FINAL PROJECT REPORT

WTFRC Project Number: 3043-3815

Project Title: Dynamics of woolly apple aphids on organic and conventional orchards

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Cooperators: Apple growers throughout Washington State

Total Project Request: **Year 1:** $56,279 **Year 2:** $57,669

Other funding sources

Agency Name: Washington State Department of Agriculture, Specialty Crop Block Grant Program

Amount Awarded: $194,910

Notes: This award expanded our project to include an analysis of how apple growers make management decisions for woolly apple aphid, other pests, and soils using in-depth interviews.

WTFRC Collaborative expenses: None

Item	**2016**	**2017**	
Salaries[1]	$27,099	$28,183	
Benefits[2]	$2,453	$2,552	
Wages[3]	$11,133	$11,322	
Benefits[4]	$594	$612	
Supplies[5]	$7,800	$7,800	
Travel[6]	$6,000	$6,000	
Total	$56,279	$57,669	

Footnotes:

[1] Project Assistant (1.0 FTE for 9 months)

[2] Project Assistant (9.055%)

[3] Summer Wages: Time-slip employee ($10 hr×40 hrs/wk×16 wks/yr); Project Assistant (1.0 FTE for 3 months)

[4] Time Slip (2.1%), Project Assistant (9.7%)

[5] Soil and leaf testing ($75/orchard for soil and $50 for leaf nitrogen×24 orchards = $3000/yr); Aphid and natural enemy and canker sampling supplies ($250/orchard ×24 orchards = $6,000/yr)

[6] Rental vehicle + gasoline + mileage + per diem + travel to research review ($6,000/yr)

Objectives:
(1) Sample populations of woolly apple aphids and natural enemies in organic and conventional apple orchards.
(2) Collect information on soil quality, plant nitrogen content, and perennial canker on these same orchards.
(3) Analyze linkages between soil quality, plant nitrogen content, pesticide-use intensity, natural enemies, and WAA populations in organic and conventional orchards.

Significant findings

- Woolly apple aphid counts in organic and conventional orchards tended to be similar on average
- Soil quality factors had no clear correlation to woolly apple aphid counts.
- Soil texture, however, was found to be associated with variation in woolly apple aphid density in orchards. In particular, densities were lower in sandier soils, perhaps because sandy soil is more difficult for woolly apple aphids to move through (aphids feeding on roots can migrate up to recolonize canopies).
- Leaf nitrogen had no clear correlation to woolly apple aphid counts.
- Perennial cankers were infested with woolly apple aphids more often than other possible feeding sites (such as burr knots), but incidence of cankers did not correlate to woolly apple aphid counts across orchards. However, this observation suggests that woolly apple aphids do prefer to feed at canker sites, which is perhaps why they have assumed to be a pathogen vector.
- Relationships between woolly apple aphid counts and green lacewings, *A. mali* wasps, and earwigs were difficult to interpret likely due to the limited resolution of our sampling strategy (only 3-5 data points per orchard per year). However, data suggest that predators (including earwigs) do play a critical role in suppressing aphid populations.
- Seasonal patterns of woolly apple aphid abundance appeared to be strongly related to temperature, with the hottest period of the summer always corresponding to crashes in woolly apple aphid populations. Insecticide applications during the hottest period of the summer are thus likely to be wasteful.
- In a greenhouse study, sandier soil reduced movement of woolly apple aphids down to roots, as did wood chip and paper slurry mulches, but migration was not completely blocked.
- In a field study, sticky bands designed to completely block woolly apple aphid movement up and down apple tree trunks did not significantly impact aboveground population dynamics. Aphids migrating up from roots were blocked, but this did not result in fewer aerial colonies.
- We expanded our study to include an investigation of the role of earwigs in woolly apple aphid control. Earwigs were released in sections of an experimental orchard. Compared to these sections, control areas with no earwigs added averaged about 400% greater woolly apple aphids at peak seasonal density, suggesting that earwigs are valuable predators of woolly apple aphids.
- The Fuji variety appeared especially susceptible to woolly apple aphid infestation in mixed plantings of Fujis, Galas, Goldens, and Jonagolds at WSU Sunrise Research Orchard.

Results and discussion

Soil quality and texture
Against expectations, no soil quality measurements differed significantly between organically and conventionally managed orchards, and neither did overall soil quality when all measurements were summarized into a normalized soil quality score from zero to one (one being the best). Though organic orchards are expected to have higher soil quality, our results are not consistent with this prediction. In our orchards, these findings might be explained by greater similarity in commercial organic vs. conventional management than in certain relatively controlled scientific studies.
There was no clear relationship between soil quality and woolly apple aphid abundance in either year of study (Figure 1). However, three of the orchards had especially high sand content in their soil (>60%) and these orchards also had low woolly apple aphid counts in both years of study (Figure 2). The low woolly apple aphid counts in these sandy orchards may have occurred because previous studies suggest that woolly apple aphids cannot easily move through sandy soil, thus preventing recolonization of canopies from root-feeding aphids.

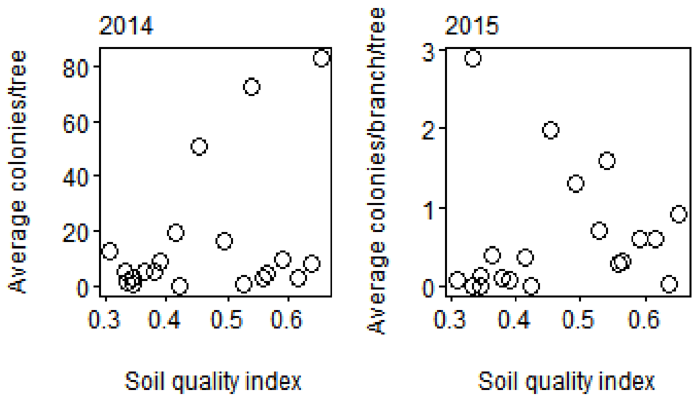

Figure 1. Woolly apple aphids and soil quality. Woolly apple aphid colonies were counted on entire trees (2014) or on each of 10 approx. 1' long branches on 16 trees per orchard (2015) on each of 3 to 5 visits throughout the season. Counts averaged to one number per orchard per year. The soil quality index is a score from 0-1 (0 = worst, 1 = best score) representing overall soil quality.

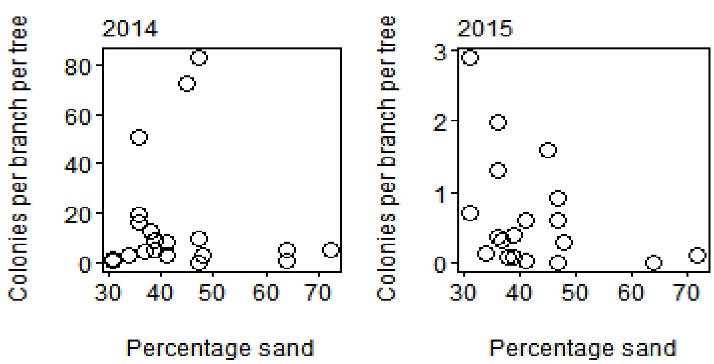

Figure 2. Woolly apple aphids and soil texture. Woolly apple aphids were counted as in Figure 1. Soil sand content was determined for each orchard by SoilTest Farm Consultants (Moses Lake, WA)

To follow-up on this, a greenhouse experiment was conducted to test a sandy potting mix, wood chip mulch, and a paper slurry mulch for blocking woolly apple aphid access to roots. Sandy soil and both mulches reduced woolly apple aphid infestation of roots (Figure 3). Similarly, sandy soil may reduce woolly apple aphid risk. ***Therefore, use of mulches on an orchard could be expected to reduce woolly apple aphid infestations***. This experiment was conducted in a greenhouse on small trees, and thus we should be careful with the inference from these results. It remains to be seen whether these results could be replicated under more realistic field conditions – this is potentially an area of future study that would be beneficial for improving management of woolly apple aphid.

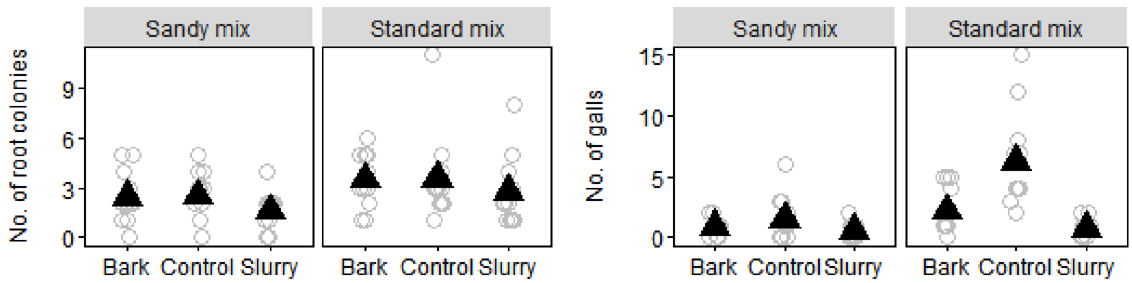

Figure 3. Soil and mulch greenhouse experiment. Woolly apple aphids were introduced to canopies of potted trees with different soil and mulch combinations. After two months, trees were pulled for root inspection and colonies and galls were counted. Circles represent counts on individual trees and triangles are the means for each group. The standard soil mix was equal parts perlite, vermiculite, and peat, while the sandy soil mix was 60% sand and 40% standard mix. The bark mulch was a 10 cm layer of chipped apple trees and the slurry is paper pulp poured wet and allowed to dry into resemblance of egg carton material.

Effect of blocking upward woolly apple aphid migration on aerial population dynamics in the field

To complement our mulch study, in 2017 we tested the hypothesis that upward movement of woolly apple aphids from roots to aerial parts of the tree significantly boosts aerial population abundance. In our experiments, even though thousands of migrating aphids were blocked from moving up tree trunks (data not shown), the trees with tanglefoot blocks did not have significantly lower aerial colony counts at any time during the season compared to the 'open' trees (Figure 4).

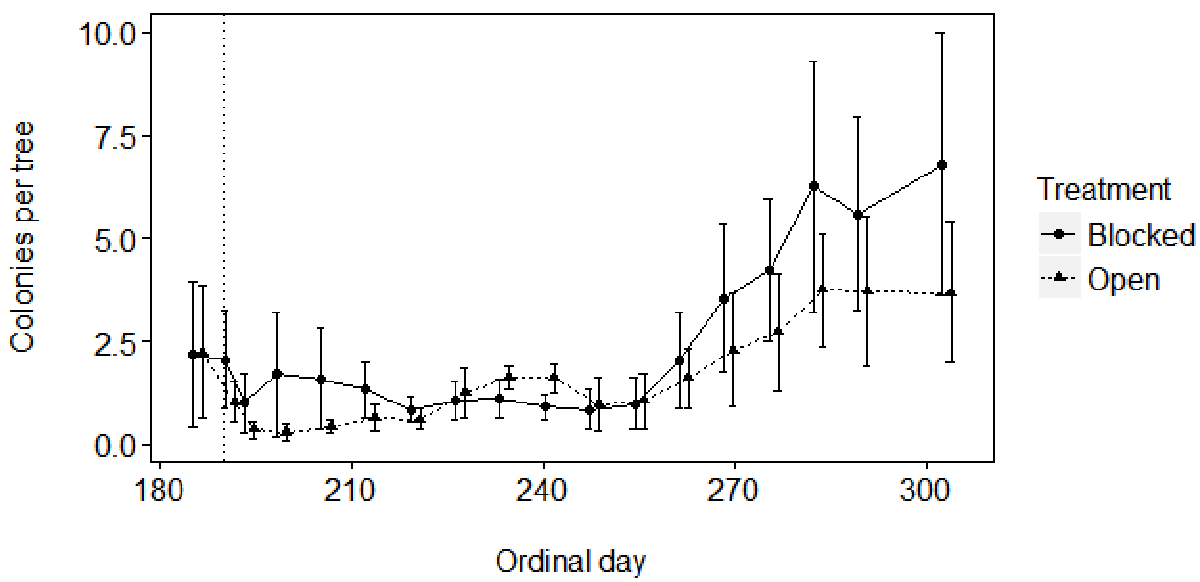

Figure 4. Woolly apple aphid colony counts on 'blocked' trees with tanglefoot bands and control 'open' trees. At Washington State University Sunrise Research Orchard, 12 sections of 12 trees were selected for study. Half of the sections received tanglefoot bands at the base of their trunk. The border trees in these sections were separated from neighbor trees by pruning and the addition of tanglefoot bands to trellis wires. The other 6 sections received no manipulation. All sections were monitored once a week from July until October. The total number of woolly apple aphid colonies found on the west side of each tree was counted. Each point shows the average number of aphid colonies per tree of the 6 sections, and error bars show 95% confidence intervals of the mean of aphid colonies per tree within each treatment. The vertical dotted line shows when the sticky tanglefoot bands were applied.

Our results do not support the hypothesis that blocking upward woolly apple aphid movement will ease aerial outbreaks. Apparently, existing aphid colonies in the canopy are a more important source of new aphid colonies in this situation. Because woolly apple aphids can overwinter aboveground, and are unlikely to be completely locally eradicated by pesticides or natural enemies, it seems unlikely that cutting off woolly apple aphid movement in and out of the soil will be an effective management tactic for growers. However, reduction of populations in the soil could still provide other benefits, despite the need for management of aerial colonies as well.

Plant nitrogen content

There was no clear relationship between leaf nitrogen and woolly apple aphid abundance in either year of our study (Figure 5). It was expected that new growth flushes, which can be spurred in part from nitrogen fertilization, would be associated with increased woolly apple aphid populations. Nitrogen can be a limiting factor for aphid growth, and woolly apple aphids often are found on new growth of apple trees. We did not observe this, however, perhaps because of the low resolution of sampling (3-5 visits throughout the whole season) or because leaf nitrogen is not a reliable proxy for phloem nitrogen, which is where aphids feed from.

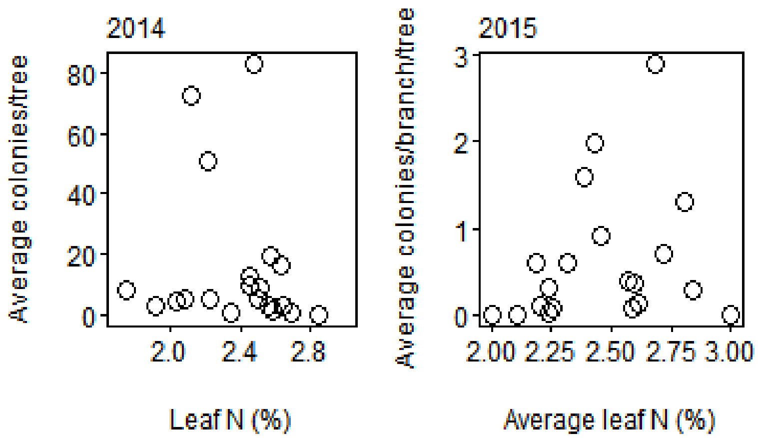

Figure 5. Woolly apple aphids and leaf nitrogen. Woolly apple aphids were counted as in Figure 1. Leaf nitrogen measurements were obtained from samples of mid-terminal fully expanded leaves sent to SoilTest Farm Consultants (Moses Lake, WA). Leaf samples were collected on one visit (2014) or three separate visits to each orchard throughout the growing season and (2015).

Pesticide use intensity

There was no clear correlation between pesticide use intensity and woolly apple aphids (Figure 6). We predicted that heavy use of broad-spectrum insecticides would induce woolly apple aphid outbreaks because of disrupted biological control, but this was not the case.

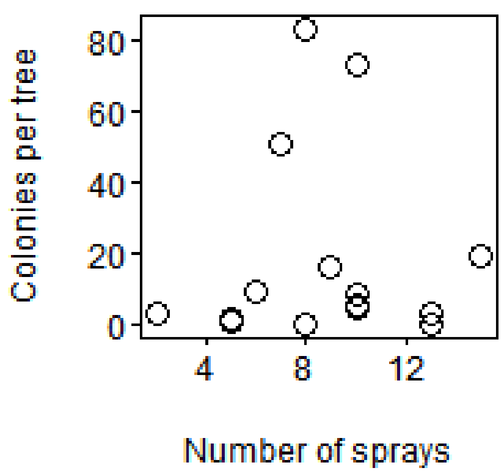

Figure 6. Woolly apple aphids and management intensity (broad spectrum insecticide sprays). Woolly apple aphid colonies were counted as in Figure 1. Oil and broad spectrum pesticides were included in this analysis, while more specific insecticides such as *Bt* and codling moth granulosis virus were not included.

Perennial cankers
Cankers were found at only one of the twenty study orchards, but they were rare (32 perennial cankers out of 4,500 trees inspected). While 90% of the perennial cankers were found to be infested with woolly apple aphids, there was not a clear connection between woolly apple aphid and perennial canker across all study locations because the 19 other orchards lacked perennial cankers. The high infestation rate of perennial cankers suggests that they are highly suitable feeding sites, but woolly apple aphids do not spread or cause first-year cankers. Furthermore, it was previously demonstrated that woolly apple aphids do not transmit the perennial canker fungus.

Natural enemies
Orchards with higher abundance of natural enemies (green lacewings, *Aphelinus mali* wasps, earwigs) tended to have lower woolly apple aphid counts, although results were highly variable, likely due to the other conditions on orchards. To follow-up on these results, a controlled experiment was conducted with earwigs, which appeared to be an important predator in our field surveys. The experiment clearly shows that the addition of this generalist predator resulted in fewer woolly apple aphids (Figure 7). Therefore, earwig conservation through timing and selection of pesticide sprays, and timing of tillage (to avoid destroying underground earwig overwintering nests) is suggested as a new integrated management tactic for woolly apple aphids. In addition, apples were inspected in the field for damage. Earwigs were sometimes found feeding in stem bowl cracks, but there was no evidence of any damage initially *caused* by earwigs because the occurrence of stem bowl cracks and overall damage was not higher in the earwig sections.

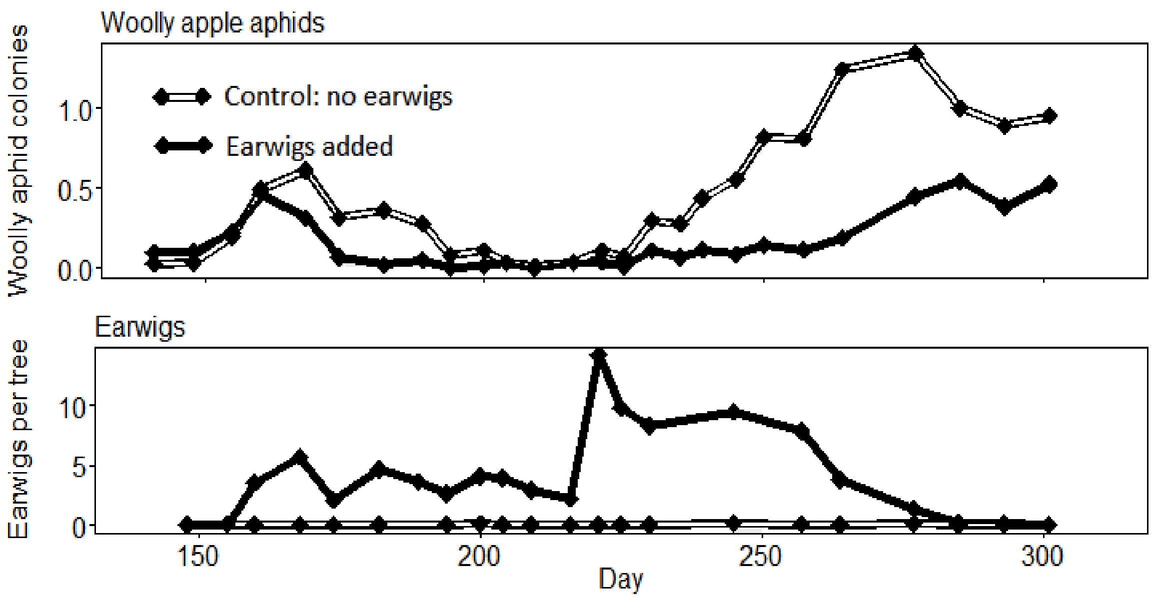

Figure 7. Earwig biocontrol experiment. Two years of observations indicated that no earwigs were initially present at the study block. Earwigs were first introduced to five 10 X 10 meter sections of the block on Ordinal Day 155 (see bottom chart) and were monitored each visit with counts in rolls of corrugated cardboard. A total of 675 earwigs per section was released between Ordinal Day 155 and 176. On Ordinal Day 217, 1,000 earwigs per section were released. The number of woolly apple aphid colonies (top chart) were counted on each of 10 branches of 21 trees in each of five earwig release sections and five unmanipulated control sections. Counts in the different section types were averaged to one number per visit for presentation here. The drop-off in earwig numbers at the end of the season is due to earwigs moving underground to nest over winter.

Woolly apple aphids and temperature
Temperature appeared to be an important predictor of woolly apple aphid population dynamics. Previous laboratory experiments showed that woolly apple aphids die at temperatures over 90 F. Consistently, when summer temperatures reached over 90 F for summer days, woolly apple aphid populations declined (Figure 8). We expect that in future years woolly apple aphids will also decline during extreme summer heat and management actions meant to control woolly apple aphids during such periods would be superfluous.

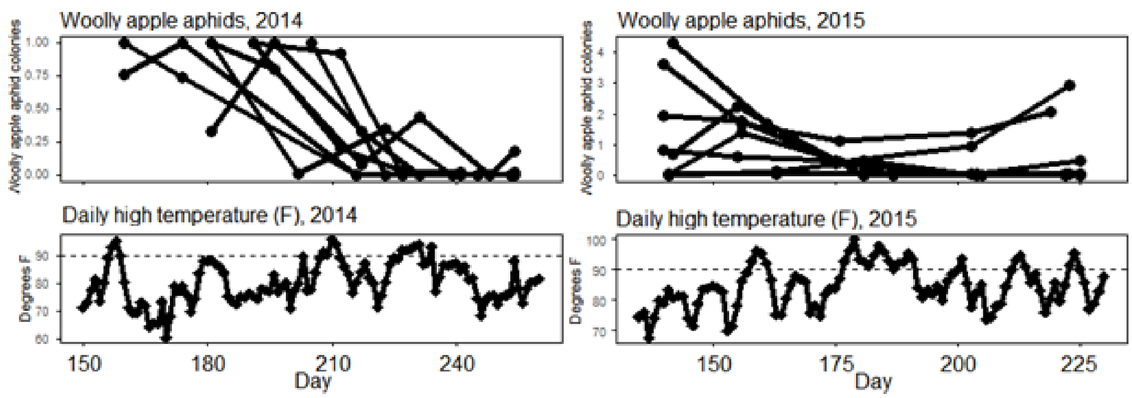

Figure 8. Temperature and season-wide woolly apple aphid counts. Woolly apple aphid counts (as in Figure 1) at orchards near Quincy, WA over time are presented along with daily high temperatures in degrees F. The dotted lines in temperature graphs are at 90F, above which woolly apple aphids do not grow well. Because of wide variation in woolly apple aphid counts in 2014, counts within each orchard were standardized values between 0 and 1 for purposes of visualization, while the 2015 chart shows average colonies per tree.

Woolly apple aphids and apple varieties
In our main study, only Fuji and Gala orchards were studied. In both years, woolly apple aphid counts averaged about twofold higher in Fuji orchards compared to Galas. Because of this, and because growers sometimes mentioned that they thought Fujis are more susceptible, we counted woolly apple aphid colonies in mixed plantings in the WSU Sunrise Research Orchard. The results suggest that Fujis are indeed more susceptible to woolly apple aphid infestation (Figure 9).

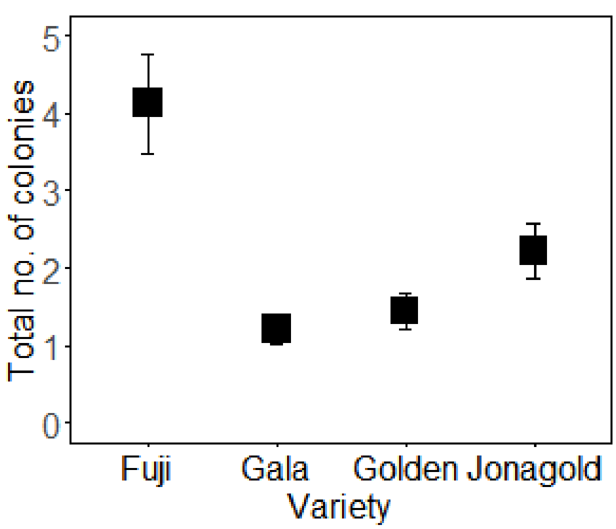

Figure 9. Woolly apple aphid counts on different apple varieties. In 3 mixed-planted blocks at the WSU Sunrise Research Orchard (containing alternating rows of Fujis, Galas, Goldens, and Jonagolds, the number of woolly apple aphids on October 6, 2015 were counted on ten ~1’ long twigs on each of 312 total trees. Average counts per tree for each variety are shown with standard errors.

Executive summary

Summary of findings

- Our two-year observational study suggested that both temperature, natural enemies, and soil texture were important factors affecting variation in woolly apple aphid densities. Aphids were less common at high temperatures, in orchards with sandy soils, and in orchards with high natural enemy populations (earwigs in particular were key woolly apple aphid predators)
- In our two-year observational study, there was not clear evidence showing how soil quality, leaf nitrogen, organic management, and pesticide use influence woolly apple aphid incidence.
- Higher soil sand content may hinder woolly apple aphid movement into and out of soil, resulting in lower prevalence of aboveground colonies. Wood chip mulch and paper slurry mulch also reduce movement through soil, but our field study suggests that even complete blockage of woolly apple aphid movement up from roots may not help management efforts against aerial colonies. However, mulch or sand amendments might help prevent issues associated with colonies in the soil of orchards.
- Woolly apple aphids are often found feeding in perennial cankers, suggesting these are preferred wound sites for apples. However, a high abundance of woolly aphids does not induce canker outbreaks because woolly apple aphids do not transmit the fungus that causes perennial canker.
- Hot summer temperatures above 90°F are associated with woolly apple aphids die-offs, but woolly apple aphids resurge when temperatures cool off. Pesticide sprays at temperatures above 90°F are likely to be superflous
- Earwigs are important and underappreciated woolly apple aphid predators. Conserving earwigs has been shown to directly reduce aphid populations
- The Fuji variety is more susceptible to woolly apple aphid infestation than Galas.

Significance to industry

- Insecticide sprays for woolly apple aphids during peak summer heat appear to be unwarranted because the aphids will die anyway from the heat.
- Orchards planted on sandy soil may at lower risk of woolly apple aphid infestation.
- Fuji orchards may be at elevated risk for woolly apple aphids.
- Earwig conservation could reduce woolly apple aphid problems.
- Better IPM of woolly apple aphids that moves away from chemical strategies

Future directions

- New projects in our lab in 2017 expanded upon our ideas about earwig biological control. We have now produced strong evidence that earwigs are important aphid predators based on field manipulation studies and video recording studies. We will continue these investigations.
- PhD student Robert Orpet plans to compile and publish guidelines on earwig conservation for biological control of woolly apple aphids.
- PhD student Robert Orpet will compile current best recommendations for presentation at meetings.
- Continue to educate growers on strategies to improve aphid management
- Evaluation of survey data to better understand how growers make decisions concerning management of woolly apple aphid and other pests
- Evaluation of mulches in larger field settings as a method to reduce belowground aphid colonies