iii) Biological control.
While results of the work with *B. thuringiensis* were disappointing, further testing of new strains should be undertaken. The strains currently available to control insects from a wide range of groups suggest that a new strain that has good activity against some or the entire weevil complex may be discovered in the future. The same situation would apply to the pathogenic fungi of the genera *Beauvaria* and *Metarhizium*.

The encouraging results from the nematode bioassays on garden weevil suggest that field trials are warranted. The strain that gave good levels of mortality, *Heterorhabditis zealandica* X1, is Australian, which obviates the need for quarantine restrictions for field trials.

The extensive survey for egg parasites of garden weevil and Fuller’s rose weevil lends support to the idea of importing parasites from areas where they have been reported - South Africa and eastern Australia, respectively. The fact that egg viability for apple weevil was very low in the survey for egg parasites means there is some doubt over the results where no parasites were recovered. A procedure to improve egg viability of this species needs to be determined before a repeat of the survey is undertaken. Because no reports of the occurrence of egg parasites have been found in the literature, surveys for egg parasites in the area of origin of this species would be worthwhile.

(iv) Birds.
From the studies on the role of birds in managing garden weevil in orchards it seems they may play a role in reducing pest abundance, while for apple weevil, they did not appear to have any effect.

This result for the 2 weevil species is somewhat surprising because apple weevil adults will burrow into soil, thereby being available for predation by birds. To counter this the dark brown colour of apple weevil adults could make them more cryptic in the soil, compared to the lighter colour of garden weevil adults.

The positive result for garden weevil provides encouragement for orchardists with a garden weevil pest problem and who are seeking an alternative to insecticide for control. The results over 2 seasons at Stoneville suggest that a longer period may be required before acceptable levels of weevil damage to fruit occur. In this study, weevil damage at 5% was recorded after 2 seasons' use of birds. To use birds requires some expenditure, planning and monitoring. Provision of water and feeding points as well as management to reduce predation of the birds by foxes are some issues to be considered.

(v) Insecticides.
The tests with the auto butt drencher were inconclusive because of low weevil abundance at trial sites. Problems in setting up the butt drencher to apply insecticide to two rows of trees simultaneously in commercial apple orchards, have meant that the machine has failed to be used by the industry, where further studies on its efficiency might have been undertaken. The advantages of reducing labour input
in applying the butt drench by machine could be considered great enough to encourage orchardists to review its use.

The insecticide screening trial on garden weevil indicates that the new insecticide Regent may have a role to play in weevil management. Further trials to substantiate its efficacy, especially clarifying the most appropriate rate, are required. At the same time, the impact of foliar applications of this product on non-target pests and beneficials in the orchard ecosystem require clarification.

The insecticide screening trials on apple weevil also indicate that the insecticides Talstar and Regent are effective in its control. More work is required on the effectiveness of Neem. The results from this trial also indicate that foliar application of Dominex is effective. The trials showed that foliar application of Dominex is best if applied at night. For Regent and Talstar, foliar application was made only during the day and night respectively. Because Talstar is thought to be active primarily as a contact insecticide, night spraying is probably most appropriate. Regent is considered to be a stomach poison and spraying during the day is probably satisfactory. The trial clarified appropriate rates for the effective insecticides – for Dominex and Talstar 50ml/100L, for Regent 30ml/100L. Further trial work to confirm this is required. As was the case for the work on garden weevil, the implications of foliar applications of these insecticides on non-target insects and mites is essential before applications to register them can be considered.

Summary
Sticky bands excluded garden weevil but not apple weevil from the trees. Promising results were obtained with prototype baits but further field trials are required before recommendations can be made.

The most promising biocontrol agent appears to be the Australian nematode *Heterorhabditis zealandica* XI. Birds may have an important role in control of garden weevil but were not effective against apple weevil. The insecticides Dominex®, Talstar®, and Regent® gave promising results but further work is required before registration could proceed.

5.9 How do we stop Fullers Rose Weevil from blocking microdrippers and microsprinklers?

Introduction
Apart from chewing leaves and fouling fruit Fullers Rose Weevil has the unfortunate habit of laying eggs in the orifices of micro-drippers and micro-sprinklers. This often leads to blockages and in the case of micro-sprinklers can also prevent the spinning mechanism from working. Such effects often go undetected by the orchardist until the trees start to show signs of water stress.

This section reports on susceptibility of various micro-drippers and micro-sprinklers to blocking by Fullers Rose Weevil.

Materials and Methods
(i) Drippers
Eight dripper types were compared in a peach orchard at Lyra, Qld in February-March and repeated in an apple orchard at Cottonvale, Qld in late March 1997. The drippers were placed in an additional 12.7 mm diameter polythene trickle line so that the drippers were 50 cm either side of the trees. The trial design was a randomised block with 5 replicates. The treatments consisted of the following different types of micro-dripper: Key; Turbo; Winchester; Netafilm 4.0 L/hr; Netafilm 4.0 L/hr drilled to 3 mm; Button dripper 4.0 L/hr; Netafilm with cap 4.0 L/hr; Netafilm 8.0 L/hr.

Blockage of drippers was tested and recorded by pumping water through the line with a portable motorised spray unit. Blockages were cleared with a fine wire.

A laboratory trial was conducted in 1997 by caging weevils on short lengths (150 mm) of trickle hose into which the test drippers were placed randomly. Blockage was checked visually and also by running water through drippers to confirm results.

In 1998 two dripper trials were conducted in the Cottonvale apple orchard. The first of these was a randomised block with 15 replicates comparing Netafilm standard 4.0 L/hr; Netafilm 4.0 L/hr drilled to 3 mm; Hardie Turbo 4.0 L/hr; and Key 4.0 L/hr. Existing dripper lines were
replaced with new drippers in the irrigation line. The treatment drippers watered young bearing apple trees, with larger guard trees between treatments having standard Netafilm 8.0 L/hr drippers. Dripper blockages were checked during irrigation events at approximately weekly intervals and any egg masses were removed. The second trial contained 40 replicates comparing Netafilm standard 4.0 L/hr drippers with Netafilm 4.0 L/hr drippers drilled to 4.0 mm to see if the enlarged orifice prevented blockages. The larger trees were used for these treatments and blockages were checked as per the first trial.

(ii) Micro-sprinklers

Field trials were established at 4 sites in 1997.
1. A young peach orchard at Lyra, Qld which had some heavy infestations of weevils in preliminary sampling.
2. Pink Lady apples in Western Australia
3. Amber Jewel plums and Golden Queen peaches in W.A
4. Golden Queen peaches in W.A.
Sites 2, 3 and 4 had a history of heavy infestations of weevils and were heavily infested in the 1996-97 season.

The sprinkler treatments were: Hardie Waterbird V.4764; Ein-dor 670-861-90; Ein-dor 670-841-90; Dan Stake 2001 pressure compensated; Dan Drop assembly 2001 pressure compensated; Wingfield Orbitor OAA1605K; Wingfield Challenger SMB1605K; Wingfield Drop assembly SDA05; Amiad Rondo; Plasto Ray Jet; Amiad Tornado Take-apart; Tornado Anti-ant dynamic; Nelson R.10 (W.A trial only); Dan Upside down (W.A trial only); Dan Standard micro-sprinkler - rod mounted with green jets (Qld trial only); American design.

Each trial was set out as a randomised block with 5 replicates. The sprinklers were attached to a round line of 19 mm black polythene except for the drop assemblies which had to be placed consecutively and hung upside down about one meter from the ground from plain fencing wire attached to three steel posts. The ground line was in addition to the existing irrigation line so that blockages of sprinklers by weevil eggs could be tested at weekly intervals by pumping water through the line and removing egg masses. Sprinklers were placed at a distance of 50 cm from the base of the trees. Pesticides had not been applied to the trial sites for at least 6 weeks.

(iii) Insecticide

A small scale trial (NRA Permit No. PER 700) to test the efficacy of bifenthrin as a soil drench in a 30 cm radius of the apple tree trunk to stop weevil blockage of drippers was commenced on 2 December 1996 in part of the Cottonvale orchard. There were 2 trees per plot, 4 treatments in a randomised block design with 10 replicates. Treatments were 0.16 g a.i. bifenthrin/500 mL water; 0.23 g a.i. bifenthrin / 500 mL water; 0.48 g a.i. bifenthrin / 500 mL water; and an untreated check. Strips of Environband were used to prevent weevils accessing the drippers along the lines from outside the treated area. Blockages were checked during irrigation events. Drippers were cleared of eggs on each observation date until late in the season.

Results and Discussion

(i) Drippers

Blockage of drippers in 1997 was very patchy in both the apple and peach sites. Insufficient data were obtained for statistical analysis. Only the Netafilm 4.0 L/hr, Netafilm 8.0 L/hr and Winchester drippers were blocked. The Winchester was the most susceptible being a small barrel dripper with a 1.5 x 1.0 mm orifice.

In the laboratory cage test the Netafilm 8.0 L/hr and the Winchester were most prone to blockage. The weevils did not oviposit into the button dripper (4.0 mm orifice), the Key clip dripper, the Turbo (Rheem) dripper, or the 1.0 mm hole in the dripper line.

In the 1998 trials no blockages occurred in the Hardie Turbo or Key drippers and only one blockage was recorded for the Netafilm drilled to 3 mm (the eggs were laid deep inside the dripper). The standard Netafilm 4.0 L/hr dripper was frequently (85%) blocked for the 7 observation dates in heavily infested replicates. In the second trial the Netafilm drilled to 4 mm were much less susceptible to blockage than the standard drippers but a few blockages still occurred.
(ii) Micro-sprinklers

Although there were plenty of weevils in the orchards blockage of sprinklers was patchy. The most frequently blocked sprinklers in the Qld site were the Tornado Anti-ant Dynamic and the standard Dan micro-sprinkler, but even the upside-down sprinkler Wingfield drop assembly was blocked at times. Blockage of the turning mechanism in the rod-mounted standard Dan with green jets occurred, with egg masses being laid in the gap around either the fine spindle at the top or between the base of the spinner and the green nozzle, resulting in a stream of water as the spinner is unable to turn. The Tornado sprinkler was susceptible to partial blockage of the water supply as the weevils have long ovipositors and push eggs beneath the anti-ant plate. This causes uneven distribution of the water.

Results in W.A were similar to those from Qld except in the block of Golden Queen peaches where the infestation level was lower and the Ein-dor-670-841-90 also showed blockages.

The Tornado anti-ant Dynamic was consistently the worst performer with blockages ranging from 43-64 percent.

(iii) Insecticide

The weevil population on the site was effectively decimated when the grower applied a half-strength azinphos-methyl spray to control fruit fly on 3rd January. However the trial was still monitored as the grower was confident that blockages would still occur. Further fruit fly activity was controlled by bait spraying with chlorpyrifos. By the end of February and in March dripper blockages had increased to over 10 percent. Some blockages were occurring in all bifenthrin treatments as well as in the untreated checks and guard trees. The insecticide treatments did not give season long protection. Both the 4 L/hr and 8 L/hr Netafilm drippers were blocked. The Rheem Turbo dripper has a much larger orifice and did not block. Drilling out the 2.5 mm orifice of the Netafilm drippers to 4.0 mm appeared to reduce the likelihood of dripper blockages but weevil numbers were declining at this stage.

Summary

The selection of types of drippers and micro-sprinklers that resist oviposition by weevils is vital if growers want to avoid costly labour for checking and unblocking susceptible types. Larger gaps between spinning parts and spindles, and larger orifices for drippers are required to make these units less susceptible to blockage. The American designed sprinkler had no pivot point and no suitable gap for egg laying but it had a very wide spray pattern.

A single application of bifenthrin was insufficient to prevent weevils from blocking drippers.
5.10 Biological control of woolly aphid

Introduction

Woolly aphid (Eriosoma lanigerum (Hausmann)) (Hemiptera: Aphiidae) is an important pest of apple Malus domestica (Boisdh.) that has spread to apple growing regions throughout the world (Eastop 1966). In Australia woolly aphid occurs almost exclusively as a pest of apples, but can occasionally be found infesting hawthorn, pears and the exposed roots of Liquidambar styraciflua (Hely et al. 1982). Woolly aphids feed by piercing the bark and sucking the host plant's sap. Heavy infestations can reduce plant growth and vitality, destroy buds, lower fruit quality and reduce yield (Bertus 1986, Hely et al. 1982, Brown et al. 1995, Weber and Brown 1988). The ecology, pest status and control of this pest has been studied extensively and its occurrence under Australian conditions described (Nicholls 1919, 1932, Lloyd 1961, Thwaite and Bower 1983, 1986, Fitzgibbon 1993, Asante 1994). Woolly aphid has several Australian natural enemies and while the coccinellid Harmonia (Leis) conformis (Boisdual) has been described as the most effective of these (Asante 1995), none have matched the previously reported effectiveness of the introduced parasitoid Aphelinus mali (Haldeman) (Wilson 1960). Following its introduction into all Australian apple growing states in 1923 A. mali is recorded, in combination with use of resistant rootstock, as successfully controlling woolly aphid (Gurney 1926, Wilson 1960). In New Zealand an experimental integrated fruit production (IFP) program based on the insect growth regulator tebufenozide (Mimic®) for leafroller and codling moth control allowed A. mali populations to increase and provide effective biological control of woolly aphid over a two year period (Shaw and Walker 1996). However, in cooler climates, such as those occurring on the Northern Tablelands of New South Wales, A. mali is considered incapable of providing effective control of woolly aphid due to its higher temperature development threshold (Asante and Danthanarayana 1993). At Bathurst on the Central Tablelands of New South Wales, Nicholas et al. (1999) reported that after three years of reduced pesticide use in an integrated pest management (IPM) program parasitism of woolly aphid by A. mali reached 35%. This suggests that either the Bathurst climate was too cool, as reported by Asante and Danthanarayana (1993), or that the pesticides used to control other pests adversely affected A. mali populations. Nicholas et al. (1999) also reported significantly lower woolly aphid populations in unsprayed trees compared with those sprayed with azinphos-methyl, although the levels recorded in all treatments were unacceptably high.

The European earwig (Forficula auricularia L.) is known to feed on woolly aphid (McLeod and Chant, 1952) and is capable of consuming, under laboratory conditions, up to 106 woolly aphids in a 24 hour period (Asante 1995). European earwig is a polyphagous insect feeding on algae, mosses, fungi, arthropods and plant material including fruit (Phillips 1981), however it has not been recorded as a serious pest of apples in Australia. Field investigations (in the Netherlands) by Stap et al. 1987 and Mueller et al. 1988 concluded that European earwigs were an important biological control agent of woolly aphid with potential in IPM or IFP programs. However they did not record the orchard conditions or pesticide regimes, such as those for codling moth control, under which the trials were conducted.

The broad spectrum organophosphate insecticide azinphos-methyl used to control codling moth (Cydia pomonella L.) is highly toxic to many of the woolly aphid's natural enemies, including ladybirds, lacewings, earwigs, (Nicholas et al. 1999) and adult A. mali (Nicholas unpublished data). Through its persistent use the potential for biological control of woolly aphid is lost. However in the absence of azinphos-methyl and other broad spectrum insecticides (eg. DDT) for codling moth control, for example where they have been replaced by less toxic chemicals, such as Ryania (Lloyd et al. 1970) and fenoxycarb (Readshaw and Cambourne 1991) woolly aphid infestation is reported to decline. In both situations this reduction has been attributed to increased numbers of natural enemies. The European earwig was also identified as playing an important role in controlling woolly aphid in an experimental IPM program where the insect growth regulator diflubenzuron was used to manage codling moth, leafrollers and the apple blossom weevil (Anthonomus pomorum L.) (Ravensberg 1981). In plots treated with diflubenzuron European earwig was absent and the infestation of woolly aphid high, whereas in untreated plots where earwigs were present, woolly aphid infestation was low.

In the two seasons (1993/94 and 1994/95) preceding this trial Nicholas et al. (1999) compared levels of woolly aphid infestation under three alternative codling moth control strategies; mating disruption (MD), MD plus early season applications of fenoxycarb (an insect growth regulator)(MD+F) and MD plus early season applications of azinphos-methyl (MD+A). The MD and MD+F treatments are two potential IPM strategies capable of replacing the conventional azinphos-methyl spray program for codling moth control. In the absence of azinphos-methyl woolly aphid infestation was reduced. Nicholas et al. (1999) attributed this reduction to increased numbers of A. mali, lacewings ladybirds...
and earwigs and this finding supports those of Lloyd et al. (1970) and Readshaw and Cambourne (1991). However, in the findings of Nicholas et al. (1999), none of these natural enemies were identified as being directly responsible for the lower levels of woolly aphid infestation observed in the MD and MD+F treatments.

The present study further investigates woolly aphid infestation under alternative codling moth treatments, ie. in commercially viable IPM programs, identifies the principal biological control agents and evaluates their effectiveness.

Materials and methods
The 1.7 ha trial orchard comprised of six (3x2) discrete plots. Each plot had nine rows of 21 trees, made up of three rows of the cultivars Delicious, Granny Smith and Jonathan. All trees were grafted to MM106 (woolly aphid resistant) rootstock.

All six plots were treated in September each season with Isomate® C (supplied by Biocontrol Ltd, Brisbane, Qld, Australia) codling moth sex pheromone dispensers for mating disruption. These were applied at the rate of 1000/ha. Two of the six plots were treated with azinphos-methyl and two with fenoxycarb. The azinphos-methyl and fenoxycarb sprays were applied at the recommended label rates for codling moth control, ie. azinphos-methyl (Benthion®) 100 g/100L of 500 g/kg, and fenoxycarb (Insegar®) 20 g/100L early season, and 40 g/100L late season of 250 g/kg (Thwaite, et al. 1995). The azinphos-methyl spray program commenced in the first week of November each year. In 1995/96 this program comprised of six sprays, the last applied on the 22 February 1996. The 1996/97 program comprised of seven sprays with the last applied on the 13 February. 1997. The 1995/96 and 1996/97 fenoxycarb programs each comprised of seven sprays applied between the 20 October and the 31 January, and the 21 October and the 5 February respectively. These treatments, namely the no insecticide and the fenoxycarb and azinphos-methyl spray programs, were similar to the MD, MD+F and MD+A treatments applied in the codling moth IPM project (Nicholas et al. 1999) but with two important changes. First, the applications of azinphos-methyl and fenoxycarb previously applied only in the early part of the season, were applied throughout the growing season in this trial. Second, a pre-bloom application of chlorpyrifos, previously used for apple dimpling bug control, was withdrawn to prevent suppression of natural enemies early in the season.

A number of standard applications of pesticides were applied to all treatments. A minimal fungicide program of bitertanol (Baycor®), plus the wetting agent Agride®, and dithianon (Delan®), was used to control apple scab (Venturia inaequalis (Cke.) Wint.) and powdery mildew (Podosphaera leucotricha (Ell. & Ev.) E. S. Salmon). Winter oil (Vicol® Victorian Chemical Co.) was applied in September each year to control eggs of European red mite and San José scale (Quadraspidiotus perniciosus (Comstock)). All sprays were applied using a Hardi TS2082 air blast sprayer at 2300 L/ha (3.5 L/tree).

Woolly aphid monitoring
Woolly aphid was monitored using a visual indexing technique. Three rows of trees, one of each variety (Delicious, Granny Smith and Jonathan) from each plot were assessed, ie. 21 trees x 3 varieties x 6 plots. Assessment commenced in September and was carried out fortnightly. Each tree was rated on the scale: 0 = nil infestation; 1 = trace infestation; 2 = up to 10% of the tree with severe infestation; 3 = up to 25% of the tree with severe infestation; 4 = more than 25% of the tree with severe infestation. Trace infestations were defined as ≤20 small colonies per tree and were commonly found in leaf axils or pruning cuts. Severe infestations were defined as laterals extensively covered with large colonies. The tree ratings were totalled and the mean of the two replicates was used as an infestation index for statistical analysis.

Parasitism
Woolly aphid colonies were checked monthly throughout the 1995/96 season for parasitism by A. mali using the technique described by Nicholas et al. (1999). Samples consisted of woolly aphid colonies cut from all three apple varieties, taken from trees and rows not monitored for other purposes.

Earwig exclusion
The effect of European earwigs in the orchard was assessed using an exclusion technique during the 1996/97 season. Adult European earwigs can fly, but rarely take to the wing (Phillips 1981). In both the no insecticide and fenoxycarb treatments eight pairs of trees (four / replicate) were selected from each of the three varieties, ie. a total of 48 pairs. To prevent earwigs entering the
canopy the trunk of one tree from each pair was banded with a 150 mm wide strip of green plastic sheet (plastic tarpaulin) coated on both sides with a sticky barrier (Tree Tanglefoot Pest Barrier, Tanglefoot Co. USA). The external sticky surface was scraped clean and replenished as required. To reduce the movement of earwigs between trees each tree was individually pruned to maintain a minimum 150 mm air gap. A seedling tree heavily infested with woolly aphid was attached to each tree (banded and unbanded) within the tree canopy to ensure the presence of woolly aphid above the bands. Sticky bands and woolly aphid infested seedlings were applied on the 12 December 1996. The general tree population of woolly aphid (not those of the infested seedling) were monitored fortnightly. The presence of earwigs was monitored fortnightly using refuge bands made from rolled corrugated cardboard (100 mm x 400 mm). One refuge band was applied to each tree by pinning it above the sticky bands and in the shade of the canopy. Earwigs occupying the refuge bands were counted fortnightly and released at the base of the tree from which they were collected.

Data analysis
Differences in levels of woolly aphid infestation and numbers of earwigs present in refuge bands between treatments for each sampling date were determined by analysis of variance (ANOVA). All treatment differences were compared at the 5% level (P<0.05) of significance and Student’s t-test (Samuels 1991) was used to separate means if ANOVA indicated significant differences.

Results
In both seasons small, isolated, established feeding colonies of woolly aphid were first observed in early October in all treatments (Fig. 39a (18.10.95) and Fig. 39b (15.10.96)). These colonies were often not present on subsequent monitoring dates, indicating that early in the season, prior to full leaf maturity and the start of the spray programs, colony establishment was suppressed either by adverse environmental conditions, the presence of predators or both.

Figs. 39 a & b. Woolly aphid infestation ratings under three different codling moth control strategies - 1995/96 and 1996/97.
Woolly aphid infestation in the azinphos-methyl treatment increased markedly from late November in 1995 and early December in 1996, and remained at levels significantly higher than those in the no insecticide and fenoxycarb treatments (Fig. 39a and b). Infestation remained low in the no insecticide and fenoxycarb treatments throughout the growing season, although slight increases were observed between late February and late April. There was no significant difference in infestation levels between the no insecticide and fenoxycarb treatments in either season (Fig. 39a and b).

**Fig. 40.** Number of adult European earwigs monitored in artificial refuges in banded and unbanded trees - 1996/97.

Sticky bands significantly reduced the number of earwigs entering the tree canopy (Fig. 40). Banded trees incurred significantly greater infestations of woolly aphid than unbanded trees (Fig. 41). In the no insecticide and fenoxycarb treatments there was a negative correlation between the mean number of earwigs / tree in the refuge bands and the woolly aphid seasonal mean infestation rating in all apple cultivars (Table 21). The data recorded from banded and unbanded trees in each cultivar and each treatment was found to be clustered (Fig. 42a-f). In banded trees data points were clustered close to the y axis, showing high woolly aphid infestation levels and low numbers of earwigs in refuge bands. Conversely, the data points from unbanded trees were clustered close to the x axis, showing high numbers of earwigs in refuge bands and low levels of woolly aphid infestation (Fig. 42a-f). There was no significant difference in the number of earwigs recorded in refuge bands on sticky banded or unbanded trees in the no insecticide and fenoxycarb treatments. However there was a significant difference in the level of woolly aphid infestation between the unbanded trees of each cultivar, where the cultivars Jonathan and Granny Smith incurred significantly lower levels of infestation than Delicious (Fig. 42a-f).
Fig. 41. Woolly aphid infestation ratings in banded and unbanded trees - 1996/97.

![Graph showing woolly aphid infestation ratings]

Fig. 42(a-f). Seasonal relationship between woolly aphid infestation and number of earwigs monitored in banded and unbanded trees - 1996/97.

(a) Mating disruption - cv. Jonathon
(b) Fenoxycarb - cv. Jonathon
(c) Mating disruption - cv. Granny Smith
(d) Fenoxycarb - cv. Granny Smith
(e) Mating disruption - cv. Delicious
(f) Fenoxycarb - cv. Delicious

The level of parasitism of woolly aphid by *A. mali* on the 25 February 1997 was 60%, 55% and < 1% in the no insecticide, fenoxycarb and azinphos-methyl treatments respectively. By the last sampling
date (12 May 1997) the level of parasitism had reached 66%, 78% in the no insecticide and fenoxycarb treatments respectively. The last application of azinphos-methyl was made on the 24 February 1997 and the level of parasitism in these plots had increased to 24% by 12 May 1997.

Discussion

The significantly higher level of woolly aphid infestation in the azinphos-methyl treatment compared with the no insecticide and fenoxycarb treatments supports the finding of Nicholas et al. (1999) that azinphos-methyl suppresses woolly aphid's natural enemies and therefore prevents effective biological control. Although regular monitoring ceased in late May, casual observations made after this date noted that infestations persisted in the azinphos-methyl treated plots until after the first frost and heavy rainfall of winter.

In the two seasons preceding this trial (1993-1995) Nicholas et al. (1999) reported that whilst a trend towards decreasing levels of woolly aphid in the no insecticide and fenoxycarb treatments occurred, effective biological control had not been established. The pre-bloom application of chlorpyrifos, conventionally applied to control of apple dimpling bug, was withdrawn to prevent suppression of natural enemies early in the season. In the first season (1995/96) of this study, i.e., the season following the withdrawal of chlorpyrifos, biological control of woolly aphid was achieved. This indicates that either it had taken three years for the populations of natural enemies to reach sufficient numbers to be fully effective, or the pre-bloom application of chlorpyrifos suppressed natural enemy populations, principally earwigs and A. mali, to the extent that effective biological control could not be achieved within the time frame of one growing season. We consider that a combination of both factors, primarily the latter, contributed to the result.

The lack of a significant difference in woolly aphid infestation between the no insecticide and fenoxycarb treatments indicates that the full season program of fenoxycarb did not reduce biological control of woolly aphid. In particular, there was no significant difference in parasitism levels between these two treatments, indicating that fenoxycarb did not suppress the A. mali population. In the azinphos-methyl treatment however, parasitism remained below 1% until after the spray program was completed, confirming that azinphos-methyl was toxic to adult A. mali. The increase in parasitism from 35% recorded by Nicholas et al. (1999) in the preceding trial to the 66% and 78% recorded in the present trial is most likely due to the removal of the pre-bloom application of chlorpyrifos. The level of parasitism in the no insecticide and fenoxycarb treatments reached 60% and 55% respectively by February (1997), indicating A. mali was playing a major role in reducing the level of woolly aphid infestation throughout the 1996/97 season. However as A. mali is an alate, highly mobile insect which would have been unaffected by the exclusion trial's sticky bands it could not be responsible for the significant differences recorded in woolly aphid infestation between banded and unbanded trees.

Where levels of woolly aphid infestation appeared early in the season, tagged colonies frequently disappeared, indicating that predators were playing a significant, if not principal, role in their control. In the exclusion trial significant differences between banded and unbanded trees both in the level of woolly aphid infestation (Fig. 41), and in the numbers of earwigs in the refuge bands (Fig. 40) showed data to be strongly clustered about the respective axes in both the no insecticide and fenoxycarb treatments (Fig. 42a-f).

These results identify the European earwig as the principal control agent. Only another predator of woolly aphid, similarly unaffected by fenoxycarb and accessing the tree canopy, principally via the trunk, could have produced the observed result. No such predator was detected either on the sticky bands or during monitoring of the orchard fauna by branch tapping when carried out by Nicholas et al. (1999) during the preceding trial. The negative correlation between the level of woolly aphid and the number of earwigs in refuge bands also supports this finding (Table 21). However the data cannot be used to assess actual numbers of earwigs needed to provide effective biological control because the refuge bands measured relative rather than absolute earwig density. The number of earwigs counted in refuge bands can also vary through the season depending on factors such as the availability of natural refuge sites and weather (Phillips 1981).
Table 21. The correlation between number of earwigs counted in refuge bands (seasonal mean) and the level of woolly aphid infestation (seasonal mean) in apple cultivars.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>No insecticide</th>
<th>Fenoxycarb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r )</td>
<td>( P )</td>
</tr>
<tr>
<td>Delicious</td>
<td>-0.86</td>
<td>0.011</td>
</tr>
<tr>
<td>Granny Smith</td>
<td>-0.86</td>
<td>0.005</td>
</tr>
<tr>
<td>Jonathan</td>
<td>-0.78</td>
<td>0.008</td>
</tr>
</tbody>
</table>

16 observations / sample

In the unbanded trees the cultivar Delicious incurred significantly higher levels of woolly aphid infestation than Granny Smith and Jonathan in both treatments (Fig. 42a-f). This supports a previous finding that Delicious is the cultivar most susceptible to woolly aphid infestation at the Bathurst site (Nicholas 1996). However the higher level of infestation in this variety indicates that naturally occurring numbers of European earwig may not provide adequate control in the more susceptible cultivars.

The reduced insecticide programs in this IPM trial may have allowed the survival of other natural enemies of woolly aphid. Consequently this trial does not conclude that the low level of woolly aphid in the no insecticide and fenoxycarb treatments was a consequence of predation by European earwig and parasitism by \( A. mali \) alone. However, other natural enemies of woolly aphid, such as lacewings, ladybirds and hoverflies, known to be present at the Bathurst site (Nicholas et al. 1999), were not considered to be good candidates for effective control of woolly aphid. Lacewings were discounted because they generally occurred early in the season, as were ladybirds and hoverflies due to their very low numbers.

While many authors have reported that European earwig has the potential to reduce woolly aphid infestations in IPM programs, this trial has shown that under the conditions described, it is capable of reducing infestations to below a grower's action threshold. Early in the season growers normally spray at the first sign of woolly aphid. The level of infestation recorded in the banded trees, those with few earwigs, would not have been tolerated by most commercial growers and an appropriate aphicide would have been applied.

Summary
This study shows that European earwigs have considerable potential as a control agent of woolly aphid in IPM programs. Their polyphagous feeding habit means that although they have a preference for live prey, particularly aphids (Asgari 1966), their long term survival in an orchard and hence their availability as a control agent is, unlike \( A. mali \), not wholly dependant on the presence of woolly aphid. However a number of issues must be addressed before the potential of \( F. auricularia \) can be fully realised in commercial IPM programs. These include an assessment of the toxicity of other orchard chemicals to European earwig and the extent to which they may cause damage to fruit.
5.11 How toxic to adult European earwigs are residues of chemicals commonly used in apple orchards?

Introduction
The European earwig (Forficula auricularia L.) (Dermaptera: Forficulidae) is an important predator of the woolly aphid (Eriosoma lanigerum Hausm.) and it can consume approximately 70 woolly aphids per night (earwigs are nocturnal) (Noppert et al. 1987). Field experiments carried out in the Netherlands (Stap et al. 1987 and Mueller et al. 1988) and now Australia (see Section 5.9) to assess the efficacy of earwigs against woolly aphid conclude that earwigs are an important biological control agent with the potential to control woolly aphid in integrated pest management (IPM) and integrated fruit production (IFP) programs.

In addition to woolly aphid, apples are subjected to a wide range of insect and mite pests and diseases and some will be a persistent problem in IPM programs. Consequently pesticides will continue to play a significant role in orchard management. The toxicity of these chemicals to earwigs has the potential to disrupt the biological control of woolly aphid. However, because earwigs are nocturnal and take refuge in cool dark cracks and crevices, e.g., under flaking bark or leaf litter during the day, they are more likely to be come into contact with dried chemical residues the following night than in direct contact aqueous sprays at the time of application. This section describes the methods and equipment used to assess a range of chemicals commonly used in orchard management for their toxicity to earwigs. The relative toxicity is given and an assessment of the chemical's potential to disrupt the biological control of woolly aphid made.

Materials and methods

Earwigs.
Earwigs were collected only from gardens declared pesticide-free in the Bathurst district, following an appeal in the local press. They were kept in ventilated chambers and fed lettuce and pollen until testing.

Chemicals.
Commercially available (propriety formulation) pesticide preparations were tested. Chemicals were divided into two groups; group 1 consisted of those chemicals expected to be toxic to earwigs (e.g., insecticides). Group 1 chemicals included abamectin (Avid®), alpha-cypermethrin (Fastac® 100), azinphos-methyl (Gusathiori®), carbaryl (Bugmaster®), chlorpyrifos (Lorsban® 500 EC), endosulfan (Nutram® Endosulfan 350) fenithion (Lebaycid®), fenoxycarb (Insegar® 250 W), imidacloprid (Confidor® 350 SC), parathion-methyl (Penncap M®), pirimicarb (Pirimor® WG), propargite (Omite®), taufluvalinate (Mavrik®), tebufenpyrad (Pyranica®), and vanidochlor (Kilval®). Group 2, those considered to be less toxic, e.g., fungicides, a weedicide and a crop regulator. Group 2 chemicals included bupirimate (Nimrod®), dithianon (Dodine®), ethephon (Ethrel®), mancozeb (Dithane®), penconazole (Topas® 100 EC), and thiram (Thiramgran®), the weedicide glyphosate (Glyfos®) and the crop regulator benzyladenine (BA) (Cylex®).

Bioassay procedure.
Standard 90 mm diameter (internal base area 58 cm²) sterile plastic Petri dishes were modified and used as disposable bioassay chambers. Each chamber was connected to an air supply to prevent the build up of condensation. The air supply was filtered and drawn through distilled water to moderate the humidity. Air was exchanged 3 times / minute (flow rate 200 cm³ / per min.) and vented through a voile (nylon) gauze covered 15 mm diameter hole in the lid.

The sprays were applied to all internal surfaces of the chamber using a Potter tower (Burkard, model S. T. 4. Rickmansworth, England). The Potter tower was calibrated with an air flow pressure 7 psi, suction flow rate 0.5 mL/second. To ensure the earwigs could not avoid contact with the chemical the spray distribution pattern on the chamber surface was checked. This was done by recording the weight of solution deposited on five microscope cover slips placed on the chamber surface. Droplet size and distribution was checked on the cover slips using a microscope. The results showed the spray pattern, both in weight and droplet size, to be evenly distributed across the spray surface. The lid and base were sprayed separately with 3 mL of aqueous pesticide or with distilled water (control). This resulted in a aqueous deposit of 1.4 mg/cm² which was left to dry for
Preliminary tests were conducted for each chemical and a narrow range within which the LD\textsubscript{50} would occur was identified. For chemicals in group 1, each test was made up of five concentrations and a distilled water control. The concentrations tested were evenly distributed within the range identified for each chemical during preliminary testing. Each test was replicated six times. On each test occasion the five concentrations were sprayed in the order of lowest to highest to prevent higher than intended concentrations through cross sample contamination. The Potter tower was cleaned between tests. Ten female earwigs were placed in each chamber and exposed to the dried residues for 24 hours, after which the level of mortality was assessed. Moribund earwigs were classed as alive if when turned onto their back they were able to regain their feet. Those unable to turn over were classed as dead. Preliminary trials showed 24 hours to be optimum period of exposure. Less than 24 hours and the results were spurious, more than 24 hours and cannibalism occurred.

The number of earwigs tested over the six replicates was 300 per chemical, thus exceeding the minimum 120 proposed by Robertson \textit{et al.} (1984) for accurate lethal dose estimations. The test was rejected if the control mortality exceeded 15%. Probit regressions were calculated using Probit 5 (Gillespie 1995) and the LD\textsubscript{50} and LD\textsubscript{90} of each chemical estimated.

Group 2 chemicals were tested as per group 1 chemicals, but at concentrations one and ten times the product’s recommended field rate. The control was distilled water. Group 2 tests were replicated four times. Insufficient earwigs prevented further replication.

Results

The relative toxicity of insecticides at the estimated LD\textsubscript{50} indicates that parathion-methyl, alpha-cypermethrin, chlorpyrifos, carbaryl and fenthion are all extremely toxic to earwigs at rates less than the recommended field rate for use in apple orchards (Table 22). Azinphos-methyl had an estimated LD\textsubscript{50} below the recommended field rate and an estimated LD\textsubscript{50} higher than the recommended field rate. Imidacloprid, endosulfan, tau-fluvalinate pirimicarb and vamidothion all had LD\textsubscript{50} estimates greater than their respective recommended field rates. During pre-trial range-finding tests fenoxycarb, propargite and tebufenozide failed to kill earwigs at concentrations equivalent to 100 times the recommended field rate. These chemicals were wettable powder formulations and higher concentrations could not be applied using the available Potter tower due to spray nozzle blockage. The relative toxicity of insecticides at the estimated LD\textsubscript{50} indicates that parathion-methyl, alpha-cypermethrin, chlorpyrifos, carbaryl and fenthion are all extremely toxic to earwigs at rates less than the recommended field rate for use in apple orchards (Table 22). Azinphos-methyl had an estimated LD\textsubscript{50} below the recommended field rate and an estimated LD\textsubscript{50} higher than the recommended field rate. Imidacloprid, endosulfan, tau-fluvalinate pirimicarb and vamidothion all had LD\textsubscript{50} estimates greater than their respective recommended field rates. During pre-trial range-finding tests fenoxycarb, propargite and tebufenozide failed to kill earwigs at concentrations equivalent to 100 times the recommended field rate. These chemicals were wettable powder formulations and higher concentrations could not be applied using the available Potter tower due to spray nozzle blockage. The toxicity of abamectin was also low, killing only 20% at a concentration equivalent to 100 times the recommended field rate. Fenoxycarb, propargite, tebufenozide and abamectin were included in group 2.

Table 22. Log-dose probability regression summary of field collected European earwig (\textit{Forficula auricularia} L.) tested against insecticide residues to show relative toxicity at the LD\textsubscript{50}, LD\textsubscript{90}, and recommended field rates.

<table>
<thead>
<tr>
<th>Active ingredient</th>
<th>$\chi^2$ (d.f.)</th>
<th>Slope (± s.e.)</th>
<th>LD\textsubscript{50} (95% F.L.)</th>
<th>$x \text{ FR}$</th>
<th>LD\textsubscript{90} (95% F.L.)</th>
<th>$x \text{ FR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parathion-methyl</td>
<td>0.7 (2)</td>
<td>6.5 (0.46)</td>
<td>0.03 (0.03-0.02)</td>
<td>0.06</td>
<td>0.04 (0.05-3.45)</td>
<td>0.08</td>
</tr>
<tr>
<td>alpha-cypermethrin</td>
<td>1.6 (3)</td>
<td>1.7 (0.41)</td>
<td>0.01 (0.05-0.002)</td>
<td>0.07</td>
<td>0.06 (0.11-3.75)</td>
<td>0.43</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>0.9 (2)</td>
<td>4.0 (0.38)</td>
<td>0.05 (0.06-0.94)</td>
<td>0.07</td>
<td>0.10 (0.19-4.96)</td>
<td>0.14</td>
</tr>
<tr>
<td>Carbaryl</td>
<td>1.9 (3)</td>
<td>5.1 (0.67)</td>
<td>0.1 (0.11-0.99)</td>
<td>0.07</td>
<td>0.18 (0.24-0.13)</td>
<td>0.12</td>
</tr>
<tr>
<td>Fenthion</td>
<td>0.8(2)</td>
<td>2.2 (0.25)</td>
<td>0.2 (0.49-0.08)</td>
<td>0.17</td>
<td>0.74 (1.32-0.41)</td>
<td>0.64</td>
</tr>
<tr>
<td>azinphos-methyl</td>
<td>2.0 (3)</td>
<td>3.3 (0.56)</td>
<td>0.35 (0.42-0.29)</td>
<td>0.52</td>
<td>0.84 (1.57-0.44)</td>
<td>1.22</td>
</tr>
<tr>
<td>Imidacloprid</td>
<td>2.6 (2)</td>
<td>4.2 (0.78)</td>
<td>2.47 (3.11-1.95)</td>
<td>3.0</td>
<td>4.81 (7.68-3.01)</td>
<td>5.77</td>
</tr>
<tr>
<td>Endosulfan</td>
<td>0.7 (3)</td>
<td>2.9 (0.19)</td>
<td>3.25 (4.29-2.46)</td>
<td>3.5</td>
<td>8.71 (12.0-6.34)</td>
<td>9.35</td>
</tr>
<tr>
<td>tau-fluvalinate</td>
<td>2.4 (4)</td>
<td>1.6 (0.17)</td>
<td>0.36 (0.56-0.23)</td>
<td>5.4</td>
<td>2.01 (3.51-1.07)</td>
<td>30.05</td>
</tr>
<tr>
<td>Tebufenpyrad</td>
<td>0.2 (2)</td>
<td>4.7 (0.17)</td>
<td>1.0 (1.3-0.77)</td>
<td>14.3</td>
<td>1.84 (2.71-1.24)</td>
<td>26.29</td>
</tr>
<tr>
<td>Pirimicarb</td>
<td>0.5 (3)</td>
<td>3.1 (0.17)</td>
<td>18.97 (23.4-15.4)</td>
<td>54.2</td>
<td>47.62 (72.8-31.16)</td>
<td>136.1</td>
</tr>
<tr>
<td>Vamidothion</td>
<td>1.8 (2)</td>
<td>1.7 (0.63)</td>
<td>295 (7982-109)</td>
<td>421.0</td>
<td>1555 (683073-3.5)</td>
<td>2222.0</td>
</tr>
</tbody>
</table>

\(1\) ai \(\mu g/cm^2\). \(2\) multiple of field rate.

All the chemicals in group 2, with the exception of abamectin and vamidothion, had a zero mortality rate at concentrations equivalent to 10x their respective recommended field rates. Abamectin and
vamidothion had a five percent mortality rate at 10x their respective recommended field rates (Table 23).

On the basis of their estimated $LD_{50}$ the chemicals have been assessed for their potential to disrupt the biological control of woolly aphid according to their respective recommended field rate and its toxicity to earwigs. The chemicals have been ranked as low = $LD_{50} > 10x$ field rate, moderate = $LD_{20} 1-10x$ field rate and high = $LD_{50} < 1x$ field rate (Table 3).

Table 23. Chemicals tested for toxicity to European earwig (Forficula auricularia L.) at 1 and 10 times the recommended field rate*.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Product</th>
<th>Mortality at 10 X FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insecticides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>abamectin</td>
<td>Avid®</td>
<td>5%</td>
</tr>
<tr>
<td>fenoxycarb</td>
<td>Insegar®</td>
<td>0</td>
</tr>
<tr>
<td>propargite</td>
<td>Omite®</td>
<td>0</td>
</tr>
<tr>
<td>tebufenozide</td>
<td>Mimic®</td>
<td>0</td>
</tr>
<tr>
<td>vamidothion</td>
<td>Kilval®</td>
<td>5%</td>
</tr>
<tr>
<td>Fungicides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bepirimate</td>
<td>Nimrod®</td>
<td>0</td>
</tr>
<tr>
<td>dithianon</td>
<td>Delan®</td>
<td>0</td>
</tr>
<tr>
<td>dodine</td>
<td>Dodine®</td>
<td>0</td>
</tr>
<tr>
<td>mancozeb</td>
<td>Dithane®</td>
<td>0</td>
</tr>
<tr>
<td>penconazole</td>
<td>Topas®</td>
<td>0</td>
</tr>
<tr>
<td>thiram</td>
<td>Thiragranz®</td>
<td>0</td>
</tr>
<tr>
<td>Chemical thinners</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ethephon</td>
<td>Ethrel®</td>
<td>0</td>
</tr>
<tr>
<td>benzyladenine (BA)</td>
<td>Cylex®</td>
<td>0</td>
</tr>
<tr>
<td>Weedicide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>glyphosate</td>
<td>Glyfos® (Bayer)</td>
<td>0</td>
</tr>
</tbody>
</table>

*All chemicals listed have an $LD_{50} > 10$ times the recommended field rate for use in the apple orchards of NSW, Australia (Thwaite et al. 1997).

Discussion

The chemicals, alpha-cypermethrin, carbaryl, chlorpyrifos, fenithion and parathion-methyl, that had $LD_{90}$ estimates at rates lower than their respective recommended field rate are extremely toxic to earwigs and are very likely to disrupt the biological control of woolly aphid with a single application. The estimated $LD_{50}$ of azinphos-methyl was close to the recommended field rate and is also rated as highly disruptive. Endosulfan, imidacloprid and tau-fluvalinate had estimated $LD_{50}$ of greater than one but less than 10 times the recommended field rate and are rated as moderate. They are likely to be disruptive to the biological control of earwigs if applied early or repeatedly in the growing season. Imidacloprid, a systemic insecticide applied as a root drench early in the growing season to control woolly aphid, is likely to kill earwigs nesting close to the tree. The surrounding soil, containing residues, may also be toxic to earwigs en route to the tree.

Tebufenpyrad and pirimicarb, with estimated $LD_{90}$'s equivalent to 14.3 and 54.2 times the recommended field rate respectively, were rated as low and are unlikely to disrupt the biological control of woolly aphid. In group 2 abamectin and vamidothion were found to have low levels of toxicity at 10 times the recommended field rate (Table 23). All the other chemicals tested in this group showed no indication of being toxic. Consequently all chemicals in group 2 were ranked as low. The results of this study will assist growers in selecting chemicals that are least toxic to earwigs and therefore least disruptive to the biological control of woolly aphid. However, the effectiveness of a chemical and consequently the number applications likely to be applied must be taken into account. A chemical (or combination of chemicals) ranked as moderate or low could be as disruptive as one ranked high if applied repeatedly.

Further work is required to evaluate chemical toxicity to the immature life stages and possible sub-lethal effects, such as reductions in longevity or fecundity.
Table 24. Chemicals commonly used in apple orchards and the toxicity of their residues to adult European earwigs (*Forficula auricularia* L).

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Product tested</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insecticides</strong></td>
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</tr>
<tr>
<td>alpha-cypermethrin</td>
<td>Fastac®</td>
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</tr>
<tr>
<td>azinphos-methyl</td>
<td>Gusathion®</td>
<td>high</td>
</tr>
<tr>
<td>carbaryl</td>
<td>Bugmaster®</td>
<td>high</td>
</tr>
<tr>
<td>chlorpyrifos</td>
<td>Lorsban® (500 EC)</td>
<td>high</td>
</tr>
<tr>
<td>fenthion</td>
<td>Lebaycid®</td>
<td>high</td>
</tr>
<tr>
<td>parathion-methyl</td>
<td>Penncap M®</td>
<td>high</td>
</tr>
<tr>
<td>endosulfan</td>
<td>endosulfan (Nufarm)</td>
<td>moderate</td>
</tr>
<tr>
<td>imidacloprid</td>
<td>Confidor®</td>
<td>moderate</td>
</tr>
<tr>
<td>tau-fluvinate</td>
<td>Mavrik®</td>
<td>moderate</td>
</tr>
<tr>
<td>pirimicarb</td>
<td>Pirimor®</td>
<td>low</td>
</tr>
<tr>
<td>tebufenpyrad</td>
<td>Pyranica®</td>
<td>low</td>
</tr>
<tr>
<td>vimidolobion</td>
<td>Kilval®</td>
<td>low</td>
</tr>
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<td>abamectin</td>
<td>Avid®</td>
<td>low</td>
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<tr>
<td>fenoxycarb</td>
<td>Insegar®</td>
<td>low</td>
</tr>
<tr>
<td>propargite</td>
<td>Omite®</td>
<td>low</td>
</tr>
<tr>
<td>tebufenozide</td>
<td>Mimic®</td>
<td>low</td>
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<td><strong>Fungicides</strong></td>
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<td>bupirimate</td>
<td>Nimrod®</td>
<td>low</td>
</tr>
<tr>
<td>dithianon</td>
<td>Delan® (750 SC)</td>
<td>low</td>
</tr>
<tr>
<td>dodine</td>
<td>Dodine (Rhone-Poulenc)</td>
<td>low</td>
</tr>
<tr>
<td>mancozeb</td>
<td>Dithane®</td>
<td>low</td>
</tr>
<tr>
<td>penconazole</td>
<td>Topas®</td>
<td>low</td>
</tr>
<tr>
<td>thiram</td>
<td>Thiragranz®</td>
<td>low</td>
</tr>
<tr>
<td><strong>Chemical thinners</strong></td>
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<td></td>
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<tr>
<td>carbaryl</td>
<td>Bugmaster®</td>
<td>high</td>
</tr>
<tr>
<td>benzyladenine (BA)</td>
<td>Cylex®</td>
<td>low</td>
</tr>
<tr>
<td>ethephon</td>
<td>Ethrel®</td>
<td>low</td>
</tr>
<tr>
<td><strong>Weedicides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glyphosate</td>
<td>Glyfos® (Bayer)</td>
<td>low</td>
</tr>
</tbody>
</table>

**Summary**

Carbaryl is toxic to earwigs and should not be used in the thinning program if woolly aphid is an issue. Other pesticides highly toxic to earwigs are alpha-cypermethrin, azinphos-methyl, chlorpyrifos, fenthion and parathion-methyl. Endosulfan, imidacloprid and tau-fluvinate are moderately toxic. Tau-fluvinate is less toxic than chlorpyrifos to earwigs but it is more toxic to the predatory mite *Typhlodromus occidentalis* used for biological control of pest mites.
5.12 Does European earwig damage apple fruit?

Introduction
The European earwig (Forficula auricularia L.) (Dermaptera: Forficulidae) is an important aphid predator which in the absence of broad spectrum pesticides, such as azinphos-methyl and chlorpyrifos, is capable of providing biological control of woolly aphid (Eriosoma lanigerum Hausm.) (see Technical Summary 1). European earwigs are also recorded as preying on European red mite (Panonychus ulmi (Koch)) eggs, codling moth (Cydia pomonella L.) eggs and larvae, oystershell scale (Quadraspisidius ostreaeformis (Curtis)) apple mussel scale (Lepidosaphes ulmi L.) and woolly aphid (Lit ter 1918, McLeod and Chant 1952, Phillips 1981). However, the European earwig is omnivorous and better known as a serious pest of vegetables, ornamentals and stone fruit. In Australia European earwigs are recorded as a serious pest of cherries, peaches, nectarines, apricots, plums and prunes (Hely et al. 1982, Bower 1992). In apple orchards earwigs are classed as both a minor pest, and an important predator with a preference for aphids (Phillips 1981). Entering the tree in spring earwigs feed on the foliage, pollen, flowers and fruit, as well as green algae, mosses and fungi (Phillips 1981). Laboratory trials have shown that earwigs initiate fruit damage (primary damage) in the absence of alternative sources of food (Phillips 1981). In the orchard damage to the foliage and flowers is reported as only minor. However, in one orchard ca 10% of the harvested fruit from the variety Lord Lambourne had some earwig damage (Phillips 1981). Other varieties damaged were also varieties not currently grown commercially in Australia, ie. Cox’s Orange Pippin, Laxton’s superb and James Grieves. Although European earwigs are capable of causing primary damage under laboratory conditions, ie. in the absence of alternative food sources, the extent to which they cause primary fruit damage in the orchard is unknown. European earwigs also feed on fruit damaged by other means (secondary damage), such as damage caused by codling moth, lightbrown apple moth, birds or orchard equipment.

This section reports on work to identify fruit damaged by European earwig and to establish the extent to which they cause primary fruit damage in integrated pest management programs.

Materials and methods
Six apple varieties (Bonza, Golden Delicious, Granny Smith, Red Fuji, Smoothee and Sundowner) currently grown commercially in Australia were tested at harvest for their susceptibility to earwig damage. This experiment was conducted in advance of field trials so that the damage could be accurately described. Seven apples from each of six varieties were checked to ensure they were free from damage and skin abrasions. Each fruit was placed in a plastic cage with 10 earwigs that had not been feed for 72 hours. Cage covers were made from voile netting (small meshed nylon). Damage to the fruit was recorded every 24 hours for seven days. From day three onward all damage to fruit was sealed using a non toxic adhesive compound (Bostik Blu-Tack, Australia) to prevent feeding and promote new primary damage. On day 7 a number of the fruit were picked with a dress makers pin. Each day the fruit were checked for damage and, where present, its approximate location recorded as calyx, stalk or body.

The potential of earwigs to damage fruit in the field was examined by caging a section of branch and a single fruit with different densities of earwigs; viz. 0, 2, 4, 8, 16, and 32. Each cage contained equal numbers of male and female earwigs. Each earwig density was replicated twice in each of three apple varieties, Red Delicious, Granny Smith and Jonathan. After 14 days the branches were pruned off and removed to the laboratory for assessment. The trial was carried out each month from December 1997 to March 1998.

The fruit was harvested from eight trees, four fitted with sticky earwig exclusion bands and four unbanded in each of the three apple varieties, Red Delicious, Granny Smith and Jonathan and assessed for earwig damage. This was replicated in four orchard plots, giving a treatment sample of fruit from 16 banded trees and 16 unbanded trees in each variety.

Analysis of variance, at the 5% level of significance (P<0.05), was used to determine differences in levels of earwig damage to fruit between banded and unbanded trees and between varieties. Treatment
differences were compared and the Student's t-test (Samuels 1991) was used to separate means if significant differences were indicated.

Results
Typical earwig damage is a small circular or oblong hole with the skin edges turned into the hole. The excavated hole is generally a smooth rounded depression that with further feeding can be tunnelled below the skin. During the day the earwig can occasionally be found sheltering inside the fruit.

The fruit used in the laboratory trial were checked thoroughly for skin damage prior to the test. However it was possible that the visual inspection did not locate minute damage, so the earwigs were allowed three days to search the fruit for further skin damage. After three days all previous damage was sealed and all new damage sealed each day using adhesive compound. The number and nature of damage to selected varieties of apples is given in Table 25. The results show that of the varieties tested Golden Delicious was the most vulnerable to earwig damage followed by Sundowner and Bonza. Most damage occurred around the calyx of the fruit, however the flesh of Golden Delicious was also vulnerable.

Table 25. Number and nature of damage to apples by European earwig (*Forficula auricularia* L.) in plastic cages.

<table>
<thead>
<tr>
<th>Variety</th>
<th>1</th>
<th>2</th>
<th>3 (S)</th>
<th>4 (S)</th>
<th>5 (S)</th>
<th>6 (S)</th>
<th>7 (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonza</td>
<td>B</td>
<td>B,B,B</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>G. Delicious</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>B,C</td>
<td>--</td>
<td>C,C</td>
<td>B,C</td>
</tr>
<tr>
<td>G. Smith</td>
<td>--</td>
<td>--</td>
<td>CS</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Red Fuji</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Smoothe</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Sundowner</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>S</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Region of damage: B - body, C - calyx, S - stalk. Comma between letters indicates different fruit (S) - Daily damage sealed with adhesive compound.

In the field cages no fruit damage occurred in the Granny Smith apples in any month. All Red Delicious apples were free of damage in December, January, and February, however in March one apple in a cage with 16 earwigs was damaged. This damage occurred on the flesh (body) of the fruit, ie. not near the calyx or stalk. Jonathans were damaged in December when the damage occurred around the calyx in cages containing 4 (replicate 1), 8 (replicates 1 and 2) and 32 (replicates 1 and 2) earwigs. Jonathans did not incur damage in January or February (Jonathans were harvested prior to the March assessment).

At the harvest assessment analysis of the data showed that there was no significant difference in the level of fruit damaged between banded (1.52%) and unbanded (1.28%) trees. There was a significant difference (p< 0.05) in the level of damaged fruit between Jonathans (2.07%) and Granny Smiths (0.44%) and between Red Delicious (1.71%) and Granny Smiths. However the difference between Jonathan and Red Delicious was not statistically significant.

Discussion
The laboratory cage trial showed that where no alternative food source is available, earwigs can cause primary damage to some varieties of apple. The field cage trial supports this finding, where only Jonathan were susceptible to earwig damage and only early in the season, whereas mature fruit were not damaged.

At harvest it was found that the trial plots had up to 30% fruit damage from codling moth and earwigs were recorded feeding in old codling moth wounds. There was also some fruit damage by lightbrown apple moth (*Epiphyas postvittana* (Walker)). Lightbrown apple moth often web leaves to the fruit and burrow into the fruit for protection. The burrow is similar in appearance to damage caused by earwigs and when left vacant by the lightbrown apple moth is an ideal earwig feeding site. By harvest some decay had occurred in the damaged fruit, making assessment for earwig damage difficult and some what subjective. From the results there was no significant difference between banded and unbanded
trees in terms of damage attributed to earwigs, lightbrown apple moth or both, indicating that either earwig damage could not be distinguished from other pest damage or that none of the damage was directly attributable to earwigs. However, in the field cage trial Jonathans were damaged in December, consistent with the variety having the most damage at harvest.

Summary
Earwigs will cause some primary damage to fruit particularly in varieties where short stemmed fruit are clustered and provide the earwigs with a day time refuge. Primary damage is most likely to occur early in the season, when alternative food sources are not readily available and after harvest if fruit is left exposed. Earwigs can also feed on fruit previously damaged by another means, causing the fruit to be further down graded. Earwig frass deposited in refuges, particularly around the stalk, may also become a problem requiring the fruit to be washed.

Further work is required to determine if other varieties than Jonathan are susceptible to primary damage in the field.

5.13 What happens to the level of woolly aphid infestation during introduction of an IPM program?

Introduction
In apple orchard integrated pest management (IPM) programs, based on the mating disruption technique (Isomate® C) or fenoxycarb (Insegar®) for codling moth (Cydia pomonella L.) control, European earwigs (Forficula auricularia L.) can provide excellent biological control of woolly aphid (Eriosoma lanigerum Hausm.). European earwigs are highly mobile and known to migrate considerable distances, at speeds up to 3m / minute in search of food and shelter (Noppert et al. 1987). However, it is not known how quickly they can migrate into an orchard block and control woolly aphid when an IPM program is initially implemented.

In this study the level of woolly aphid infestation and the number of earwigs were monitored in two blocks of apples that were under a fenoxycarb program for the first year (1997/98). The benefit of providing artificial refuges was also assessed.

Materials and methods
The trial blocks had previously been under a conventional, broad spectrum pesticide, azinphos-methyl program that is known to suppress earwig populations significantly (Nicholas et al. 1999). Each of the two blocks was adjacent, on two sides, to blocks that had been under a fenoxycarb program for the previous two years (1995-97). These adjacent blocks were 12 m from the trial plots and each contained a large population of earwigs. All orchard blocks received a full season commercial spray program of fenoxycarb and a minimal fungicide program for apple scab and powdery mildew control, as described in Technical Summary 1. No other insecticides, such as chlorpyrifos for apple dimpling bug or endosulfan for budworm control, were applied. Woolly aphid was monitored fortnightly using rolled up corrugated cardboard refuges placed in the tree canopy. Starting in the first or second tree in alternate rows, the refuges for earwig monitoring were placed in every second tree throughout the trial blocks.

Results
The level of woolly aphid infestation in the trial blocks for the 1995/96 and 1996/97 seasons under a conventional azinphos-methyl program and the 1997/98 season under the fenoxycarb IPM program is shown in Fig. 43. There was no significant difference in infestation levels between the two seasons under azinphos-methyl (95/96 and 96/97), however, infestation was significantly lower under the fenoxycarb program (97/98) when European earwigs were present.
Fig. 43. Seasonal comparison of woolly aphid infestation 1995-1998

The level of woolly aphid infestation in plots under their first season of fenoxycarb were not significantly different from plots under their third season of a fenoxycarb program (Fig. 44). There was also no significant difference in the level of woolly aphid infestation between trees fitted with refuge bands and those without.

Fig. 44. Comparison of woolly aphid infestation in the 1st and 3rd seasons of an IPM program 1997/98

Discussion

The significantly lower level of woolly aphid infestation under the fenoxycarb program, compared with those of the two previous seasons under the azinphos-methyl program, indicates that natural enemies can migrate quickly into blocks when broad spectrum pesticides are withdrawn and IPM programs implemented. Monitoring showed a significant population of earwigs had migrated into the trial blocks, presumably from the adjacent blocks where populations have been present and controlling woolly aphid for two years. Seasonal variation in weather patterns, ie. adverse weather conditions, can account for lower levels of woolly aphid infestation in some seasons. However, the weather was not considered a contributing factor in this study given that a nearby block of apples sprayed with azinphos-methyl had severe woolly aphid infestation.

The lack of a significant difference in woolly aphid infestation between blocks in the first year and those in the third year of a fenoxycarb IPM program, and the presence of earwigs throughout the season, shows that not only did the earwigs migrate into the block quickly, but that the populations were large enough to provide similar levels of biological control.
The lack of a significant difference in the level of woolly aphid infestation between trees fitted with artificial refuges and those without, shows that providing earwigs with artificial diurnal refuges in the tree canopy does not improve the control of woolly aphid.

Summary
Earwigs migrate quickly and can control woolly aphid infestations in the first year of an IPM program if sufficient numbers of earwigs are present in nearby vegetation or adjacent blocks.

5.14 Will using a butt spray of alpha-cypermethrin for weevil control affect control of woolly aphid by European earwig?

Introduction
Weevils occur in all apple growing regions of Australia, but are a particular pest problem in Western Australia and Queensland where they can cause severe defoliation, damage buds and roots and block irrigation systems by depositing egg clusters in dripper outlets. Weevils are not usually a major problem in NSW where their populations are thought to be suppressed by the broad-spectrum organophosphate azinphos-methyl used to control the key pest codling moth (Cydia pomonella (L.)). In integrated pest management (IPM) programs, where azinphos-methyl for codling moth control is replaced by the mating disruption technique or the insect growth regulator fenoxycarb, there is potential for weevil populations to increase to the extent that they may become a significant pest problem in other states. In Western Australia weevils are controlled by spraying the trunks and butts of trees with the insecticide alpha-cypermethrin (Dominex® or Fastac®) applied every 14 to 21 days during the season (Woods et al. 1996).

European earwigs (Forficula auricularia (L.)) over-winter at ground level with females rearing their young in subterranean nesting chambers. In spring they move up into the trees where they feed on the eggs of European red mite (Panonychus ulmi (Koch)) (McLeod and Chant 1952), the eggs and larvae of codling moth (A.H. Nicholas unpublished data) and woolly aphid (Eriosoma lanigerum Hausmann). Our work and that carried out in the Netherlands (Stap et al. 1987 and Mueller et al. 1988) indicates that earwigs are an important biological control agent and capable of controlling woolly aphid in integrated pest management (IPM) and integrated fruit production (IFP) programs.

Alpha-cypermethrin is highly toxic to earwigs under laboratory conditions (LD$_{90}$ <0.5 x recommended field rate) and its application every 14-21 days throughout the season could have considerable potential to disrupt the biological control of woolly aphid.

The trial reported in this section was designed to assess the potential of alpha-cypermethrin butt sprays to reduce the number of earwigs entering a tree and whether any reduction would result in increased woolly aphid infestation.

Material and methods
The trial was carried out in four discrete plots of apples during the 1997/98 season. Each plot was made up of nine rows of 21 trees, i.e. three rows of the cultivars Delicious, Granny Smith and Jonathan. All trees were grafted to MM106 (woolly aphid resistant) rootstock. Fenoxycarb (Insegar®) sprays were applied to all plots at the recommended label rates for codling moth control, i.e. three applications of 20 g/100 L (250 ai g/kg) at weekly intervals commencing 13 October 1997 and four applications of 40 g/100 L at monthly intervals commencing 4 November 1997 (Thwaite, et al. 1997). No other insecticides were used. A minimal fungicide program and winter oil program was applied. All sprays were applied using a Hardi TS2082 air blast sprayer at 2300 L/ha (3.5 L/tree).

The number of earwigs and the level of woolly aphid infestation was compared in three treatments; (i.) trees butt sprayed with alpha-cypermethrin; (ii.) trees fitted with earwig exclusion (sticky) bands; (iii.) unbanded trees. An apple seedling heavily infested with woolly aphid was attached to each tree within the canopy to ensure the initial presence of woolly aphid above the level of treatment. The untreated trees in each row were monitored to provide an indication of the orchard’s underlying level of woolly aphid infestation.

Each treatment was applied to four trees in each of the three apple varieties in four plots, a total of 12 replicates per treatment, per variety. Alpha-cypermethrin (Fastac®) butt sprays, at the label rate of 100
mL/100 L, were applied 1L per tree using an 8L sprayer fitted with a hand lance. Earwig exclusion bands were made from 150 mm wide strips of green plastic sheet (plastic tarpaulin) and coated on both sides with a sticky barrier (Tree Tanglefoot Pest Barrier, Tanglefoot Co. USA). The external sticky surface was scraped clean and replenished as required. All treatments were applied on the 27 October 1997. The level of woolly aphid infestation in these treatments was compared with a group of untreated control trees (three trees / variety / plot) that did not have woolly aphid infested seedlings attached or earwig refuge bands.

Although adult earwigs can fly they rarely do so (Phillips 1981). However to discourage movement of earwigs between trees, each tree was individually pruned to maintain a minimum 150 mm air gap.

The presence of earwigs was monitored fortnightly using refuge bands made from rolled up strips of corrugated cardboard (100 mm x 400 mm). One refuge band was applied to each tree by pinning it above the sticky bands and in the shade of the canopy. Earwigs occupying the refuge bands were counted and released at the base of the tree from which they were collected. The general tree populations of woolly aphid (not those of the infested seedlings) were monitored fortnightly. Woolly aphid infestation was monitored as described in Section 5.10 “Biological control of woolly aphid”.

Differences in levels of woolly aphid infestation and numbers of earwigs present in refuge bands between treatments for each sampling date were determined by analysis of variance (ANOVA). All treatment differences were compared at the 5% level (P<0.05) of significance and Student’s t-test (Samuels 1991) was used to separate means if ANOVA indicated significant differences.

Results
The alpha-cypermethrin butt spray significantly reduced the number of earwigs for up to 14 weeks after application, ie. until mid-January (excluding the sampling date 2 December 1997) (Fig. 45). The number of earwigs counted in trees with sticky exclusion bands was significantly lower than all other treatments throughout the season (Fig. 45) and this corresponded with a significantly higher level of woolly aphid infestation (Fig. 46). There was no significant difference between the alpha-cypermethrin and the unbanded treatments (Fig. 46). The untreated trees had significantly lower levels of woolly aphid infestation than the other treatments (Fig. 46). There was no significant difference between varieties in the number of earwigs counted in refuge bands.

Fig. 45 Number of European earwigs caught in refuge bands in butt drenched (alpha-cypermethrin) and exclusion banded trees.
Discussion

Alpha-cypermethrin, rated as highly toxic to earwigs in laboratory experiments, significantly reduced the number of earwigs in trees for 14 weeks following a single application as a butt drench. However, the lack of a significant difference in level of woolly aphid infestation between butt drenched trees and unbanded trees indicates that the single application of alpha-cypermethrin did not reduce earwig numbers to the extent that the biological control of woolly aphid was lost.

The high level of woolly aphid infestation and low numbers of earwigs in banded trees indicates that sticky bands kept earwigs below the number required to provide adequate control. This suggests that other natural enemies of woolly aphid, such as *Aphelinus mali* (Haldeman), lacewings and ladybirds, all of which are highly mobile and able to fly, were not present in sufficient numbers to adequately control woolly aphid.

The untreated trees, that did not have woolly aphid infested seedlings attached, had a significantly lower level of woolly aphid than all the treated trees, indicating the background level of woolly aphid infestation in the orchard.

The effect of a full season program of alpha-cypermethrin butt sprays (applications every 14 to 21 days as recommended for weevil control) is unknown, but it is reasonable to suggest that a further reduction in earwig numbers would occur if the earwigs constantly came in contact with freshly sprayed residues. However the extent to which this would affect the population and hence the biological control of woolly aphid is unknown and merits further investigation.

Summary

Alpha-cypermethrin significantly reduced the number of earwigs in trees for 14 weeks following a single application as a butt drench but did not appear to reduce earwig numbers to the extent that the biological control of woolly aphid was lost. The impact of multiple sprays is not known.
Technology transfer

Reports from all sub-project leaders were prepared for annual meetings of the WWAPM project team in 1996 (Melbourne), 1997 (Orange) and 1998 (Perth). Project updates were included in the Cropwatch Newsletters during the life of the project and the findings of the project team have been incorporated into Cropwatch training sessions. The material has also been used in training staff from agrichemical resellers during their training as Crop Health Services Agents. Various articles were published in Pome Fruit Australia. Scientific papers were prepared and submitted for publication. Posters were prepared and displayed at various scientific and industry conferences. Copies of the posters were given to AAPGA for use in their technology transfer activities.

Posters

Identifying weevils in apple orchards

Susceptibility of apple cultivars to mildew and scab

Woolly aphid

Biological control of Woolly Aphid in Apple Orchard IPM programs

Blockage of irrigation sprinklers/drippers by Fullers Rose Weevil

Controlling Garden Weevil – One for the birds?

Industry seminars and workshops

Woolly aphid, its pest status and control in IPM programs. Batlow Fruit Co-operative Technical Workshop 1995

Woolly aphid in IPM. Batlow Fruit Co-operative Technical Workshop 1996


Powdery Mildew. Training session for Dow Agroscience Technical Field Staff, October 1998

Control of weevils, woolly aphids and powdery mildew. Crop Health Services Agent Training Sessions (various)


Blocking of sprinklers by Fullers Rose Weevil. Donnybrook Orchard Improvement Group.

Blocking of sprinklers by Fullers Rose Weevil. Manjimup Horticultural Research Institute Field Day.


Use of birds to control Apple Weevil and Garden Weevil. Manjimup Horticultural Research Institute Field Day

Trade Journals


HRDC Project AP488 WWAPM: Integrated Management of Woolly Aphid and Powdery Mildew


Scientific Conferences, Seminars


Nicholas, A.H. (1998) Woolly aphid blockbuster, coming to an orchard near you. Orange Agricultural Institute, Orange NSW.

Scientific papers (refereed)
Recommendations

Monitoring for mildew will assist in decision-making for mildew control. The level of mildewed terminals in winter can be used to help plan mildew control strategies for the coming spring. Shoots with infected terminal buds can be assessed immediately after flowering using a minimum of 10 trees per block. Even a few percent mildewed terminals in winter can give significant mildew in the following season. In the UK more than 2% primary mildewed shoots is considered high.

For assessment of secondary mildew, label 15 trees per ha and assess 4 extension shoots per tree. Assess the top 5 unfolded leaves per shoot for mildew, and record the incidence of mildewed shoots. Assess the same trees at intervals during the growing season. If mildew levels increase over time then control measures may need to be improved. Less than 10% shoots with secondary mildew are considered low in the UK; more than 30% is considered high.

Methods to assess mildew are important and mild symptoms are easily overlooked, therefore training is important.

Sprays for mildew control should be targeted to critical times eg. from pink to first cover. Beyond that period spraying is necessary until the end of shoot growth to protect new buds from infection.

Use higher activity mildew fungicides such as penconazole (SBI's), closer spray intervals and high volume sprays when monitoring indicates high disease or increasing disease levels.

The ranking of cultivars for susceptibility to mildew (and scab) is useful when planning monitoring schedules in mixed blocks, as monitoring should take into account the most susceptible cultivar. Growers can also use it when planning new plantings, to minimise fungicide spraying.

Very low levels of weevils can cause significant damage to fruit. Correct identification and monitoring of weevil populations is essential to determine the best timing for sprays.

Although a linear relationship between weevil numbers and damage was not established, the numbers in monitoring bands in the first weeks of emergence gave an indication of the likely population size later in the season.

The delay between peak weevil emergence and maximum proportion of adults with mature eggs was 8-10 weeks for Apple Weevil, 5 weeks for Garden Weevil, and 2-3 weeks for Fullers Rose Weevil.

Cardboard bands should be used to monitor Garden Weevil and Apple Weevil but limb jarring is the best method for Fullers Rose Weevil.

Dandelions, capeweed and sorrel should be controlled to help limit weevil populations. Control of these weeds will also assist with control of LBAM.

The selection of types of drippers and micro-sprinklers that resist oviposition by weevils is vital if growers want to avoid costly labour for checking and unblocking susceptible types. Larger gaps between spinning parts and spindles, and larger orifices for drippers are required to make these units less susceptible to blockage. The American designed sprinkler had no pivot point and no suitable gap for egg laying but it had a very wide spray pattern.

European earwigs have considerable potential as a control agent of woolly aphid in IPM programs. Their polyphagous feeding habit means that although they have a preference for live prey, particularly aphids, their long term survival in an orchard and hence their availability as a control agent is, unlike A. mali, not wholly dependant on the presence of woolly aphid. Earwigs migrate quickly and can control woolly aphid infestations in the first year of an IPM program if sufficient numbers of earwigs are present in nearby vegetation or adjacent blocks.

Carbaryl is toxic to earwigs and should not be used in the thinning program if woolly aphid is an issue. Other pesticides highly toxic to earwigs are alpha-cypermethrin, azinphos-methyl, chlorpyrifos, fenithion and parathion-methyl. Endosulfan, imidacloprid and tau-fluvalinate are moderately toxic. Tau-fluvalinate is less toxic than chlorpyrifos to earwigs but it is more toxic to the predatory mite Typhlodromus occidentalis used for biological control of pest mites.
Earwigs will cause some primary damage to fruit particularly in varieties where short stemmed fruit are clustered and provide the earwigs with a day time refuge. Primary damage is most likely to occur early in the season, when alternative food sources are not readily available and after harvest if fruit is left exposed. Earwigs can also feed on fruit previously damaged by another means, causing the fruit to be further down graded. Earwig frass deposited in refuges, particularly around the stalk, may also become a problem requiring the fruit to be washed.

Further work is required to determine if other varieties than Jonathan are susceptible to primary damage in the field.

Future work

More work is required to determine monitoring thresholds for powdery mildew under Australian conditions, and under different planting types and for different cultivars.

More work is needed to define threshold levels of mildew that, if exceeded, will require increased control measures eg. more frequent sprays, use of more active fungicides.

Biocontrol agents and compounds including sodium bicarbonate at low rates combined with oil sprays should be considered for further testing against powdery mildew. The bicarbonates showed good efficacy against mildew in glasshouse tests and, if safe to use on apples, could have good potential as alternative protectant mildew fungicides. Biocontrol agents have been shown to be effective in other crops against mildews, and may be a useful supplement to field control of mildew. We were not able to obtain sufficient supplies of viable powdery mildew biocontrol agents to conduct meaningful trials.

The DCTron Plus treatments showed relatively low efficacy against mildew in field trials, and caused significant phytotoxicity including reduced crop and leaf damage. They may have a place in reduced pesticide control of mildew, but more work is required to define conditions for their safe use.

A number of issues must be addressed before the potential of earwigs can be fully realised in commercial IPM programs. These include an assessment of the toxicity of other orchard chemicals to European earwig and the extent to which they may cause damage to fruit. Earwigs will cause some primary damage to fruit particularly in varieties where short stemmed fruit are clustered and provide the earwigs with a day time refuge. Further work is required to determine if other varieties than Jonathan are susceptible to primary damage in the field. Alpha-cypermethrin significantly reduced the number of earwigs in trees for 14 weeks following a single application as a butt drench but did not appear to reduce earwig numbers to the extent that the biological control of woolly aphid was lost. The impact of multiple sprays is not known and further work is needed to determine how disruptive they may be to both woolly aphid control and mite control.

The role of food plants on the fecundity of weevils was not investigated during this study. The main species of plants found on the orchard floor, and the fruit crop itself, should be included in any such studies.

Promising results were obtained with prototype baits for weevils but further field trials are required before recommendations can be made.

Entomopathogenic nematodes showed promise in these trials against weevils but more work is required to establish efficacy and determine protocols for their use.

Use of birds in orchards resulted in reduced levels of damage by Garden Weevil. This method of pest management will be promoted to growers.

The insecticides Dominex®, Talstar®, and Regent® gave promising results against weevils but further work is required before registration could proceed.
Acknowledgements:

Funding for this project was provided by the Horticultural Research and Development Corporation, the Australian Apple and Pear Growers Association, Evergreen Marketing International P/L, the Department of Natural Resources and Environment through Agriculture Victoria, Agriculture Western Australia, NSW Agriculture, Tasmanian Institute of Agricultural Research, CSIRO, Queensland Department of Primary Industries, Primary Industries South Australia, and the University of Western Sydney.

Many orchardists provided essential assistance through allowing trials to be conducted on their properties and took part in surveys, both questionnaires and field surveys for parasites. Their cooperation was very much appreciated. Special thanks go to Fleming’s Monbulk Nurseries for the supply of apple trees, and to Apted and Sons orchard for co-operation and risking part of their orchard with the field trial in Victoria.

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Helen Nicol (Orange Agricultural Institute), Graham Hepworth (Institute for Horticultural Development), and Jane Speijers (Agriculture Western Australia, South Perth) provided valuable biometric advice.

Henry Kotula of Evergreen Marketing Intl. P/L provided a commercial focus and was an active participant in discussions and planning of activities within the project.
APPENDIX 1. The most common orchard floor plants in Western Australia.

(a)

<table>
<thead>
<tr>
<th>Plant Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clover</td>
</tr>
<tr>
<td>Couch (water &amp; summer)</td>
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<tr>
<td>Fat hen</td>
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<tr>
<td>Oxalis (sour sob)</td>
</tr>
<tr>
<td>Paspalum</td>
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<tr>
<td>Wild radish</td>
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<tr>
<td>Capeweed</td>
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<tr>
<td>Guildford grass</td>
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<tr>
<td>Kikuyu</td>
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<tr>
<td>Deadly nightshade</td>
</tr>
<tr>
<td>Ryegrass</td>
</tr>
<tr>
<td>Wireweed</td>
</tr>
<tr>
<td>Prince of Wales feather</td>
</tr>
<tr>
<td>Milk thistle</td>
</tr>
<tr>
<td>Dock</td>
</tr>
<tr>
<td>Sorrel</td>
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<tr>
<td>Portulaca</td>
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<tr>
<td>Barley grass</td>
</tr>
<tr>
<td>Marshmallow</td>
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<tr>
<td>Chokweed</td>
</tr>
<tr>
<td>Doublegey</td>
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<tr>
<td>Nut grass (sedge)</td>
</tr>
<tr>
<td>Willow herb</td>
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<tr>
<td>Erodium</td>
</tr>
<tr>
<td>Staggerweed</td>
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<tr>
<td>Johnson</td>
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<tr>
<td>Bromegrass</td>
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<tr>
<td>Pimpernel</td>
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<tr>
<td>wild oats</td>
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<tr>
<td>African lovegrass</td>
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<tr>
<td>Fumitory</td>
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<tr>
<td>flat wood</td>
</tr>
<tr>
<td>Yorkshire fog</td>
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<tr>
<td>witch</td>
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<tr>
<td>medic</td>
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<tr>
<td>bracken</td>
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<tr>
<td>plantan</td>
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<tr>
<td>kangaroo grass</td>
</tr>
<tr>
<td>lamb's tongue</td>
</tr>
</tbody>
</table>

Fig. 47 (a). Average abundance rating for plants occurring on the orchard floor in WA apple orchards.
Fig. 47 (b). Average abundance rating for plants occurring on the orchard floor in apple orchards in the Perth Hills of WA.
Fig. 47 (c). Average abundance rating for plants occurring on the orchard floor in apple orchards in the Donnybrook region of WA.
Fig. 47 (d). Average abundance rating for plants occurring on the orchard floor in apple orchards in the Manjimup/Pemberton region of WA.