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# Abundance and natural control of the woolly aphid *Eriosoma lanigerum* in an Australian apple orchard IPM program

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**Abstract.** Woolly aphid (*Eriosoma lanigerum* Hausmann) (Hemiptera: Aphididae), was monitored over three growing seasons (1995–1998) to assess its abundance and management under apple IPM programs at Bathurst on the Central Tablelands of NSW, Australia. Woolly aphid infestations were found to be extremely low in IPM programs utilising mating disruption and fenoxycarb for codling moth *Cydia pomonella* L. (Lepidoptera: Tortricidae) control. This was the direct result of increased numbers of natural enemies. No insecticides were applied for woolly aphid control. Under the IPM strategies tested the principal control agent was identified as European earwig (*Forficula auricularia* L.) (Dermaptera: Forficulidae). Earwigs in combination with *Aphelinus mali* (Haldeman) (Hymenoptera: Aphelinidae) reduced woolly aphid infestations below the action threshold set by commercial growers. However, *A. mali* together with other flying natural enemies, e.g., ladybirds, lacewings and hoverflies, did not provide commercially acceptable control of woolly aphid in the absence of earwigs. Under the conventional spray program, using the broad-spectrum insecticide azinphos-methyl for codling moth control, the level of woolly aphid infestation increased with each successive season and biological control was not established. When azinphos-methyl was withdrawn, natural enemies migrated in and provided control of woolly aphid within one season. This is the first study to show that the biological control of woolly aphid can be achieved in a commercially viable IPM program.

**Key words:** *Aphelinus mali*, biological control, *Eriosoma lanigerum*, *Forficula auricularia*

## Introduction

Woolly aphid (*Eriosoma lanigerum* Hausmann) (Hemiptera: Aphididae) is an important pest of apples causing hypertrophic gall formation on the roots and limbs of the tree (Brown et al., 1991). The galls restrict sap flow and frequently rupture providing further feeding sites for woolly aphid and allow the invasion of fungal diseases (Childs, 1929; Weber and Brown, 1988). Heavy infestations can reduce tree growth and vitality, destroy buds, reduce cropping, and lower fruit quality (Childs, 1929; Essig, 1942; Bertus, 1986; Brown and Schmitt, 1990; Brown et al., 1995).

Under Australian conditions, woolly aphid over-winter as adult females on both the aerial and edaphic parts of the tree. Those over-wintering below ground continue developing and reproducing at a slow rate, while those over-wintering aerially are for the most part dormant, especially in the cooler regions (Thwaite and Bower, 1983). In late spring–early summer, when the soil temperature is approximately 10 °C, young nymphs produced by over-wintering females move up from below ground to the aerial parts of the tree (Nicholas et al., 2003). Early colonies develop on vulnerable, thinly barked areas, such as around pruning cuts, or splits caused by past heavy cropping. As the season progresses colonies develop on the new season's growth. Once feeding has commenced woolly aphid remains sessile unless disturbed (Asante, 1994). In autumn nymphs migrate to the roots (Lloyd, 1961). In Australia, where there are few alternative winter hosts, e.g., American elms (*Ulmus americana* L.), woolly aphid is for all practical purposes anholocyclic, living on apple as an asexual viviparae (Nicholls, 1919). Commercial control of woolly aphid has relied on resistant rootstocks and chemicals since the early 1900s (Froggatt, 1903; Nicholls, 1919; Thwaite, 1997). Woolly aphid has several natural enemies in Australia, including lacewings, ladybirds, hoverflies and earwigs, all of which are suppressed by azinphos-methyl (Asante, 1997; Nicholas et al., 1999). Introduced in 1923 the parasitoid *Aphelinus mali* (Haldeman) (Hymenoptera: Aphelinidae) is reported to have provided a significant level of control (Wilson, 1960). The European earwig *Forficula auricularia L.* (Dermaptera: Forficulidae), which is wide spread in Australia, is capable of consuming up to 106 aphids per day (McLeod and Chant, 1952; Asante, 1995).

Earwigs have, by association, been shown to play an important part in controlling woolly aphid in the absence of broad-spectrum insecticides (Anon, 1969; Ravenberg, 1981; Stap et al., 1987; Mueller et al., 1988). However none of these trials showed that natural enemies could control woolly aphid under commercial conditions, i.e., while controlling other key pests.

Two techniques, namely mating disruption and the insect growth regulator fenoxycarb, are now firmly established in Australian apple orchards as viable methods of controlling codling moth (*Cydia pomonella* L.), which is the key pest of apples in mainland Eastern Australia (Thwaite, 1997). These techniques are the basis of current commercial IPM programs in Australia (Thwaite, 1997). Codling moth mating disruption is highly species specific (Rumbo et al., 1993) with no direct effect on woolly aphid or its natural enemies. In conventional pesticide programs, controlling codling moth with azinphos-methyl requires 6–8 applications during the season (Thwaite et al., 1995) and these sprays affect many secondary pests and their natural enemies. Adopting an IPM strategy, thereby reducing the use of broad-spectrum insecticides, is likely to have indirect effects the orchard's other inhabitants, including the woolly aphid and its natural enemies (Nicholas et al., 1999).

Woolly aphid has been studied extensively under conventional pesticide programs, but its abundance in IPM programs was previously unknown. The aim of this study was to assess the abundance of woolly aphid in IPM programs (i.e., in the absence of broad-spectrum insecticides) and investigate the potential of natural enemies to suppress the pest population.

## Materials and methods

### *The trial site*

This study was conducted at Bathurst Agricultural Research Station located on the Central Tablelands of New South Wales, Australia (Lat. 33° 26′ S. Long. 149° 34′ E). The orchard, planted in 1977, was a 1.7 ha block of apple trees divided into six (3×2) discrete 0.3 ha blocks of 189 trees each. Each block had nine rows of 21 trees, made up of three rows each of the cultivars Red Delicious, Granny Smith and Jonathan. All trees were grafted on to Merton Malling Series (MM) 106 (woolly aphid resistant) rootstock. Planting distances were 5 m between rows and 3 m between trees. Blocks were 10 m and 12.5 m apart on their long and short boundaries respectively. The trees were pruned to the central leader system and an average height of 3 m. Groundcover was controlled with herbicides within tree rows and mown between rows, as per commercial practice. The trees were irrigated at the rate of 8 l/h for 4 h on 3 days/week, as required during dry periods.

### *Treatments 1995/1996 and 1996/1997 seasons*

Two of the six blocks were treated with codling moth sex pheromone dispensers (mating disruption technique (MD)), (Isomate® C, Biocontrol Ltd, Brisbane, Qld, Australia), two with azinphos-methyl plus pheromone (AMD) and two with fenoxycarb plus pheromone (FMD). The three treatments were arranged so that all adjacent blocks received different treatments. Pheromone dispensers were applied each September at the rate of 1000 $ha^{-1}$. The azinphos-methyl and fenoxycarb sprays were applied at the recommended label rates for codling moth control, i.e., azinphos-methyl (Benthion® 500 g/kg) 100 g/100 l and fenoxycarb (Insegar® 250 g/kg) 20 g/100 l early season and 40 g/100 l late season (Thwaite et al., 1995). The azinphos-methyl program commenced the first week of November each year. In 1995/1996 this program comprised six sprays with the last applied on February 22 1996. The 1996/1997 program comprised seven sprays with the last applied on February 24 1997. The 1995/1996 and 1996/1997 fenoxycarb programs each comprised seven sprays applied between October 20 and January 31 and October 21 and February 5 respectively.

### *Treatment 1997/1998 season*

The MD and AMD treatments were discontinued and all blocks were put under a fenoxycarb only program. This consisted of nine applications of fenoxycarb commencing on October 13 1997. Thus, there were four blocks under a fenoxycarb program for the first time and two that were in their third season. The ex-AMD blocks were used to monitor the migration and efficacy of any natural enemies of woolly aphid in the first season of an IPM program.

### *Other pesticide applications*

A minimal fungicide program using bupirimate, dithianon, dodine, fenarimol and penconazole, as appropriate, to control apple scab (*Venturia inequalis* (Cke.) Wint.) and powdery mildew (*Podosphaera leucotricha* ((Ell. & Ev.) E. S. Salmon) was applied each season. Winter oil (Vicol® Victorian Chemical Co.) was applied at the rate of 3% in September each year to control European red mite (*Panonychus ulmi* (Koch)) 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).

### *Monitoring*

In the 1996/1997 season early colonies were observed to disappear quickly, and prompted several colonies in each treatment to be tagged to aid further observations. Colonies were tagged by tying a small length of fluoro-pink wool to the colonised limb approximately 75 mm above the colony.

Woolly aphid was monitored visually. Each tree was rated on a scale where: 0 = no infestation; 1 = trace infestation, 2 = up to 10% of the tree with severe infestation; 3 = 11–25% of the tree with severe infestation; 4 = more than 25% of the tree with severe infestation (modified from Bower, 1987). Trace infestation was defined as ≤20 small colonies per tree and severe infestation as laterals extensively covered with large colonies. One row of trees/cultivar/block were assessed (21 trees × 3 treatment × 3 cultivars × 2 blocks). Assessment was carried out every 2 weeks from the beginning of September to the end of May each year.

*Parasitism*

Woolly aphid colonies were checked monthly throughout the 1996/1997 season for parasitism by *A. mali*. Small colonies or short sections (22 mm) of woolly aphid infested laterals were taken from each cultivar not monitored for other purposes. The aphids were dip-washed in methylated spirit (70% ethyl alcohol, 30% methanol) to remove the wool, removed from the lateral and dried on tissue paper. The proportion of black, mummified aphids was used as a relative measure of parasitism.

*Predation*

Predators were monitored using rolled strips of corrugated cardboard (100 mm × 400 mm) as artificial refuges (shelters). One shelter was pinned to the trunk of each tree in a shady position. Predators occupying shelters were counted every 2 weeks and released at the base of the tree. This method took advantage of nocturnal species taking refuge during the day.

*Predator exclusion*

Non-flying predators were prevented from entering the canopy of eight trees in each cultivar in the MD and FMD treatments (four per replicate). The trunks were banded with a 150 mm wide strip of green plastic sheet coated on both sides with the sticky chemical polybutene (Tree Tanglefoot Pest Barrier, Tanglefoot Co., USA). The polybutene was cleaned and replenished as required. A minimum air gap of 150 mm was maintained to reduce the movement of non-flying predators between adjacent trees.

Sticky bands have the potential to reduce the upward migration of woolly aphid crawlers from the roots early in the season (Barnes et al., 1994). To overcome this, an apple seedling, heavily infested with woolly aphid, was attached in the canopy of each banded tree, and an adjacent unbanded tree. Sticky bands and woolly aphid infested seedlings were applied on December 12 1996 (1996/1997 season) and October 27 1997 (1997/1998 season). Woolly aphid infestation, excluding those on the infested seedlings, was monitored every 2 weeks. The artificial shelters for predators were positioned above the exclusion bands.

*Data analysis*

Analysis of variance (ANOVA) was used to determine significant differences between treatments and cultivars for levels of woolly aphid infestation, and the number of predators in artificial shelters. All differences were compared at the

5% level ($p \leq 0.05$) of significance and Tukey's multiple comparison test was used to separate means if significant differences were found. Pearson's product–moment correlation coefficients were calculated to test the relationship between the number of earwigs occupying artificial shelters and the level of woolly aphid infestation. Non-linear regression analysis of the combined data from trees fitted with predator exclusion bands and unbanded trees was used to estimate the number of earwigs, as recorded in artificial shelters, required to eliminate woolly aphid from each apple cultivar.

## Results

### *Woolly aphid infestation*

In the 1995/1996 and 1996/1997 seasons, small isolated colonies of woolly aphid were first observed in early October in all treatments and in all cultivars (Figures 1 and 4). These colonies (tagged with fluoro-pink wool) were often not present on subsequent monitoring dates. Under the AMD treatment there was no significant difference in the level of woolly aphid infestation between the 1995/1996 and 1996/1997 seasons, however it was significantly lower during the 1997/1998 season when the AMD plots were put under a fenoxycarb only program (Figure 2).

There was no significant difference in the level of woolly aphid infestation when comparing blocks in their first season under a fenoxycarb only (IPM) program with those in their third season (Figure 3).

### *Cultivar effects*

There was no significant difference between the cultivars in the level of woolly aphid infestation within individual treatments, although in all treatments the trend was for Red Delicious to have slightly higher infestation than Granny Smith and Jonathon. However, pooling the treatment data showed that Red Delicious had significantly higher levels of infestation than in either Granny Smith or Jonathan in both the 1995/1996 and 1996/1997 seasons (Figure 4a and b).

### *Treatment effects*

After pooling the cultivar data, woolly aphid infestations in the AMD blocks were shown to increase markedly from late November in 1995 and early December in 1996. Infestation then remained significantly higher than in the MD and FMD treatments (Figure 1a and b). Infestation remained low in the

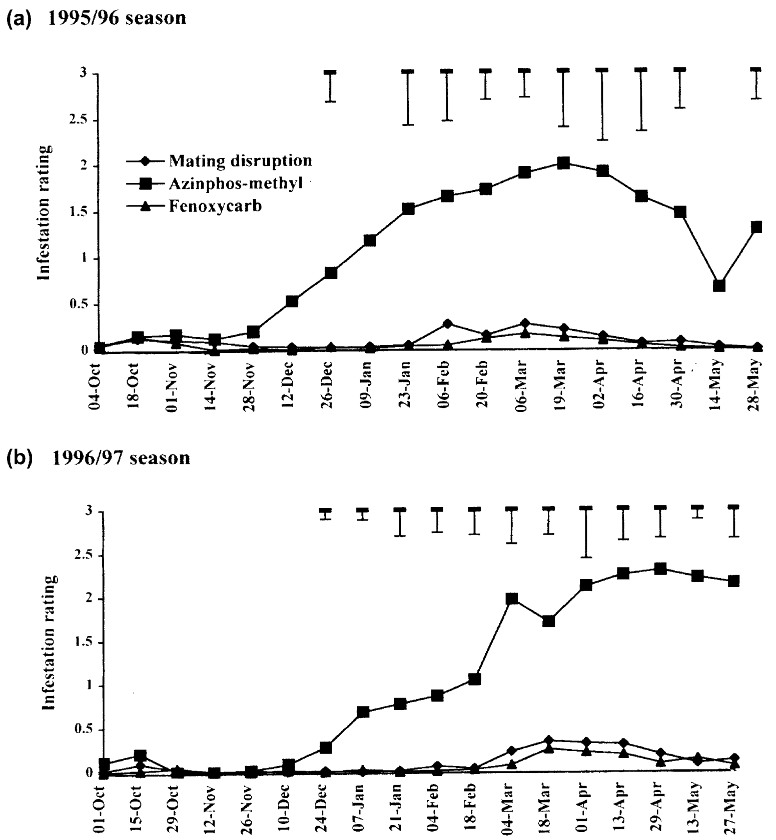


*Figure 1.* Woolly aphid infestation under three treatments for codling moth control, mating disruption (MD, fenoxycarb plus MD (FMD), and azinphos-methyl plus MD (AMD). Error bars = LSD ($p \leq 5\%$).

MD and FMD treatments throughout the season. There was no significant difference in infestation between the MD and FMD treatments in either season (Figure 1a and b).

*Parasitism*

Due to the low levels of woolly aphid infestation in the MD and FMD treatments, the samples collected were small (350–2,500 aphids) compared with those from the AMD treatment (up to 8,000 aphids). On February 23 1997 the level of parasitism by *A. mali* had reached 60, 55 and < 1% in the MD, FMD and AMD treatments respectively. The last application of azinphos-methyl was made on February 24 1997 and by May 12 1997, the last sampling date, the

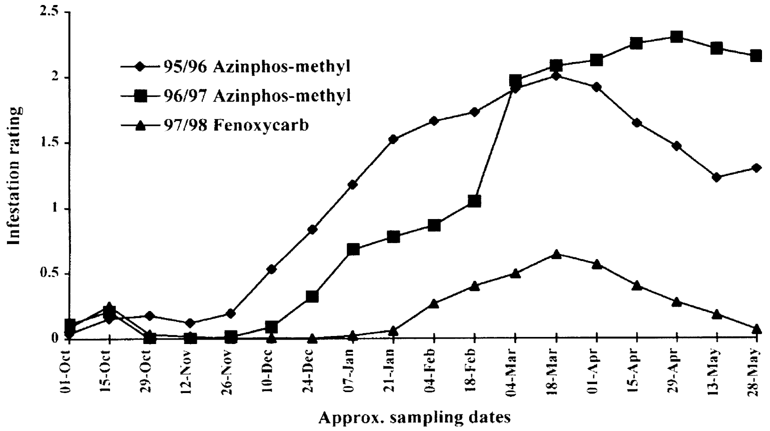


*Figure 2.* Seasonal comparison of woolly aphid infestation in AMD blocks over three seasons 1995–1998.

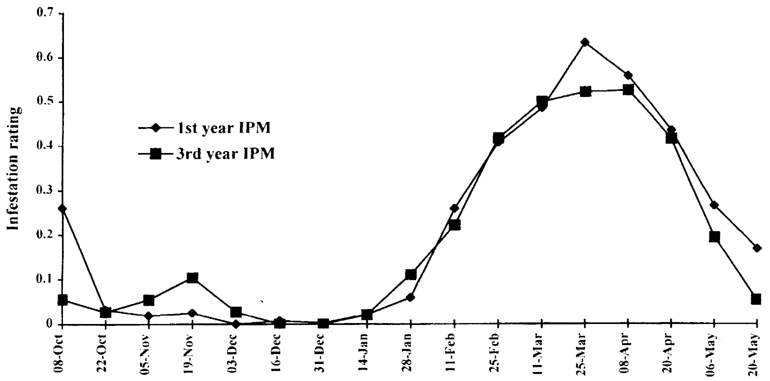


*Figure 3.* Comparison of woolly aphid infestation in the first and third seasons of an IPM program during the 1997/1998 season.

level of parasitism had risen to 66, 78 and 24% in the MD, FMD and AMD treatments respectively.

## *Predation*

Ladybird, *Harmonia conformis* Boisduval, and hoverfly, *Macrosyrphus confrator* (Weid.), larvae were occasionally observed feeding on woolly aphid during the monitoring program. The only predators of woolly aphid found occupying the artificial shelters were European earwig *Forficula auricularia* L (hereafter referred to as earwigs).

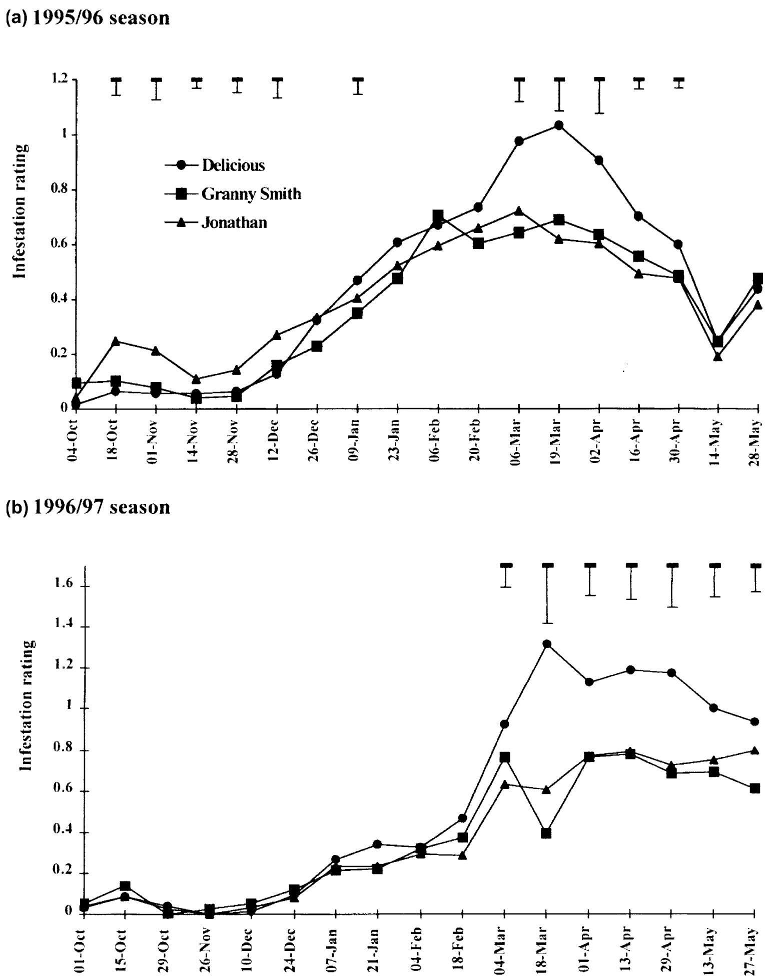


*Figure 4*. Woolly aphid infestation rating in three apple cultivars Red Delicious, Granny Smith and Jonathan, as the mean of three treatments, MD, FMD and AMD. Error bars = LSD ($p \leq 5\%$).

### *Effect of predator exclusion bands*

The predator exclusion bands significantly reduced the number of earwigs entering the tree canopy during the 1996/1997 season ($p \leq 0.001$, assessed every 2 weeks). Banded trees had $<1$ tree$^{-1}$ on each sampling date compared with $>3$ tree$^{-1}$ (range 3–14 decreasing towards the end of the season) in the unbanded trees. There was no significant difference between the MD and FMD treatments in the number of earwigs in artificial shelters in trees fitted with exclusion bands, or between these treatments in unbanded trees. Trees fitted with exclusion bands were found to have significantly greater infestations of woolly aphid than unbanded trees from December 24 1996 through until May 27 1997 when monitoring ceased. In the MD and FMD treatments there was a high negative correlation between the mean number of earwigs/tree in the artificial shelters and the mean woolly aphid seasonal infestation rating in all cultivars (Delicious MD $r = -0.86$ $p = 0.01$, FMD $r = -0.67$ $p = 0.02$, Granny Smith MD $r = -0.86$ $p = 0.005$, FMD $r = -0.78$ $p = 0.005$, Jonathan MD $r = -0.78$ $p = 0.008$, FMD $r = -0.82$ $p = 0.017$). The 1996/1997 data, for each cultivar in each treatment, was clustered into two groups, exclusion-banded and unbanded trees (Figures 5 and 6). Data points from the exclusion-banded trees were clustered close to the $y$-axis, showing high levels of woolly aphid infestation with low numbers of earwigs in artificial shelters. Conversely, the data points from unbanded trees were clustered close to the $x$-axis, showing high numbers of earwigs in artificial shelters and low levels of woolly aphid infestation. The exponential regression model $y = a + b \quad r \quad x^2$, where $a$ = minimum number of earwigs counted, $b$ = estimated point of zero woolly aphid infestation, and $r = 0.1$ (slope), was used to fit a curve to the pooled data, i.e., exclusion-banded and unbanded seasonal means of earwigs counted in artificial shelters and woolly aphid infestation. This estimated the number of earwigs required to occupy artificial shelters to prevent or eliminate woolly aphid infestation, and was represented by the point at which the fitted curve crossed zero. The fitted curve's accuracy is given as the percentage of variance accounted for by the curve and shown on each graph. For the 1996/1997 season the model estimated a required seasonal mean of 7.98 and 8.30 (Granny Smith), and 4.98 and 5.02 (Jonathan) earwigs in the MD and FMD treatments respectively to eliminate aerial colonies of woolly aphid. When applied to the data from the cultivar Red Delicious the slope of the fitted curve did not pass through zero in either treatment (Figures 5a and 6a). The same analysis was carried out on the 1997/1998 season data, when all plots were treated with fenoxycarb. The results showed the data to be clustered as in the 1996/1997 season, but more varied in woolly aphid infestation between trees in all cultivars. The fitted curve did not pass through zero for any cultivar and the number of earwigs required to eliminate woolly aphid could not be predicted.

*Predictions of woolly aphid infestation*

Early season monitoring of earwigs would be a valuable tool if it could predict the level of woolly aphid infestation later in the season, thus indicating whether continued monitoring and control measures would become necessary. To determine this the exponential regression model was used to fit a curve to the number of earwigs counted in artificial shelters in both exclusion-banded and unbanded trees in the first four sampling dates of the season (December 24,

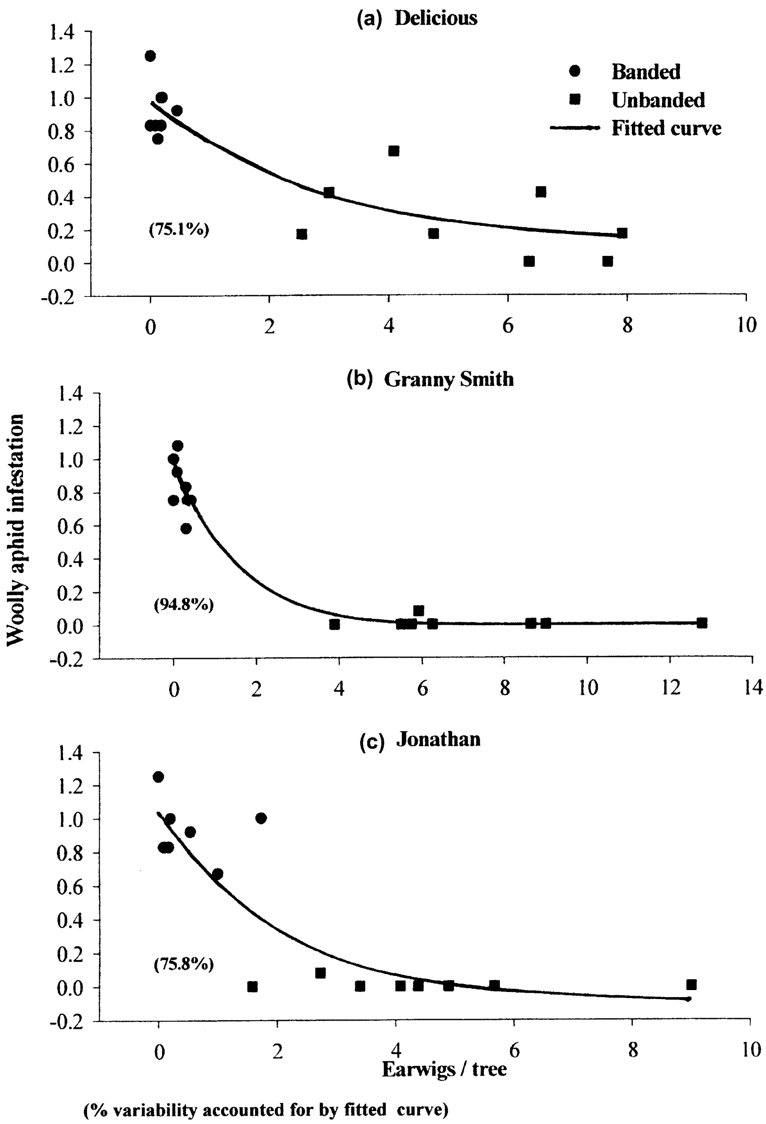


*Figure 5.* Relationship between European earwigs (seasonal mean) and woolly aphid (seasonal mean) in trees fitted with predator exclusion bands and unbanded trees under a MD treatment for codling moth control during the 1996/1997 season.

January 8 and 22 and February 5) and the seasonal mean woolly aphid infestation. The results showed that in the 1996/1997 season the prediction model based on early season data supported the full season model. This indicated that earwigs would eliminate, or reduce to extremely low levels, the aerial colonies of woolly aphid in the cultivars Granny Smith and Jonathan

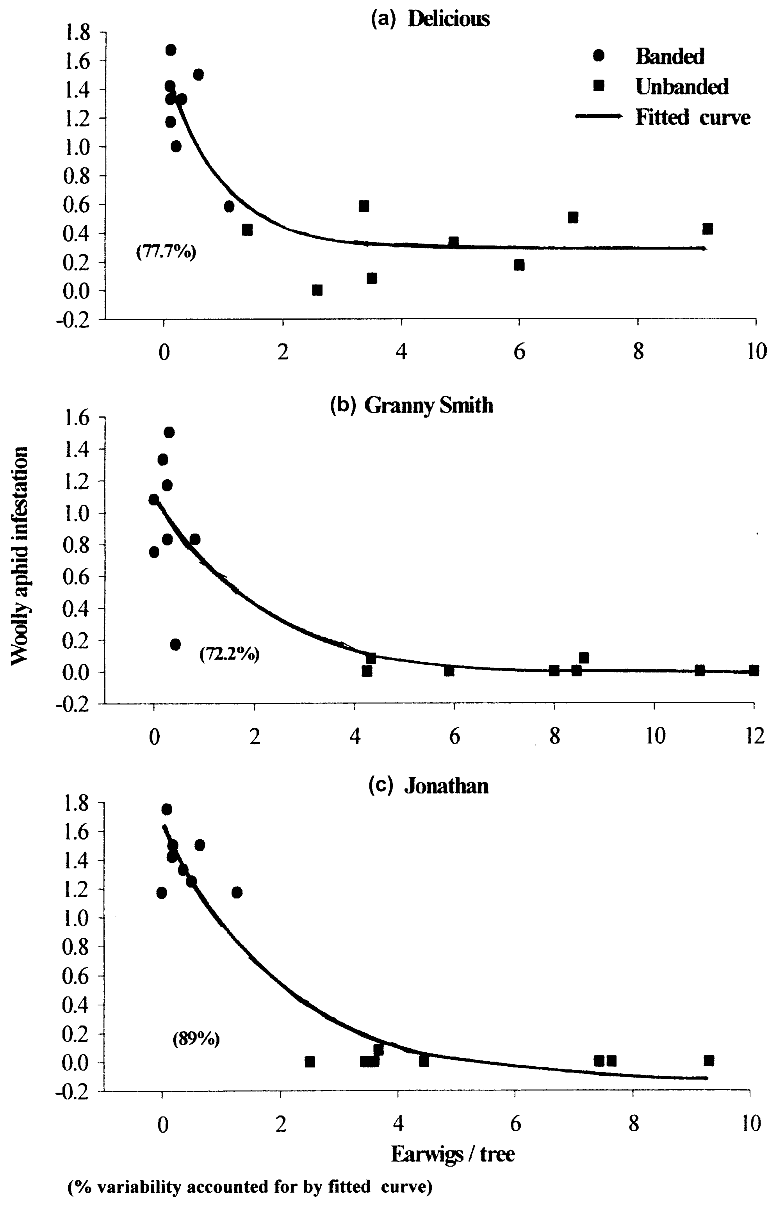


*Figure 6*. Relationship between European earwigs (seasonal mean) and woolly aphid (seasonal mean) in trees fitted with predator exclusion bands and unbanded trees under a FMD treatment for codling moth control during the 1996/1997 season.

under MD and FMD treatments (Figures 7b, c, 8b and c). A higher level of variation between trees was evident in data collected from the cultivar Red Delicious early in the season and the model predicted that woolly aphid

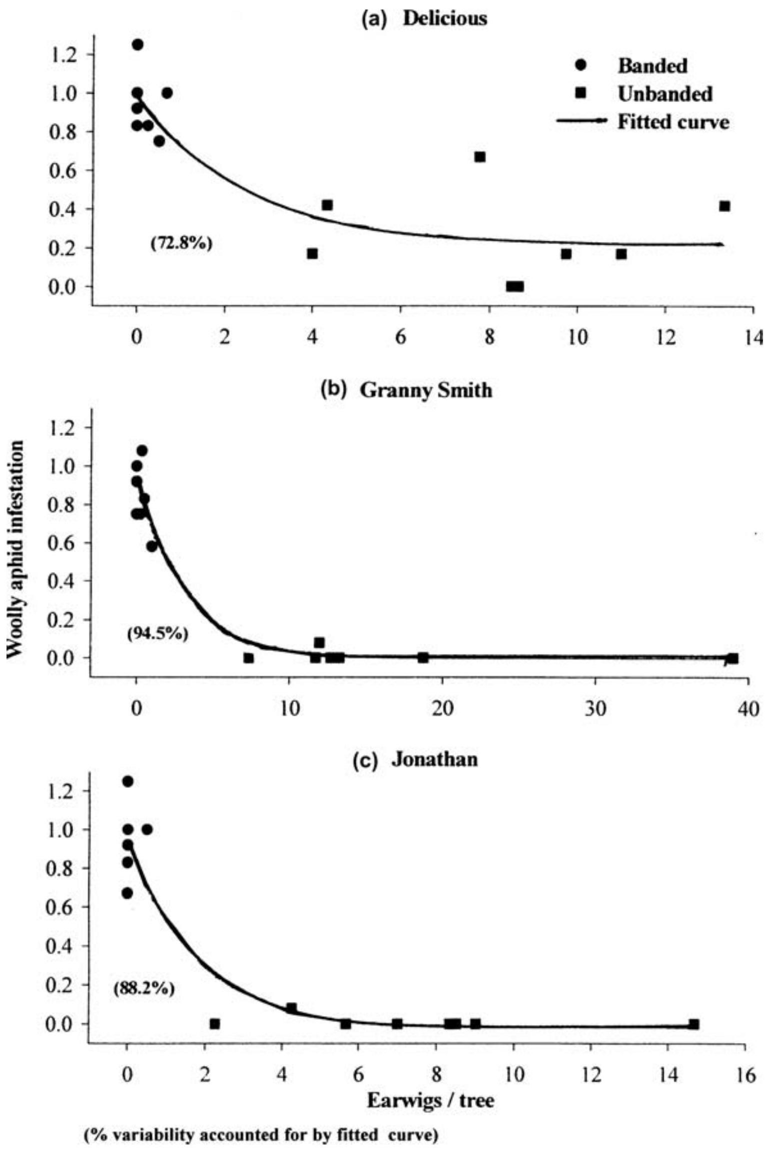


*Figure 7*. Relationship between European earwigs (mean of sampling dates, 24 December, 8, 22 January and 5 February) and woolly aphid (seasonal mean) in trees fitted with predator exclusion bands and unbanded trees under a MD treatment for codling moth control during the 1996/1997 season.

infestation in this cultivar was going to be higher than in the other two cultivars and supported the full season prediction model (Figures 7a and 8a). Early season predictions could not be determined for the 1997/1998 season because the full season data was too variable.

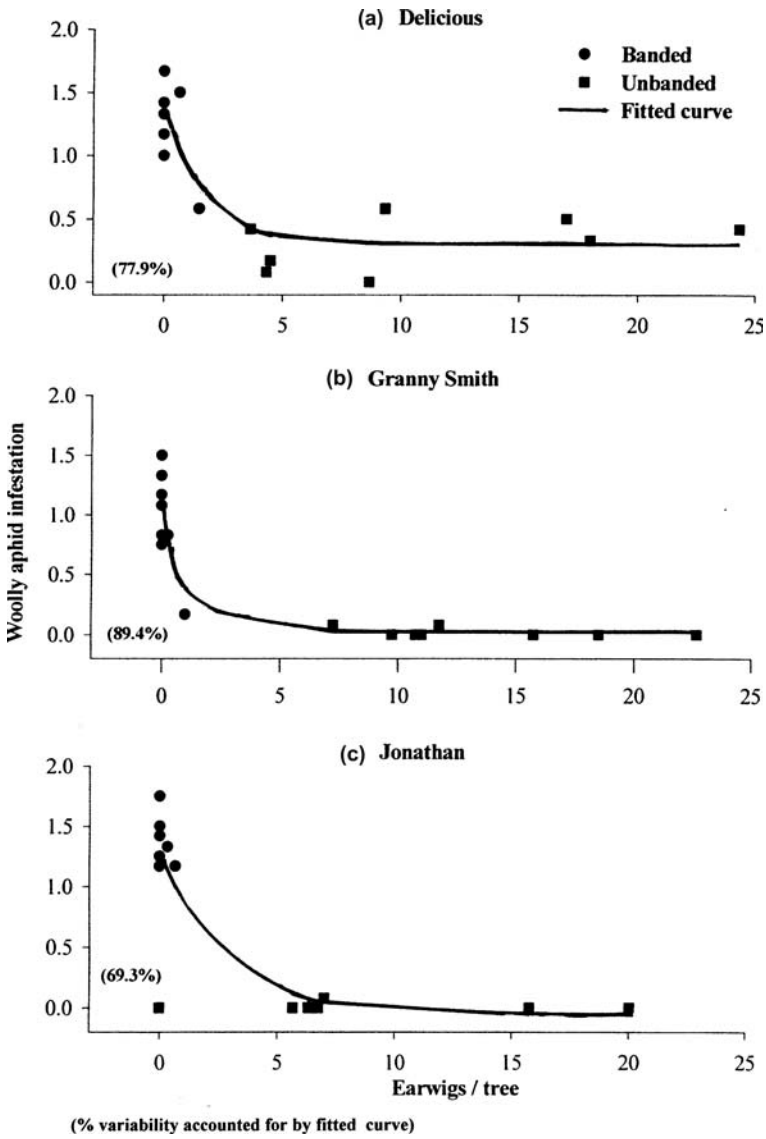


*Figure 8*. Relationship between European earwigs (mean of sampling dates, December 24, January 8, 22 and February 5) and woolly aphid (seasonal mean) in trees fitted with predator exclusion bands and unbanded trees under a FMD treatment for codling moth control during the 1996/1997 season.

## Discussion

The significantly lower levels of infestation in the MD and FMD treatments in the 1995/1996 and 1996/1997 seasons, compared with that in the AMD treatment, shows that under the conditions of this trial, the abundance of woolly aphid in IPM programs was very low. The fungicide program was applied to all treatments and, although it is unclear whether it adversely affected beneficial species (or woolly aphid), it did not prevent biological control of woolly aphid.

The action threshold employed by Australian apple growers to woolly aphid is very low. They usually apply an aphicide at the first sight of infestation or early in the season before the colonies become established, often purely as a preventative measure. This is not because woolly aphid infestation causes heavy crop loss but because severe infestation makes the task of picking fruit messy and unpleasant. Contract pickers are reluctant to work in heavily infested areas. Any infestation rated >1 would not be acceptable to Australian growers. The level of infestation that occurred in the IPM treatments reported here (where no trees were rated 2), would probably not have been detected by most commercial growers, and therefore additional control measures would not have been considered necessary. The woolly aphid infestation recorded in trees treated with azinphos-methyl (many of which were rated 4), and those fitted with predator exclusion bands (i.e., those with fewer natural enemies), would therefore not be tolerated by commercial growers. The higher levels of infestation in Red Delicious occurred late in the season and were present well past the harvest period of late February to mid-March, suggesting that natural enemies may not provide adequate control in more susceptible cultivars. Similarly, adequate control may not be possible in growing districts where climatic conditions are more favourable to woolly aphid development or less favourable to natural enemies.

The significantly higher level of woolly aphid infestation in blocks treated with azinphos-methyl, together with higher *A. mali* and earwig populations in the MD and FMD treatments, supports the findings of Moreton (1969) and Nicholas et al. (1999) that azinphos-methyl suppresses the woolly aphid's natural enemies and prevents effective biological control. There was no evidence in this trial, nor in the reviewed literature, that azinphos-methyl stimulated development or fecundity in woolly aphid.

The lack of significant differences in woolly aphid infestation between the MD and FMD treated blocks indicate that either the full season program of fenoxycarb did not negatively impact on the biological control of woolly aphid, or its effects were only short lived and natural enemies moved in from adjacent blocks. It also shows that the use of MD allows for the establishment of biological control agents. The levels of parasitism in the MD and FMD treatments suggest that *A. mali* played an important role in suppressing the woolly aphid population, although the data should be interpreted carefully because of the small sample size. There was no significant difference in the percentage of parasitism per tree between these two treatments, indicating that fenoxycarb did not suppress the *A. mali* population. This suggests that when applied as a spray to the aerial parts of the tree fenoxycarb did not adversely affect larvae developing in the mummified woolly aphid or the emerged adults. In the AMD treatment however, parasitism remained below 1% until after the spray program was completed, confirming that azinphos-methyl was toxic to *A. mali*. The results suggest that this toxic effect lasts for up to 6 weeks following application. The level of parasitism in the MD and FMD treatments had 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 1996/1997 season. However, as *A. mali* is an alate and highly mobile insect which would have been unaffected by the exclusion bands, it could not have been responsible for the significant differences recorded in woolly aphid infestation between banded and unbanded trees.

Where woolly aphid appeared early in the season, tagged colonies frequently disappeared, indicating that predators rather than parasites were playing a significant, if not the principal, role in controlling the population. In the exclusion trial, significant differences were found between trees fitted with predator exclusion bands and unbanded trees in both the numbers of earwigs in the artificial shelters and the level of woolly aphid infestation. The correlation between the level of woolly aphid and the number of earwigs in artificial shelters indicates the earwig as the principal predator and hence control agent. Only another predator of woolly aphid, similarly unaffected by fenoxycarb and able to access the tree canopy principally by moving up the trunk could have produced the observed result. No such predator was detected on the exclusion bands, in the artificial shelters or during monitoring of the orchard fauna in earlier trials (Nicholas et al., 1999). Adult earwigs can fly but rarely take to the wing (Phillips, 1981).

The fact that earwigs can control woolly aphid is well known in Europe (Stap et al., 1987; Mueller et al., 1988). However these trials appear to have been conducted in experimental orchards where the management of other pests and diseases was not addressed. As part of the present trials, laboratory experiments confirmed that earwigs were capable of consuming woolly aphid (unpublished data).

While earwigs were considered the key regulating agent of woolly aphid in this study, it was not possible to investigate the control of woolly aphid in the absence of *A. mali* or other flying natural enemies. The reduced insecticide programs used in this IPM field trial would have allowed survival of other natural enemies, including *A. mali,* lacewings, ladybirds and hoverflies. All were known to occur at the trial site (Nicholas et al., 1999) and are likely to have had a complementary effect, further reducing the level of woolly aphid infestation in the orchard. However, the high level of woolly aphid in the trees fitted with predator exclusion bands indicates they were not, individually or collectively, capable of controlling woolly aphid in the absence of earwigs.

The polyphagous feeding habit of earwigs 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. This means that earwigs can be introduced and remain established in orchards in the absence of woolly aphid. Noppert et al. (1987) used a simple deterministic simulation model to determine that eight earwigs, searching randomly, could search the average apple tree for prey with 90% efficiency. They calculated the earwig's predation rate at approximately 70 aphids/earwig/night and found that, even at the lowest predicted predation rate, earwigs could 'eliminate' woolly aphid. Counting earwigs in artificial shelters is a relative rather than absolute measure of abundance, which can vary through the season depending on factors such as the availability of alternative refuge sites and weather (Phillips, 1981). However our finding, (based on the 1996/1997 season's data), that a seasonal mean of eight and five earwigs are required to eliminate woolly aphid from the Granny Smith and Jonathan trees respectively supports the findings of Noppert et al. (1987). The data suggest that to maintain effective control of woolly aphid in Red Delicious more earwigs would be required than were present in the orchard during the 1996/1997 season. Earwigs effectively suppressed woolly aphid below the >1 rating in the cultivars Granny Smith and Jonathan during the 1997/1998 season, although not as effectively as in the previous season. The regression model did not predict the elimination of aerial colonies, indicating that naturally occurring populations of earwigs may not always provide 'full' control, particularly in seasons favourable to woolly aphid development. The failure of the model to predict the number of earwigs required to eliminate woolly aphid during the 1997/1998 season is probably due to the variability in the data. The reason for this variability is unclear but climate may have affected woolly aphid development. Availability of alternative food and the effects of sustained fenoxycarb use can also affect earwig development, their population and hence the predator–prey relationship (Blaisinger et al., 1990; Sauphanor and Staubli, 1994).

The regression model predictions based on the first four sampling dates for earwigs in the 1996/1997 and 1997/1998 seasons follow the trend of the full season models. These similarities suggest that with further research over successive seasons, it may be possible to develop a strategy that would enable growers to make decisions regarding the control of woolly aphid based on the potential of earwig populations to provide adequate biological control.

In the 1997/1998 season, when the azinphos-methyl treatment was discontinued, the plots were put under a fenoxycarb program to monitor the effectiveness of natural enemies in newly implemented IPM programs. The significantly lower woolly aphid infestation under fenoxycarb, compared with the previous two seasons under azinphos-methyl, suggests that natural enemies migrated into the blocks rapidly. Seasonal variation in weather patterns can account for lower levels of woolly aphid infestation in some seasons, however this was not considered a contributing factor during this season, as a nearby block of apples treated with azinphos-methyl recorded severe woolly aphid infestation. Earwigs are highly mobile and known to migrate considerable distances (up to 3 m/min) in search of food and shelter (Noppert et al., 1987). This suggests that they have the potential to colonise orchards quickly following the removal of broad-spectrum pesticides. The blocks used in this trial were relatively small and further investigation is required to assess migration of earwigs into larger orchards.

The lack of a significant difference in woolly aphid infestation between the blocks in the first year of the fenoxycarb program and those in their third year, together with the presence of earwigs early in the season, shows that earwigs not only migrated into the blocks quickly, but their populations were sufficient to provide a similar level of control. The lack of any significant difference in woolly aphid infestation between trees fitted with artificial shelters and those without shows that providing earwigs with artificial diurnal shelters in the tree canopy did not improve the control of woolly aphid.

Fenoxycarb has low toxicity to earwigs and is known to reduce fertility when applied to adults reaching or at the end of vitellogenesis (Blaisinger et al., 1990; Sauphanor and Staubli, 1994). It also delays pre-oviposition in the offspring of earwigs treated at the third nymphal instar (Blaisinger et al., 1990). This could result in a reduction in the earwig population, a delay in its spring emergence or both. However no such effects were observed over the 3 years of this study. The lack of any significant difference between the MD and FMD blocks in the number of earwigs present in artificial shelters indicates that either the full season program of fenoxycarb did not suppress the earwig populations, or that they continually migrated in from the MD treatment or surrounding vegetation. The physiological effect of wing twisting observed in a few earwigs during this trial is consistent with that caused by fenoxycarb in some other insects, e.g., the German cockroach *Blattella germanica* L. (King and Bennett, 1989). This observation indicates that at least some of the earwig population had been in contact with and were adversely affected by fenoxycarb. It is thought possible that earwig fecundity could be reduced, as reported by Blaisinger et al. (1990), and this may adversely affect woolly aphid control in the longer term. The effect on earwigs of other pesticides commonly used in commercial apple orchards and the possible impact of earwigs on fruit quality requires further investigation.

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