Vulnerability of pest management in New Zealand apples: pesticide toxicity to *Aphelinus mali* (Hymenoptera: Encyrtidae)

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Abstract New pest management practices in New Zealand's apple sector have provided ecological and economic outcomes that are recognised by growers and exporters. Integrated Fruit Production (IFP) pest control systems that combine biological control, selective insecticides and mating disruption have been developed to achieve these outcomes. Although pest management in apple orchards is now more sustainable, it is also highly vulnerable to pesticide-induced disruption. The toxicity of four pesticides (spinetoram, thiacloprid, spinosad and spirotetramat) on the natural enemy of woolly apple aphid, *Aphelinus mali*, was examined. While applications of spinetoram were the primary cause of aphid outbreaks in 2007–08, other insecticides can contribute to the instability of this biocontrol system. The consequences of applying these disruptive pesticides to aphid control are discussed, together with strategies to mitigate the vulnerability of the IFP programme to pest outbreaks.

Keywords woolly apple aphid, *Aphelinus mali*, “off-target” toxicity, Integrated Fruit Production, insecticides.

INTRODUCTION

Implementation of the Integrated Fruit Production (IFP) programme in the New Zealand pipfruit sector has improved market access and orchard environments (Batchelor et al. 1997; Walker et al. 1998; Walker et al. 2009; Kaye-Blake & Zuccollo 2012). Increased biological control from this integrated approach has led to many pests such as the lightbrown apple moth (*Epiphyas postvittana*) becoming less abundant (Varela et al. 2010). Although these outcomes have led to greater sustainability (Suckling et al. 1999), current pest management practices are also highly vulnerable to pesticide-induced disruption.

Woolly apple aphid (WAA, *Eriosoma lanigerum* (Hausemann) (Homoptera: Pemphigidae)) is a

common pest in New Zealand apple orchards and can cause considerable damage to the shoots and buds of infested trees (Bradley et al. 1997; Mols & Boers 1999), reducing both fruit quality and productivity. If WAA increases to high numbers, the insects can also infest fruit and restrict market access. The serious woolly apple aphid outbreaks that occurred in Hawke's Bay during the 2007–08 pipfruit season provide a good case study of the vulnerability of the current control systems (Rogers et al. 2011).

Aphelinus mali (Hald.) (Hymenoptera: Encyrtidae) is a specific endoparasitoid of WAA and an important biological control agent regulating WAA populations (Shaw & Walker 1996; Monteiro

et al. 2004). It is the primary means of effecting control of WAA in the New Zealand apple sector.

This study examines the toxicity to *A. mali* of residues from applying the insecticides spinetoram, thiacloprid, spinosad and spirotetramat. The data were analysed with those from another study (Rogers et al. 2011), which examined toxicity of the residues of diazinon (organophosphate) and carbaryl (carbamate), so that all the potentially disruptive insecticides to *A. mali* could be considered together. The potential role other WAA natural enemies could have in controlling WAA is discussed along with some overall strategies to reduce the vulnerability of New Zealand's pipfruit pest management programme to aphid outbreaks.

MATERIALS AND METHODS

Field-aged laboratory bioassay

Six insecticides were applied at commercially recommended rates (Table 1) to mature apple trees during autumn between 2008 and 2010, at the Plant & Food Research orchard, Hawke's Bay. The bioassay procedure was described fully by Rogers et al. (2011) and is covered briefly here. Products were applied, allowed to dry and leaves harvested immediately (Day 0) and then at 3–7 day intervals up to 11–28 days after spraying to provide field-aged residues. Spirotetramat was tested only on day 0.

Wild *A. mali* were collected from the field on the morning of each test and confined in Petri dishes with leaves from each treatment for 24 h. The insects were considered to be 'dead' if no movement was detected and 'moribund' if they

were unable to walk in a coordinated manner. Moribund individuals often displayed twitching and paralysis and did not recover; they remained affected and were largely confined to those exposed to thiacloprid. Ten replicates (Petri dishes with one leaf and about 30 *A. mali*) were used for each treatment on each day and compared with the control. In 2008 spinetoram toxicity was compared with spinosad, while in 2009, diazinon, thiacloprid and spirotetramat were tested, all using 'Pinkie' apple leaves. In 2010 carbaryl was tested on 'Fuji'. Bioassay data for carbaryl and diazinon were reported by Rogers et al. (2011) and have been included here to complete the case study. For all these bioassays the methodology was kept the same.

Statistics

Results were corrected for mortality in the untreated controls using Abbott's correction (Abbott 1925). Minitab (Minitab® 15.1.0.0.) was used to calculate means and standard errors. Probit regression analysis was conducted on the field-aged residue data using a generalised linear model in Genstat and LT_{20} values predicted (Genstat® 14.2). The LT_{20} is the mean predicted time after application when the product being tested will affect 20% (moribund + dead) of the sample. LT_{20} values were calculated to compare the residual toxicity of pesticides, based upon the assumption that once mortality had dropped to 20% the product would be having minimal impact on the *A. mali* population. Model adequacy checks were carried out by examining various plots (scatter, histograms and normal probability) of the residuals.

Table 1 Product application rates (g active ingredient (ai)/litre) applied to apple trees at Plant & Food Research, Hawke's Bay, for *Aphelinus mali* bioassays during autumn.

Active ingredient	Trade Name	Formulation (g ai/litre)	Application rate
Control		Unsprayed	
Spinetoram ¹	Delegate®	250 as Wettable granule	0.025
Spinosad ¹	Success™ Naturalyte	120 as Suspension concentrate	0.048
Thiacloprid ²	Calypso®	480 as Suspension concentrate	0.144
Spirotetramat ²	Movento®	240 as Suspension concentrate	0.072
Diazinon ²	Diazol®	500 as Oil/water emulsion	0.5
Carbaryl ³	Sevin® Flo	500 as Suspension concentrate	0.6 ⁴

¹2008, ²2009, ³2010.

⁴rate for fruit thinning.

RESULTS

Acute mortality of *A. mali* after exposure to fresh residues (Day 0) of insecticides ranged from nearly 100% for carbaryl, diazinon and spinetoram to 1% mortality for spirotetramat (Table 2). When moribund insects were included, the affected insects (dead + moribund) associated with thiacloprid residues increased from 21.8 to 73.5% (SEM 6.4). For this product, moribund *A. mali* were characterised by repeated twitching and/or uncoordinated movement, which was not observed with the spinosyn (spinetoram and spinosad) products or diazinon and carbaryl. Affected (moribund + dead) *A. mali* for spirotetramat increased to 9.8% and so was categorised as having little toxicity.

In addition to large differences in initial toxicity, the chronic or residual toxicity of insecticides tested also varied greatly (Figure 1). Spinetoram was not only more toxic to *A. mali* than spinosad initially, but also more than twice as persistent. Spinetoram and diazinon residues both caused similar mortality to *A. mali*. Carbaryl had the greatest persistence or residual toxicity to *A. mali*, causing 85% mortality 21 days after application, which declined to about 40% mortality by 28 days (Rogers et al. 2011). Thiacloprid toxicity declined rapidly, then remained between 10 to 20% until day 15. Comparison of the LT_{20} values for *A. mali* shows that carbaryl was by far the most persistently toxic product to *A. mali*, followed by diazinon, spinetoram and thiacloprid, with spinosad much lower (Table 3).

Table 2 Mean corrected mortality ($\pm$ SEM) of *Aphelinus mali* after exposure for 24 h to residues on an apple leaf, immediately after field-application (Day 0 residue). Diazinon and carbaryl data are from Rogers et al. (2011).

Product	Mortality (%)
carbaryl	98.0 $\pm$ 0.6
diazinon	98.9 $\pm$ 1.1
spinetoram	97.5 $\pm$ 1.6
spinosad	68.2 $\pm$ 10.0
thiacloprid	21.8 $\pm$ 6.2
spirotetramat	1.2 $\pm$ 0.6

Figure 1 Mean corrected percentage of dead and moribund *Aphelinus mali* exposed for 24 h to field-aged residues (days after application) on an apple leaf. Error bars denote the SEM. Diazinon and carbaryl data are included for comparison (Rogers et al. 2011).

The mean mortality of *A. mali* in the untreated control treatments was low (6.4, 6.6 and 11.3% for 2008, 2009 and 2010 data respectively).

The introduction of spinetoram for codling moth control for the 2007–08 apple season resulted in up to three applications (mean 1.2) of this product to apple blocks in Hawke's Bay (Figure 2). By 2012, use of most of the disruptive products had declined, i.e. spinetoram use had almost ceased (99% reduction), followed by

Table 3 Mean predicted time after application (residue age) when each insecticide will affect 20% (moribund + dead, LT_{20}) of the *Aphelinus mali* exposed for 24 h to a field-aged residue on an apple leaf. LT_{20} values not followed by the same letter are significantly different based upon non overlap of the 95% confidence intervals. Diazinon and carbaryl data are included for comparison (Rogers et al. 2011).

Product	LT_{20} (days)	95% CI
carbaryl	34.5 a	29.7 – 43.4
diazinon	13.4 b	11.7 – 15.8
spinetoram	11.5 b	9.9 – 14.3
thiacloprid	6.8 bc	3.8 – 11.9
spinosad	5.2 c	4.0 – 7.3

Figure 2 The mean number of applications of *Aphelinus mali*-disruptive insecticides to Hawke's Bay apple orchards in 2008 and 2012.

thiacloprid (79%), carbaryl (64%) and diazinon (48%), with the exception being spinosad where use had increased (Figure 2).

DISCUSSION

This study sought to measure the toxicity to *A. mali* of potentially disruptive insecticides applied to pipfruit while investigating the cause of the widespread woolly apple aphid outbreaks observed in Hawke's Bay apple orchards during the 2007–08 growing season. Bioassay data presented here demonstrated that residues of spinetoram were toxic to *A. mali* adults and that the product was more persistent and toxic than the related spinosad insecticide that had been used on apples for late-season leafroller control. Spinosad is marketed as a soft insecticide compatible with IPM programmes and although mostly benign to predacious arthropods, it has long been known to have non-target effects on beneficial arthropods, especially hymenopteran parasitoids (Williams et al. 2003; Biondi et al. 2012). The present results showing spinetoram was more toxic than spinosad are consistent with the findings of Gontijo (2012) in Washington who assessed the acute and chronic toxic effect of these products on *A. mali* in slightly different bioassays, which included topical application

of the product but no measure of the field persistence. As well, spinetoram was shown to cause population increases of walnut aphid in two consecutive seasons, with a corresponding decrease in parasitism, confirming its toxicity to natural enemies (Mills et al. 2010).

The 2007–08 WAA outbreaks in Hawke's Bay were so severe that many of the leaves fell off, the ground under the trees was white with wax, the fruit were contaminated with live WAA and next season's fruit-bearing buds were encompassed in galls. Suspicion fell upon spinetoram as the cause of the outbreak because this product was newly introduced for codling moth control and replaced other insecticides (e.g. tebufenozide), which are known to be benign to parasitic Hymenoptera. Furthermore, Nelson growers did not have similar WAA issues which coincided with little spinetoram use in this region.

Was the introduction of spinetoram totally responsible for the observed WAA outbreaks, especially considering other products in the IFP programme are also toxic and some much more persistent? The use pattern of an agrichemical is also important in determining its overall effect on populations of beneficial species. For example, carbaryl was identified by Bradley et al. (1997) as causing complete kill of *A. mali* in a filter paper

bioassay, and Rogers et al. (2011) showed it was very persistent with an estimated LT_{20} of nearly 35 days (see Figure 1 and Table 3 here). Yet carbaryl had been used for many years for fruit thinning without being linked to major WAA outbreaks. The reason is two-fold. Firstly, carbaryl is used early in the season, thereby allowing time for *A. mali* populations to recover. Secondly, it is sprayed only on selected variety blocks rather than whole orchards, thereby leaving reservoirs of *A. mali* for recolonisation. In contrast, spinetoram was used on the whole orchard, later in the season, often with multiple applications if there was high codling moth pressure.

Diazinon has similar toxicity and persistence to spinetoram, yet historically has not caused WAA outbreaks. While diazinon is disruptive to *A. mali*, it also has been used successfully to control WAA. Its typical use pattern is restricted to individual variety blocks and importantly it is toxic to WAA as well as *A. mali*, whereas spinetoram is toxic only to *A. mali* and thus uncouples biological control of WAA.

While thiacloprid residues breakdown relatively quickly and it appears to be one of the least toxic of the products tested, in the present tests fresh residues caused some *A. mali* to be moribund, indicating the importance of a bioassay to measure those that are functionally dead but still twitching.

In New Zealand, WAA management currently relies entirely on biological control, predominantly by *A. mali*. This provides effective control in the absence of disruptive insecticides (Shaw & Walker 1996), as is the case also in Brazil (Monteiro et al. 2004). From the introduction of IFP until 2008 it was common practice to apply diazinon to control WAA. Since diazinon use was limited through residue constraints, there has been no aphicide available to growers if WAA thresholds are exceeded. WAA control has been vulnerable to disruption from a suite of disruptive pesticides, a situation aggravated by having no available aphicide and relying on a single parasitoid species for control. The introduction of spinetoram was the last straw for such a fragile control system.

Nicholas et al. (2005) demonstrated that under a 'soft' IPM programme in Australian pipfruit, WAA was kept under control by natural enemies alone, with the greatest contribution from European earwigs (*Forficula auricularia*) followed by *A. mali*. Without earwigs, however, control of WAA by *A. mali* and other flying natural enemies (such as ladybirds, lacewings and hoverflies) was not achieved. Under IFP in New Zealand very few earwigs are present in apple orchards, most probably because of the toxicity of the insecticides used (Shaw & Wallis 2010). Hoverflies are the most common predators of WAA in North America and the specialist *Heringia calcarata* that preys on both arboreal and root colonies of WAA is especially important in Virginia (Bergh & Short 2008; Gontijo 2012). Plant & Food Research has initiated a programme to introduce *H. calcarata* into New Zealand to reduce the vulnerability of WAA control that is reliant on *A. mali* (Gresham 2013; Gresham et al. 2013).

These toxicity data were presented to growers at a Pipfruit New Zealand Inc. technical seminar in 2008, and growers immediately reduced their use of disruptive pesticides, especially spinetoram, thiacloprid and carbaryl. Although WAA populations took several seasons to stabilise, there has not been a widespread outbreak since this period. Furthermore, prior to the introduction of new pesticides to the pipfruit IFP programme, they must now be tested for their toxicity to *A. mali*. To develop strategies to further reduce the vulnerability of WAA control, research should follow an integrated approach, focused on three broad areas: new product development, classical biological control and conservation biological control. Firstly, a new selective aphicide to augment biological control of WAA would provide additional security and help mitigate some of the disruptive effects if a broad-spectrum insecticide was required to control biosecurity threats such as the arrival of the brown-marmorated stink bug (*Halyomorpha halys*). Secondly, the introduction of *H. calcarata* would introduce a new group of predators that is currently absent from New Zealand apple orchards and is compatible with *A. mali* (Gresham et al. 2013). Finally, eliminating

pesticides that disrupt WAA predators and/or manipulating the orchard environment to enable European earwigs and other predacious insects to be more abundant would make biological control more robust.

This WAA case study highlights the vulnerability of the IFP programme in New Zealand apple orchards where pest control is reliant on a limited number of control measures. Other pipfruit pests such as mites, mealybugs and apple leafcurling midge are also subject to disruption (Lo et al. 2015). The cause of the disruption can be biological or agrichemical, and can include new pests and diseases, changes in resistance status, loss of registered products and changes in legislation. To mitigate these risks the sector requires an integrated suite of control measures utilising the most sustainable options.

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