

**Variability in abundance of the rosy apple aphid (*Dysaphis
plantaginea*), the role of its alternate host (*Plantago major*), and
potential control strategies in organic apple orchards in
British Columbia.**

by

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Abstract

The rosy apple aphid, *Dysaphis plantaginea*, (Homoptera: Aphididae) is a serious pest of apples in British Columbia (BC), Canada and especially in organic orchards where conventional controls cannot be used. The goals of this study were to determine the environmental or management factors of an orchard that lead to high aphid populations, to conduct an economic assessment of the damage, to determine the timing of autumn migration, and to test several autumn and spring chemical control methods and two novel autumn mechanical control methods targeting the aphids while on their alternate host, *Plantago major*.

To explain the variation among orchards, I evaluated several potential correlates of aphid density: abundance of the alternate host (plantain, *Plantago major*), foliar tree nitrogen, tree age, tree planting density, and the application of an oil treatment in spring. Stepwise regression indicated that foliar nitrogen and tree age explain 27% of the variation.

Orchards receiving a spring oil application had a 53% lower average aphid infestation level. Plantain abundance was not related to aphid population on apple. However, experimental manipulation of leaf angle from the ground and size showed that significantly more alate and apterous aphids occurred on large, low angle leaves. Mowing prior to spring aphid migration was associated with 75% fewer alatae and apterae on the plantain.

The loss in harvest resulting from aphid damage ranged from 3% to 76% of the crop.

Effective autumn control depends on accurate timing of aphid flight. The peak of female

flight occurred on the 27th of September, 2007 at 11:56 hours daylength (sunrise to sunset) and the peak of male flight occurred on the 12th of October, 2007 at 11:02 hours daylength. Aphid densities in the spring of 2008 were very low, making comparisons between treatments and controls difficult. Autumn applications of Superior dormant oil and kaolin clay were not effective. The PureSpray Green treatments of two October applications and one April application showed a significant reduction in rosy apple aphid infested clusters compared with the untreated control. Mowing and rotavating did not result in a significant reduction in aphid infestation level.

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Chapter 1

Variability in abundance of the rosy apple aphid, *Dysaphis plantaginea*, the role of its alternate host, *Plantago major*, and potential mechanical and chemical control strategies in organic apple orchards in the Similkameen Valley of British Columbia.

1.1 Introduction

The rosy apple aphid, *Dysaphis plantaginea* (Passerini) (Homoptera: Aphididae), is considered one of the most serious apple pests worldwide (Wyss and Daniel, 2004; Cross *et al.*, 2007). It was introduced to Canada over a century ago from Europe along with its winter and summer hosts, apple, *Malus domestica* (Rosales: Rosaceae), and plantain, *Plantago major* and *Plantago lanceolata* (Lamiales: Plantaginaceae) (Lathrop, 1928). Depending on the location and management it is categorized as a primary or sporadic pest (Croft and Hoyt, 1983). In organic orchards it has proven to be especially problematic where it is not controlled by organophosphate pesticides applied to control other pests such as mites and scale insects (L. Edwards, Ambrosia Growers Association, Personal communication.). In the future, however, it may become more of a problem in conventional orchards because there are reports of increasing resistance to insecticides (Wyss and Daniel, 2004; Delorme *et al.* 1998).

In organic agriculture, a certain level of insect damage is accepted, but pests such as rosy apple aphids may cross an economic threshold that requires action to mitigate the potential crop damage. In the case of rosy apple aphids, the economic threshold is one

fundatrix per 50 buds in the spring (Anonymous, 1977) or one fundatrix in 100 buds (Blommers, 1994). According to Croft and Hoyt (1983) there are several components in an orchard system that influence arthropod population dynamics including the trees, the ground cover, the soil and the surrounding environment. Depending on the associations of the pest species with these orchard components their populations can fluctuate as a result of tree management such as fertilization and pesticide use, of ground cover management, or of plant succession in the surrounding vegetation (Croft and Hoyt, 1983). In a given year, rosy apple aphids may remain at low levels in many organic orchards, while in other orchards, high densities can cause significant fruit damage (L. Edwards, Pers. comm.). The average level of rosy apple aphid abundance also varies from year to year dramatically (A. Brown, Personal observation). This variability among orchards and among years makes both predicting the level of aphid densities and the need for intervention very difficult.

1.2 Previous and Current Research

1.2.1 Biological Control

Conservation biological control for rosy apple aphids is often effective, but only at relatively low pest populations, and cannot prevent extensive damage in bad years (Weires and Leeper, 1980). A study conducted in Northern Switzerland by Wyss *et al.* (1999a) assessed the ability of three aphidophagous predators, *Adalia bipunctata*, *Aphidoletes aphidimyza*, and *Episyrphus balteatus* to reduce *D. plantaginea* populations. *A. bipunctata* proved to be the most effective predator killing 70% of the aphids within 48 hours. *A. bipunctata* and *E. balteaus* had additive effects on aphid population control

and reduced the aphid density to 5% of the control (Wyss et al., 1999b). In follow-up field trials, control was maximized when the release occurred in early May as opposed to early April, when a ratio of predator to prey of 5:1 was created, and when ants were excluded from the trees. This study also observed that ant-attended trees had 30% more aphids than ant-free trees (Wyss *et al.*, 1999b).

Unfortunately, the release of adult Coccinellidae is not always effective as they tend to disperse from the area of release, and thus only the larval stages provide aphid control (Trouve *et al.*, 1997). No species of *Syrphidae* is commercially available in Canada for use in aphid control. Naturally occurring *Aphidoletes* species occur in the orchards too late to be used for augmentative biological control for the rosy apple aphid (L. Edwards, pers. comm.; V. Cervantes, The Bug Factory, pers. comm.).

1.2.2 Chemical Control

Organically acceptable horticultural oils are available, but spring applications have been reported to be ineffective once aphid feeding starts and aphids are protected from sprays by the curled leaves (Bessin, 2003). As a result, much of the research focus in the past 10 years has been on autumn control of this insect using a range of both organic and conventional products (Kaolin clay, garlic oil, pyrethrum, rotenone, potassium soap (Savona), Assail (imidacloprid), Admire (imidacloprid), and Aphox (pirimicarb)) with varying levels of success (Wyss and Kehrli, 2001; Helsen, 2001; Helsen and Simonse, 2002; Wyss and Daniel, 2004; Cross et al., 2007). Wyss and Kehrli (2001) tested pyrethrum applications and found that three, four and five applications in late autumn

(September 29, October 8, 13 and 28, November 9) had a significant effect on the number of rosy apple aphids the following spring. Numbers of spring fundatrix females were reduced from approximately 35 in the control sites to between 1 and 3 in the treatments. Wyss and Daniel (2004) found that three and four applications of kaolin clay in late September and early October significantly reduced the number of gynoparae that landed on the plants in the autumn and the number of fundatrix females in the spring, compared to those on untreated branches. Helsen (2001) and Helsen and Simonse (2002) showed that a single application of imidacloprid and pirimicarb in the second week of October gave between 90 and 100% reduction of aphids the following spring compared to untreated controls. In comparison, the organically accepted product, potassium soap, gave less than 30% control when applied once or twice in October. Similarly, Cross *et al.* (2007) have shown that a single application of pirimicarb + cypermethrin on Oct. 11 gave almost 100% control. This shows a large difference in both the efficacy and the number of applications required between conventional and organic control options.

1.3 Organic Apple Production in British Columbia

In the Similkameen Valley of British Columbia (BC), organic apple production is a large and growing industry. This project was initiated, guided and supported by growers and the goals all have potential management strategies in mind.

This study is divided into two chapters. The first chapter seeks to explain the large variability in population size that was observed among orchards. In order to understand the environmental factors of the apple orchard that lead to high rosy apple aphid populations, several orchard characteristics (alternate host abundance, foliar nitrogen

levels, tree age and planting density) were measured and correlated with aphid infestation level. In the summer, the alternate host plant, plantain, is important for maintaining aphid populations and the interactions between aphids and plantain during and after spring migration were observed. The effect of plantain architecture on preference, survival and reproduction of rosy apple aphids was studied through both field observation and experimental manipulation of plantain leaf size and angle from the ground. The prediction was that larger plantain leaves with a lower angle from the ground provide higher quality habitat and thus result in higher numbers of aphids on these plants in the summer. Finally, the link between orchard mowing practices and plantain architecture is shown.

The goals of the second chapter were to conduct an assessment of the economic losses caused by the rosy apple aphid to justify the cost of management options and to assess the efficacy of several chemical and mechanical control strategies. The chemical strategies tested included three products applied in the fall (kaolin clay [Surround® WP], dormant oil [Bartlett Superior Oil®], and summer oil [PureSpray™ Green], and one product applied in the spring (PureSpray™ Green summer oil). The timing of the autumn migration is important for applying the autumn control strategy most effectively, and so the timing of migration in 2007 in Southern BC was determined using pheromone traps.

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Chapter 2¹

Variability of rosy apple aphid population size, *Dysaphis plantaginea*, and the role of its alternate host, *Plantago major*, in organic apple orchards in the Similkameen Valley of British Columbia.

2.1 Introduction

The rosy apple aphid, *Dysaphis plantaginea* (Passerini) (Homoptera: Aphididae), is an important pest of apple orchards, especially those managed according to organic standards (Nielsen et al. 2007; Wyss and Daniel, 2004; Cross et al., 2007). This pest is conventionally controlled with organophosphate pesticides applied to target other pests, but resistance has been observed (Wyss and Daniel, 2004; Delorme *et al.*, 1998). In European organic orchards spring applications of neem extract are used to control rosy apple aphids, but the timing is essential to ensure the aphids are targeted after they've hatched and before the leaves curl around the colonies (Zuber, 1995; Hoehn *et al.*, 1996; Kienzle *et al.*, 1997 and Vogt et al., 1997 as cited in Cross *et al.*, 2007). This occurs at approximately 140 degree days over the thermal constant of 4°C (Graf et al., 2006). In British Columbia (BC), neem products are not registered, but some growers choose to apply a dormant oil pre-bloom from '½ inch green' to 'tight cluster' to mitigate aphid, scale and mite problems, but many do not (L. Edwards, Pers. comm.).

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2.1.1 Aphid Lifecycle

Rosy apple aphids feed on the phloem of their primary host plant (*Malus domestica* [Rosales: Rosaceae]), causing the leaves to curl and the fruit to develop abnormally. This herbivory also affects the next year's flower buds which are developing during this time. As a result, in years of high aphid abundance, much of the fruit is unmarketable and the harvest the following year is affected (Blommers et al. 2004).

Rosy apple aphids are heteroecious requiring both a primary woody host, and a secondary herbaceous host to complete their lifecycle. This life cycle has been shaped by the nature of the primary host. In the spring, leaf growth and consequently aphid population growth, is driven by the nitrogen, in the form of amino acids, being imported into the leaves from the trunk (Dixon, 2005). In early summer, the temperature and solar radiation intensity increase, nitrogen translocation decreases, and the aphids must leave this host for higher quality habitat. Herbaceous plants are actively growing during the summer and can provide superior nutrition. Aphids have been shown to assimilate more energy per unit of sap energy consumed on herbaceous plants than trees (Dixon, 1975; Llewellyn, 1982). Being such a small insect compared with their hosts, aphids live in a very heterogeneous environment (Levin, 1968). Not all leaves are suitable for aphids and microclimate can play an important role in survival during the higher temperatures experienced during summer, which have been shown to reduce aphid growth (Dixon, 1985).

Eggs hatch on the leaves or stems of apple trees in the spring and these fundatrices feed on flower or leaf buds. Towards the end of May, the aphids begin to produce alate

(winged) morphs which migrate to their obligate alternate hosts, broad and narrow leaf plantain, *P. major* and *P. lanceolata* (Lamiales: Plantaginaceae), where they remain for the summer. These two hosts are common in the irrigated areas of the Okanagan and Similkameen Valleys of BC, but only *P. major* is found in orchards (A. Brown, Pers. obs.). The aphids reproduce by parthenogenesis through the summer, reverting to the apterous (wingless) morph (Blommers et al. 2004). In the autumn, gynoparae (alate females), are produced and these migrate back to apple trees. This production of alates seems to be triggered by decreasing daylength, but the rate of production of alates is also affected by temperature (Lees, 1966; Blommers *et al.*, 2004). On apple trees, sexual females, called oviparae, are produced by the migratory gynoparae, generally within the first 24 hrs of arriving (Blommers *et al.*, 2004). During this time, alate males are produced on the plantain and these migrate to the apple trees to mate with the oviparous females. Small black eggs are laid on the branches at the base of buds to complete the lifecycle (Wyss and Daniel, 2004).

This study considered the rosy apple aphid within the context of its orchard environment and attempted to determine the environmental and host factors that are correlated with high aphid populations. The hypothesis was that increasing plantain abundance, increasing foliar nitrogen, decreased age, increased tree density and no oil application will be associated with higher aphid populations. Increasing plantain abundance provides rosy apple aphids with a summer host, allowing them to survive the summer, return to the apples in the autumn and be present as a pest the following spring. Increasing foliar nitrogen would provide the aphids with higher quality tissues to feed on and increased

reproduction rates. Decreased tree age is expected to be associated with reduced new growth in the spring and thus, reduced availability of nitrogen during translocation (Dixon, 1985). Increasing tree density facilitates aphid movement between trees when conditions become crowded in the late spring, allowing populations to take advantage of higher quality host sites. An oil application is made by some growers as an aphid control strategy against both the rosy apple aphid and green apple aphid (*Aphis pomi* [DeGeer]). The summer, alternate host plant, plantain, is important for maintaining aphid populations, and the interactions between aphids and plantain during migration were considered in detail. Effects of plantain architecture on preference, survival and reproduction of rosy apple aphids were studied through both field observation and experimental manipulation of plantain leaf size and angle from the ground. The prediction was that larger plantain leaves with a lower angle from the ground provide higher quality habitat, as they potentially provide protection from desiccation and predators, and thus result in higher numbers of aphids on these plants in the summer. Finally, the link between orchard mowing practices and plantain architecture was also investigated, because mowing removes the upright growth and field observations indicated that orchards with taller orchard floor vegetation also had taller plantain plants.

2.2 Materials and Methods

2.2.1 Study Area

The study orchards were located in Cawston and Keremeos in the Similkameen Valley of British Columbia, Canada (49°09N, 119 °44E). The twenty four apple orchards chosen for sampling were all planted with the variety ‘Ambrosia’ and were all managed

organically according to Certified Organic Association of British Columbia (COABC) standards.

2.2.2 Monitoring Aphid Populations

Apterous aphid populations on apple trees were assessed in April, May and June in 2007; however data from the first week of June were used in analysis since they represented the peak in populations. In 2008 the apterous populations were assessed again in the second week of June in order to compare levels and determine whether it is the same orchards or different ones that have high rosy apple aphid levels each year. Both of these sampling times correspond with 650 to 750 degree-days, using the lower threshold of 4.5°C for nymphal development, determined by Graf *et al.* (1985). Levels of aphid infestation were sampled in each orchard by counting the number of infested (at least one aphid present) spurs or terminals (clusters) on every 20th tree up to maximum of 100 trees. The orchard rows were chosen in order to get an evenly distributed sample from all sections. The outer edge rows were always sampled and the middle rows were selected to be evenly spaced and provide a sample of at least 30 trees for the block. Each infested cluster was recorded as having <10 or >10 aphids. The data used in analysis, called 'percent infestation' were the percent of trees per orchard with high infestation levels (trees with at least one cluster containing >10 aphids). The 2007 and 2008 aphid population comparison was done by calculating the average percent infestation of the twenty-four orchards and then subtracting each orchard's percent infestation from the mean for that year to give a rating of above or below average for each orchard for each year. A Spearman's rank correlation analysis was done to test the relationship between the ranks assigned to each orchard in 2007 and 2008.

2.2.3 Measuring Orchard Characteristics (2007)

Sampling Plantain

Abundance of plantain for each orchard was determined in 2007 by estimating the percent cover in 0.25m^2 quadrats placed between rows every 10 or 20 paces (depending on the size of the orchard). The number of plants per quadrat was also recorded.

Measurements were made when the grass was between 0.15 and 0.25m long to minimize the variation in plantain size caused by mowing. These data was also used to determine the presence of large plants in an orchard. By dividing the percent cover by the number of plants per quadrat, the average percent cover per plant was obtained and orchards with plants larger than 0.013m^2 were categorized as containing large plants.

Foliar Nitrogen Analysis

Apple tree foliar nitrogen levels were compared among orchards. This variable was chosen in order to show whether or not higher nitrogen content of the foliage allowed for increased population growth and size. The foliar leaf samples were collected during the 18mm fruit stage on June 8th and 9th, 2007 and analyzed for percent nitrogen at Pacific Soil Analysis (Richmond, British Columbia). Samples were collected by taking the fourth, fifth and sixth leaf from terminal shoots at a height of 1.25 to 2m from 20 trees per orchard. A Welch's two sample t-test was done in R (Version 2.5.1) to show the difference between nitrogen levels of uninfested trees vs infested trees. All leaves were washed and dried before analysis to ensure that aphids and other insects were not included in the samples.

Planting Density and Age

Planting density and tree age were both provided by the growers. Planting density is the number of trees per hectare and includes the measurements of distance between rows, which varies from 3m to 3.5m, and distance between trees, which varies from 0.45m to 1.0m. Age is the time since planting in the ground or since grafting onto old rootstock. The plant is actually two years older than the age given since seedlings and whips are raised in a nursery for two years prior to planting in the orchard.

Spring Oil Application

The application of a spring oil depended on the management practices of the grower. Those that applied oil used dormant oil (Bartlett's Superior Oil) at half-inch green stage in April 2007 at a rate of 2% oil in water. The relation of aphid density to oil application was analyzed using a Welch's two sample t-test.

2.2.4 Plantain Growth Form Assessment

Sampling Plant Architecture: Observational Data

To determine the structural characteristics of plantain that promote aphid survival on the orchard floor, twenty plants in one orchard were sampled for characteristics of plant architecture in 2007. Plants were selected by walking 10 paces between samples and selecting the nearest plant. Plant height was measured and 4 leaves from each plant were sampled for the number of aphids present, leaf length, leaf angle and the difference between temperature above and below the leaf. Temperature was measured using a temperature probe (Fluke Dual Thermocouple) held 2 cm above the plant and then just below each recorded leaf. A general linear regression analysis was used to look for correlations between aphid numbers on plantain and plant characteristics using R (Version 2.5.1). The explanatory variables included in the model were leaf length, leaf

angle and temperature difference between above and below the leaf. The response variable is the number of aphids found per leaf. A Poisson distribution was used as the y-variable was count data with many zero values.

Upon closer inspection of the above data it appeared that most of the leaves found with aphids were below an angle of 15°. Leaf angle was categorized into two groups of 15° or less, or greater than 15°. The data were then analyzed using a Wilcoxon rank test. This non-parametric test was selected due to the Poisson distribution of the aphid count data.

To determine the correlation between plantain size and orchard infestation level, orchards were divided into those containing large plantain plants ($>0.013\text{m}^2$ per plant) versus those with only small plantain plants ($\leq 0.013\text{m}^2$ per plant). Percent cover per plant data were collected while assessing plantain abundance by counting the number of plants per quadrat. A Welch's two sample t-test was performed to compare the average levels of infestation in these two categories of orchard.

Manipulating Plantain Architecture: Experimental Data

In 2008, an experiment was carried out to test the effect of plantain leaf angle and leaf size on both alate aphid preference and survival (presence of migratory alates at the beginning of the migration) and survival of apterae and reproduction (presence of apterous colonies in the middle of the migration). In one orchard ten large plants (with leaf blades longer than 5 cm) and ten small plants (with leaves 5 cm or less) were selected randomly. On each plant, using strong, flexible wire, half of the leaves were pinned down to the ground at an angle of between 0 ° and 5 °, and the other half were

propped up to between 75 ° and 90 ° creating a split plot design with leaf angle nested within plant size. The wire was wrapped around the petiole and pressed into the ground to the desired height. During the beginning of aphid migration the leaves were monitored for alate and apterous aphid presence to determine preference for and survival on the different leaf types, and were monitored again twice in the middle and end of aphid migration to determine survival and reproduction on different types of leaves. The treatment levels included leaf size (small and large) and leaf angle (low and high). For each of the three sample dates, the response variables measured were both number of alatae and number of apterae found on each leaf. The data for alate and apterae numbers on leaves did not fit a normal distribution and transformation was not able to fix this problem. Therefore, the effects of plant size and leaf angle were tested in a Generalized Linear Model in JMP 7.0, with a poisson distribution and a log-link function. Factors were plant size and leaf angle nested within plant size. Effects of leaf angle within plant size were further investigated with contrasts, and a Bonferroni correction was applied to the type I error ($\alpha = 0.0125$).

Effects of Mowing

In 2008, an experiment was conducted to determine the effects of mowing on the architecture of the plantain and the number of aphids colonizing those plants. Mowed and unmowed treatments were replicated in three different orchards. The rows were mowed one week prior to aphid migration and measurements were taken of the leaf length and leaf angle from the ground from ten plants for each treatment replicate. Data were analyzed using Welch's t-test to compare treatment means for the various measurements of plantain growth form. Both measurements of plantain growth form fit a

normal distribution. To determine the effect of the mowing treatments on the number of aphids surviving on plantain, Wilcoxon rank tests were performed on the number of alatae and apterae found on each leaf of each plant sampled. A general linear regression was also done to determine the relationship between plantain growth form measurements (independent variables) and the number of aphids present on each leaf (dependent variables).

2.2.5 Regression Analysis

The spring aphid population data and environmental variables were analyzed using linear regression. The dependent variable was the percent of trees in an orchard with at least one infested cluster of at least ten aphids. The independent variables were the percent cover per hectare of plantain, the percent nitrogen in the foliar tissues, the number of trees per hectare, age of the trees (in years), and the interaction between age and nitrogen. The interaction of nitrogen and tree age was included because of the possibility of a negative correlation between these two variables ($R^2 = 0.21$, $F = 5.798$ $df = 1, 17$, $p = 0.028$). The variable of oil application was not included in the analysis because not all orchards treated with a spring application of dormant oil were suitable to be included in the regression model. Instead, the effects of oil were tested separately using a Welch's t-test to compare orchards with and without a spring oil application. Typically, proportion data are arcsine transformed before regression analysis. An arcsine transformation was tested on the 'proportion of orchard infested' response variable, however, the data showed better normality without the transformation, so the untransformed data were used in the analysis. The distribution of the dependent variable of the percent of trees infested was determined to be normal according to a linear quantile plot and according to both the

Shapiro-Wilk test ($p=0.15$) and the one-sample Kolmogorov-Smirnov test ($p=0.78$).

Backwards stepwise analysis was performed to reduce the model. All analyses were done using R (Version 2.7.2).

2.3 Results

2.3.1 Monitoring Aphid Populations

In the summer of 2007, the orchards had abnormally high levels of rosy apple aphids according to local growers. Infestation levels, measured in percent of trees in an orchard with rosy apple aphids present, ranged from 13% to 100%. When considering only 'high' infestation (ie. percent of trees with the presence of at least one colony of greater than 10 aphids) orchard infested ranged from 8% (Orchard N) to 94% (Orchard U) (Figure 1). The following summer, June 2008, aphid levels were very low varying from 0 % (Orchard Q and S) to 39% (Orchard O).

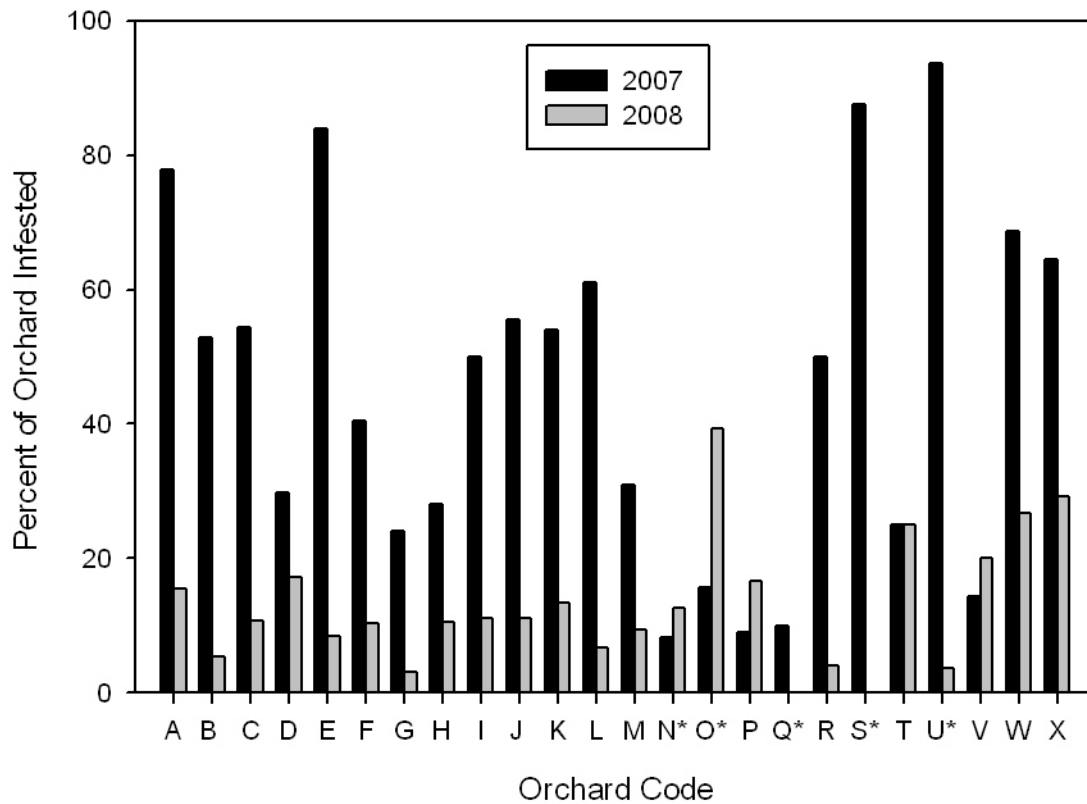


Figure 2. 1: Percent of apple trees (*Malus domestica* cv. Ambrosia) with rosy apple aphids in each orchard in 2007 and 2008. Orchards are represented by letters A to X and an asterix indicates the highest and lowest infestation orchards referred to in the text above.

In order to determine whether it is the same orchards each year or different ones that suffer high infestation levels, the mean infestation level was subtracted from each orchard's infestation level for a given year (Figure 2). Orchards did not show consistent trends in relative infestation levels between years.

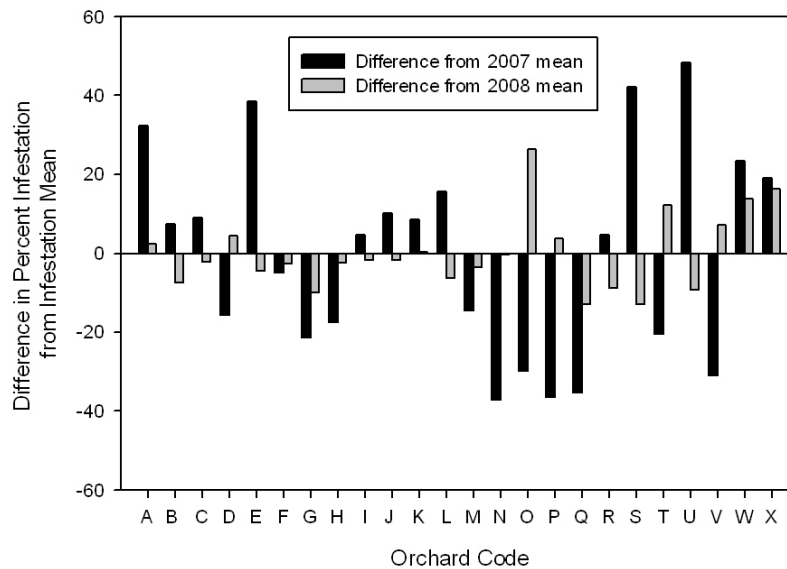


Figure 2. 2: Differences between the infestation level of each orchard and the mean infestation over all orchards for 2007 and 2008. Pairs of bars for an orchard that are in the same direction above or below the line show a similar tendency towards high or low infestation levels from year to year. Those that are in opposite directions show that aphid levels may be higher than average one year and lower than average the next.

A Spearman's rank correlation analysis also shows that the ranks assigned to each orchard in 2007 do not co-vary with the ranks assigned in 2008 ($S = 2754.797$, $df = 1, 46$, $p\text{-value} = 0.3543$, $\rho = -0.1977$).

2.3.2 Population Variability between Orchards

Only 13% of variation in rosy apple aphid infestation levels in 2007 could be explained by environmental and management factors in the full model, which included the effects of plantain abundance, foliar nitrogen, tree age, planting density and spring oil applications. Backwards stepwise regression including the possible interactions of nitrogen*tree age leaves the model with the variables of tree age, nitrogen and

nitrogen*age. The regression coefficients for nitrogen, age and nitrogen*age are -177.7, -84.0, and 35.4 respectively.

Table 2. 1: Table of regression analyses done on environmental and management variables compared with rosy apple aphid population levels. (Full: F = 1.85, df = 5, 13, p-value: 0.172, Reduced: F = 3.33, df = 3, 15, p-value = 0.048)

Model	Variables	DF	p-value	Adjusted R ²	AIC
Full	Plantain abundance	6, 12	0.567	0.1915	182.3
	Nitrogen		0.018		
	Age		0.042		
	Density		0.807		
	Nitrogen * Age		0.053		
Reduced	Nitrogen	3, 15	0.0107	0.27	178.8
	Age		0.0271		
	Nitrogen*Age		0.0363		

2.3.3 *Plantago major* Abundance

The effect of the abundance of plantain in the orchard floor on rosy apple aphid population was not significant (p = 0.818) and I therefore investigated other features of plantain in the summer of 2007. Two measures of plantain habitat quality were independently assessed: plant size and structure.

To examine the hypothesis that larger plantain plants > 0.013m² provide better habitat than small ones, average levels of infestation were compared based on the presence or absence of large plantain plants in the orchard floor (Figure 3). This shows a marginally significant increase in the infestation level in orchards with both large and small plants present (58.74%) when compared to orchards with only small plants present (37.37%) (t = 2.07, df = 16, p = 0.054).

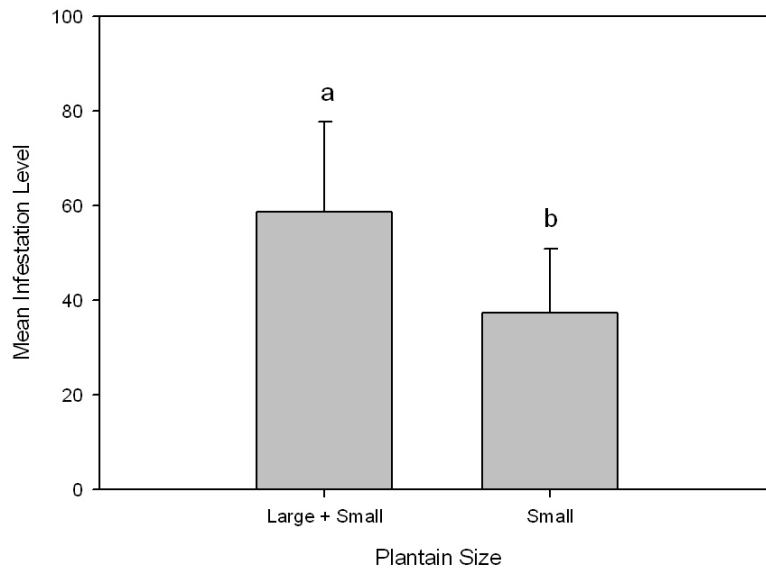


Figure 2. 3: Average infestation level (% of orchard trees with aphids present) in apple orchards containing large plantain plants compared with those containing only small plantain ($t = 2.069$, $df = 16.7$, $p = 0.054$).

2.3.4 Plant Architecture

A second hypothesis was developed that plantain structure impacts the survival of rosy apple aphids through the summer. Larger leaves with a lower angle to the ground and a larger difference in temperature above and below the leaf had significantly more aphids present on the leaf and these three factors accounted for 46.7% of the variation seen in mean aphid numbers (Table 2). Although the difference in temperature could be expected to be correlated with leaf angle, this was not the case ($F = 1.70$, $df = 1, 35$, $p = 0.20$, $\text{Adj. } R^2 = 0.02$). It was also not correlated with leaf length ($F = 0.35$, $df = 1, 35$, $p = 0.56$, $\text{Adj. } R^2 = -0.18$).

Table 2. 2: General Linear Regression Analyses on the effect of plant characteristics on number of aphids found per leaf.

Model	Variables	DF	p-value	R ²	AIC
Full	Temperature Difference	36, 33	0.002	0.467	319.05
	Leaf Length		<0.001		
	Leaf Angle		<0.001		
Reduced	Temperature Difference	36, 34	0.002	0.468	317.79
	Leaf Angle		<0.001		

This regression analysis considers leaf angle as a continuous variable. Similar results are obtained when leaf angle is categorized as $\leq 15^\circ$ and $> 15^\circ$; the mean number of aphids found on leaves with an angle of $\leq 15^\circ$ was 14.27 ± 19.51 and on leaves of $> 15^\circ$ is 0.58 ± 1.06 , a twenty-five fold difference (Wilcoxon test, $W = 247.5$, $df = 10$, $p < 0.001$; Figure 4). However, since there was some covariance amongst leaf length and angle ($F = 14.47$, $df = 1, 35$, $p < 0.001$, $Adj.R^2 = 0.27$) I designed an experiment to test the hypothesis that low angle leaves have higher numbers of aphids present than high angle leaves, and to examine potential interactions between leaf size and angle effects.

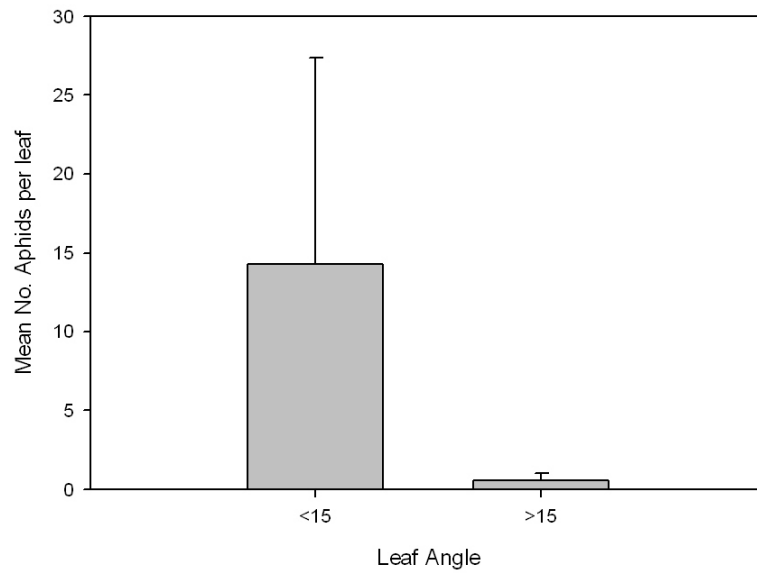


Figure 2. 4: The number of aphids found on *P. major* leaves at an angle of $\leq 15^\circ$ and $> 15^\circ$.

2.3.5 Spring Oil Application

The effect of applying oil in the spring to control aphid population levels significantly decreased the average infestation level from 46.6% to 12.2% ($t = 4.10$, $df = 7.75$, $p = 0.004$) (Figure 5).

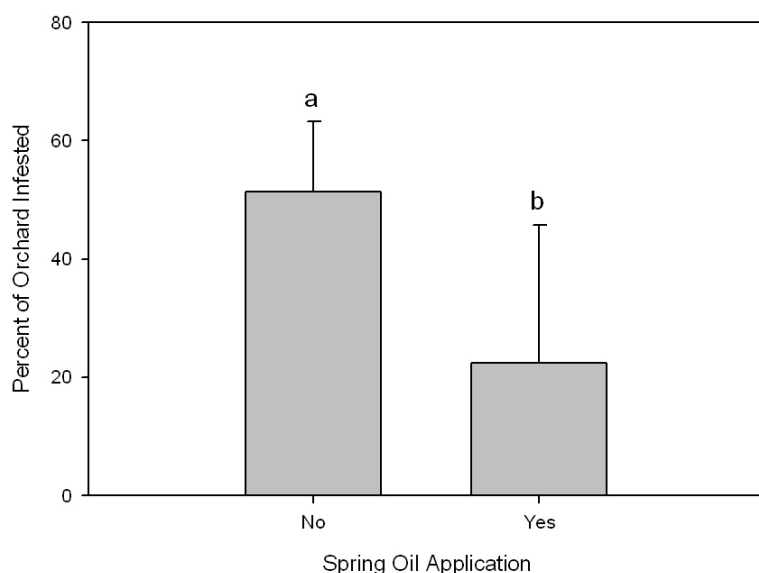


Figure 2. 5: Average infestation level in orchards that received and did not receive a spring oil application.

2.3.6 Sampling Plant Architecture: Experimental Data

The experimental manipulation of plantain architecture affected the numbers of alate aphids that landed and survived on the leaves and the numbers of apterous aphids that survived and were produced on the leaves. Both alate and apterous aphids are found in significantly higher numbers on large and low angle leaves than on small and high angle leaves (Figures 6 and 7). This trend was seen at the beginning (June 18, 2008) and in the middle (June 25 and July 8, 2008) of the migration. As the migration progressed the mean number of alates per leaf increased then decreased slightly from 0.32 on June 18 to 0.52 on June 25 to 0.21 on July 8, and the mean number of apterae per leaf increased as reproduction took place on the plantain from 0.59 to 3.18 to 6.16.

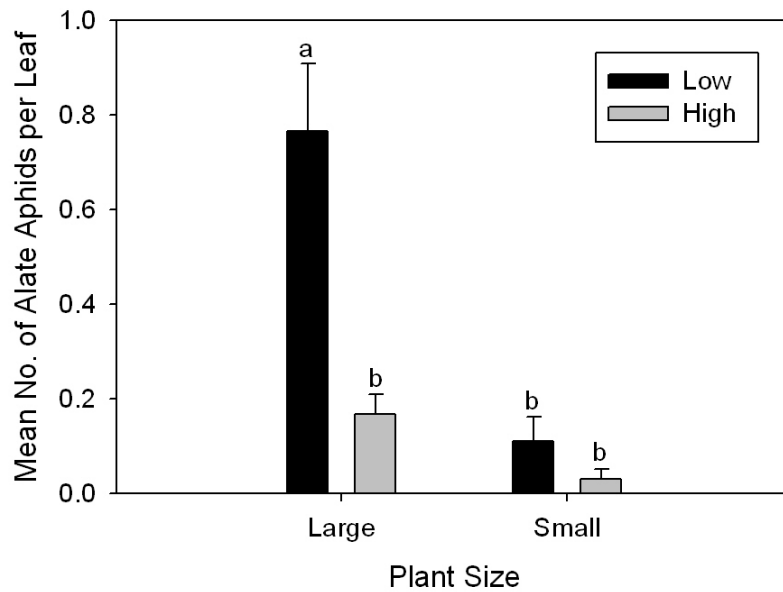


Figure 2. 6: Mean number of alate aphids (One SE) found on large and small leaves with a high and low leaf angle from the ground on June 18, 25 and July 8. Different letters show significant differences.

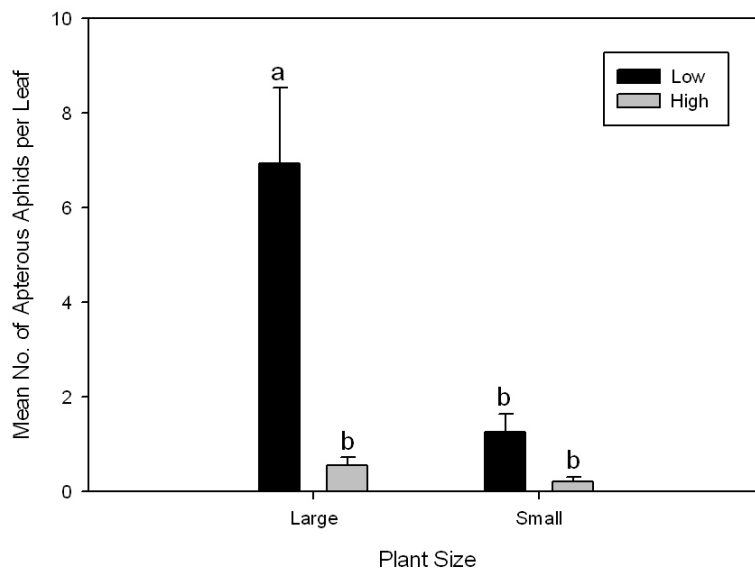


Figure 2. 7: Mean number of apterous aphids (One SE) found on large and small leaves with a high and low leaf angle from the ground on June 18, 25 and July 8. Different letters show significant differences.

An analysis of variance (Table 3) shows that plant/leaf size is a significant factor of the difference between low angle and high angle leaves for both alate and apterous aphids. There are significantly more alates on low angle leaves than high angle leaves on large plants, but not on small plants. There are significantly more apterous aphids on low angle leaves on both small and large plants.

Table 2. 3: Analysis of variance table for the number of aphids per plant compared with plantain size (L = large, S = small) and leaf angle from the ground ($\alpha = 0.0125$).

Y Variable	X Variables	DF	p-value
Alate	Size	1, 54	0.004
	Size[L]:Angle		< 0.001
	Size[S]:Angle		0.501
Apterous	Size	1, 54	< 0.001
	Size[L]:Angle		< 0.001
	Size[S]:Angle		< 0.001

The mean number of alate aphids at the beginning of the migration (June 18, 2008) was highest on larger leaves with a low angle from the ground (Table 4) as was the mean number of apterous aphids at the end of the migration (July 8, 2008)

Table 2. 4: Mean number of alate aphids (\pm SD) at the beginning of the migration and of apterous aphids at the end of the migration.

	Date	Leaf Size	Leaf Angle	Mean No. Aphids
Alate	June 18, 2008	Large	Low	0.75 \pm 0.75
			High	0.04 \pm 0.11
		Small	Low	0.15 \pm 0.31
			High	0.12 \pm 0.21
Apterous	July 8, 2008	Large	Low	14.18 \pm 12.73
			High	0.19 \pm 0.31
		Small	Low	0.30 \pm 0.67
			High	0.00 \pm 0.00

2.3.7 Effects of Mowing

Mowing had significant effects on the growth form of the plantain, encouraging shorter plants with smaller leaves and lower angles between the leaves and the ground (Figure 8).

The number of both alate and apterous aphids found in orchard rows that had been mowed was four times higher than those that had not (Figure 9, Table 5).

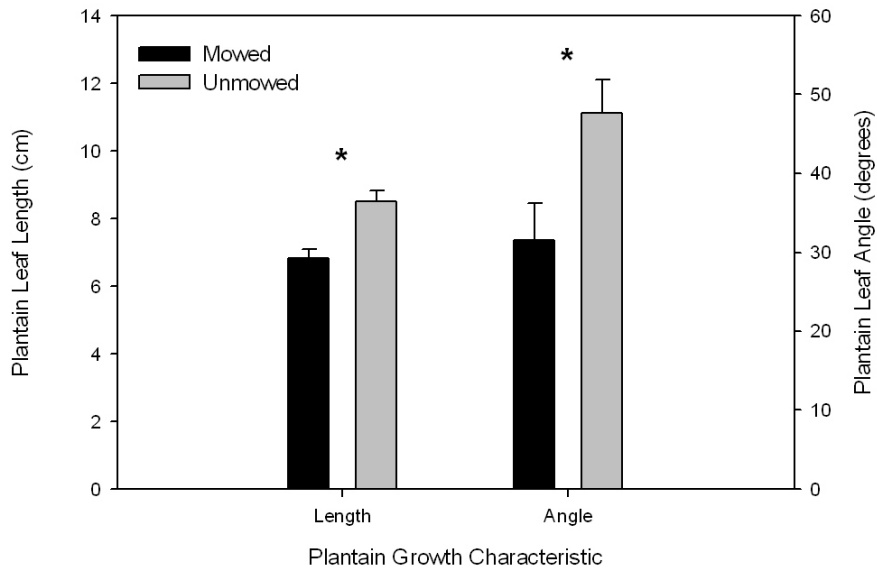


Figure 2. 8: The mean leaf length and leaf angle of plantain plants (One SE) in mowed and unmowed orchards. Length: $W = 3472$, $df = 192.6$, $p = 0.001$, Angle: $W = 3643$, $df = 183.1$, $p = 0.006$. Within each growth characteristic an asterix represents a significant difference.

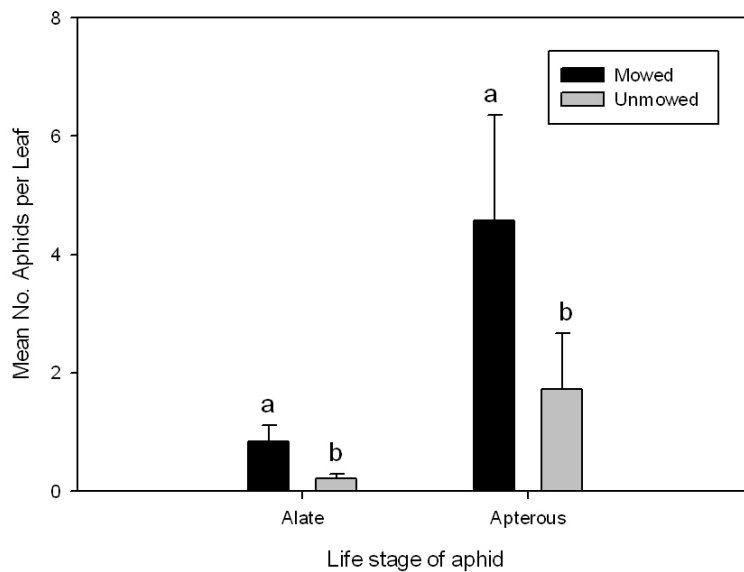


Figure 2. 9: The number of aphids, both alate and apterous, found on plantain leaves in mowed and unmowed orchards. Alate: $W = 5847$, $df = 103.7$ $p < 0.001$, Apterous: $W = 6340.5$, $df = 145.5$, $p\text{-value} < 0.001$. Within each aphid life stage different letters represent significant differences.

Table 2. 5: Mean values and test statistics for the number of alatae and apterae found in mowed and unmowed blocks and the measurements of plantain characteristics in mowed and unmowed blocks.

	Mean Alatae	Mean Apterae	Leaf Length	Leaf Angle
Mowed	0.833333	4.572464	6.826087	31.48551
Unmowed	0.216374	1.719298	8.495614	47.63158
Test value	$W = 5847$	$W = 6340.5$	$t = -2.9487$	$t = -2.9961$
df	103.7	145.5	192.6	183.1
p-value	< 0.001	< 0.001	0.004	0.003

2.4 Discussion

2.4.1 Population Variability between Orchards

Most of the variability seen in the twenty four orchards studied was not explained by the within-orchard characteristics measured. Only 27% of the variability was explained by varying nitrogen levels, the age of the tree and the interaction between these two variables. Aphid populations increased with decreasing nitrogen levels and decreasing tree age. Although this seems contradictory as higher leaf nitrogen generally supports better aphid growth (Dixon, 1985), this association usually refers to nitrogen being more available during translocation. Foliar samples were taken in July 2007 and at this point in the growing season this nitrogen is not necessarily available to the aphids. It is plausible that trees with increased nitrogen levels also had increased levels of plant defense compounds, and this covariance between nitrogen and secondary compounds is driving the significance of nitrogen in the regression. As an example of potential apple host defense compounds, herbivory by leaf miners on apple has been shown to produce much higher levels of triterpene squalene ($C_{30}H_{50}$) (Dutton *et al.*, 2002). A potential explanation for increased aphid density on younger trees, increasing age of the tree relates to reduced vigour and new growth in the spring, reducing the amount of nitrogen being translocated to this growth. Although these results are statistically significant, plots of foliar nitrogen vs. aphid infestation level and tree age vs. aphid infestation level show that the trend is not strong or consistent enough to be biologically meaningful. These factors are also not easily manipulated by growers.

After comparing infestation levels in 2007 and 2008, it was seen that the tendency for an orchard to be above or below average infestation level is not consistent from year to year.

This indicates that the factors with the most influence on high or low aphid populations may not be static within-orchard characteristics, but rather characteristics that can change from year to year, or external factors that create different conditions in the orchards each year. These could be related to stochastic events during the time of dispersal and migration back to the apple orchards in the autumn. There is also the possibility of high mortality during the over-wintering egg stage. According to studies done by Leather (1980, 1981), the bird cherry-oat aphid, *Rhopalosiphum padi*, suffered 70% and 81% mortality during this stage and the majority was due to predation by arthropods. Thus, infestation may also be related to the autumn and winter arthropod predator population of an orchard.

2.4.2 The Role of Plantain

The primary hypothesis, that orchards with a higher percent cover of plantain have higher levels of aphid infestation, has not been supported by this study. This does not, however, rule out the importance of plantain, but rather indicates the need for a more detailed analysis of the host selection of the rosy apple aphid. Originally, I hypothesized that higher abundance of plantain in an orchard provides rosy apple aphids with a summer host, resulting in higher numbers for migration back to the apple trees and increased egg production in the autumn, if aphids migrate to the closest host (plantain or apples) available. Since plantain abundance alone was not related to aphid density, I explored the hypothesis that plantain plants of higher quality (in terms of size and structure of the leaves) are preferred by migrants and allow higher survival and reproduction of aphids through the summer, and consequently higher levels of infestation the following spring.

Migrant aphids of the family *Aphididae* do not seem to identify their host from great distances, but rather show a 'dispersive type of host-finding behaviour' (Kennedy *et al.*, 1959). Observations of *Acyrtosiphon pisum* (Harris), *Hayhurstia atriplicis* (L.), *Myzus persicae* (Sulz.), *Brevicoryne brassicae* L. and *Aphis fabae* (Scop.) have shown that they alight on both hosts and non-hosts with equal frequency (Tate, 1940; Kennedy *et al.*, 1959). However, the behaviour on a non-host is different than on a host plant. Aphids generally probe only once before departing a non-host, whereas the time spent on a host leaf is longer and often involves further probing and moving to the underside of the leaf (Kennedy *et al.*, 1959). Other studies have also proven the role of plant volatiles in short-range aphid host finding. In non-flying olfactory trials, alate virginoparae *A. fabae* and *B. brassicae* were both attracted to volatiles of their herbaceous summer host plant; however, *A. fabae* failed to respond to its overwintering host, spindle (*Euonymus europaeus* L.). The study also showed that at a 1:1 ratio of host plant to non-host plant the non-host plant volatiles could mask the host-plant detection (Nottingham *et al.*, 1991). This provides some insight as to the alternate host selection of the rosy apple aphid. There are many potential hosts in the orchard floor, and many architecturally different plantain plants, so aphids engaging in dispersive host-finding will alight on many of these different hosts but select only plantain, and possibly only those plantain plants that provide high quality habitat. Alternatively, if many non-host plants are encountered then potentially the marginal value of the local orchard floor could stimulate longer distance dispersal.

The current study demonstrates that factors such as microclimate may be involved in the summer host selection of rosy apple aphids. In the first season (2007), a significant correlation was also seen between low leaf angle, large leaf length, and large difference in temperature above and below the leaf, and increased mean number of aphids per plantain leaf. Orchards containing individual plantain plants of greater than 0.013m^2 had marginally significantly higher aphid infestation levels than those without these larger plants. Leaf angle was also important, with twenty five times more aphids on leaves at angles of 15° or less to the ground than on leaves at greater than 15° .

During the second season (2008), the structure of plants was experimentally manipulated, in terms of leaf size and leaf angle, and both factors were significantly correlated with the number of aphids on a leaf. Both alatae and apterae of the rosy apple aphid were found in higher numbers on the large, low angle leaves at the beginning and end of the migration. This may indicate that the migrating alates actively select these leaf types, alighting on many plantain and non-host leaves, but only feeding and reproducing on those that provide the protection from desiccation and predators they require. The larger apterous populations towards the end of the migration indicate that more apterae are originally produced on these leaves and potentially that survival and reproduction rates are higher on such leaves. Other insects have also shown a preference for certain microclimatic conditions. The oviposition sites of the speckled wood butterfly, *Purarge aegeriu* (L.) (Satyridae), were significantly correlated with a temperature range of 24 to 30°C (Shreeve, 1989). Predator foraging success is also affected by plant architecture and plantain leaves close to the ground may make it more difficult for predators and

parasitoids to access them. Grevstad and Klepetka. (1992) show that predator mobility, falling frequency, prey accessibility and ultimately foraging success can be affected by plant morphology. However, over the course of two seasons, very few predators and zero parasitized aphids were found on the plantain, indicating that perhaps natural enemies are not the selective pressure driving habitat selection but rather microclimate and host nutrition. Parasitoid searching behaviour is thought to be determined by host density (Weisser, 1995), and the densities observed on the plantain over two summers were extremely low when compared to the densities achieved on apple.

A potential benefit derived from selecting larger leaves is the nutritional advantage for the developing colony. Whitam (1980) showed that a gall-forming aphid, *Pemphigus betae* Doane., confers higher fitness to its progeny if it selects a larger leaf on its primary, woody host, *Populus angustifolia*. This is the result of a positive correlation between leaf size and the amount and/or quality of nutrients translocated to and from the leaf.

For management of this pest, it must be considered which orchard floor management practices alter the characteristics of plantain plant height, leaf length and leaf angle. Two potential factors are the frequency of mowing and the orchard floor species composition. Decreased mowing frequency increases the overall height of the vegetation, and as the surrounding forbs and grasses grow tall, the plantain needs to grow tall as well (ie, increased leaf angle) to access sunlight. I observed in some “well maintained” orchards that mowing constantly removes the new, upright growth of plantain and encourages the growth of the low lying leaves. Results of the mowing trials show that mowing affects

plantain structure by decreasing leaf length and leaf angle. The average leaf length in the mowed blocks was 6.82cm, still categorizing it as a 'large' leaf according to the experimental manipulation of plantain architecture. The average decrease in leaf angle of 20° is more meaningful in terms of creating ideal aphid habitat. If mowing affects plantain structure and this low growing form is more conducive to aphid survival and reproduction through the summer, thus more aphids should occur in blocks that are mowed just prior to aphid migration than those blocks left unmowed, which is what the results of the mowing experiments showed. The implications of these findings are not simple. Hand thinning of the apples occurs in organic apple orchards just prior to this aphid migration and tall vegetation is related to the mosquito populations in the orchards (L. Edwards, Pers. comm.). Mowing is important for reducing mosquito populations and creating a more comfortable environment for labourers. However, it is possible that after hand thinning the orchard floor could be left unmowed for the remainder of the summer. Also, it has not been shown that a smaller aphid population on the plantain in the summer is translated to a smaller population on the apple in the spring. This depends on an assumption of localized autumn migration and a correlation between the aphids present on the plantain in the fall and the aphids present on the apples in the spring.

The orchard floor species composition is potentially related to the floor management at the time of replanting of apple trees. According to orchardists in the Similkameen valley, reseeding the orchard floor with a grass mix (Sheep fescue – *Festuca ovina*, Creeping red fescue – *Festuca rubra*, Perennial rye – *Lolium perenne*, Stonehenge hard fescue – *Festuca longifolia*) after replanting apples was common in previous years, but is no

longer practiced. The seeding of grasses may help to reduce the weeds present in the orchard floor through competition. The seed bank of plantain in the orchard floor may be substantial and it is unknown whether these species will in fact be able to out-compete this weed.

2.4.3 Spring Oil Application

There was a significant difference in orchards that had received a spring application of oil and those that had not. Timing of spring applications can use a phenology model developed by Graf *et al.* (2006) to determine when the eggs have hatched. The lower threshold for egg development is 4.0 degrees C with a thermal constant of 140 degree days (Graf *et al.*, 2006). In 2007 this fell on the 8th of April. The application of spring oil to reduce spring nymphal survival should be considered for future management strategies. Oil applications should be made before the leaves curl around the aphid colony shielding them from the spray, and before beneficial insect populations are endangered (Bessin, 2003)

2.4.4 Conclusions

Based on this study I recommend that orchardists consider management practices that (1) reduce the availability of large, low growing plantain plants on the orchard floors either by refraining from mowing until towards the end of the migration in early July, by removing plantain, or by increasing the other ground cover species and (2) consider dormant oil sprays early in the spring before aphid feeding has caused the leaves to curl. The analysis of aphid population variation among orchards and years indicates that the causes of this variation are not a result of fixed within-orchard effects, but rather within-orchard effects that can change from year to year or factors outside of the orchard system.

The current study has shown that the frequency and timing of mowing each year are potential within-orchard factors that can change from year to year and possibly impact the population of aphids migrating back to apple trees.

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Chapter 3²

The autumn migration of *Dysaphis plantaginea* in the Similkameen Valley of British Columbia as related to possible mechanical and chemical control strategies.

3.1 Introduction

The rosy apple aphid, *Dysaphis plantaginea* (Passerini) (Homoptera: Aphididae), is considered one of the most serious apple pests worldwide (Wyss and Daniel, 2004; Cross et al., 2007). It was introduced to Canada over a century ago from Europe along with its winter and summer hosts, apple, *Malus domestica* (Rosales: Rosaceae), and plantain, *Plantago major* and *Plantago lanceolata* (Lamiales: Plantaginaceae) (Lathrop, 1928). It has proven to be especially problematic in organic orchards where it is not controlled by the organophosphate pesticides applied to target other pests such as mites and scale insects. In the future, however, it may become more of a problem in conventional orchards where there are reports of increasing resistance to insecticides (Wyss and Daniel, 2004).

To understand the damage caused by the rosy apple aphid, De Bernardis et al. (1994) modeled the effect of aphid feeding on leaf and fruit growth based on trials conducted in Italy on 2 year old Golden Delicious trees. The impact on leaf growth is negligible with

² A version of this chapter will be submitted for publication. Brown, A. The autumn migration of *Dysaphis plantaginea* in the Similkameen Valley of British Columbia as related to possible mechanical and chemical control strategies.

aphid-free leaves being less than 1% larger than leaves with aphids. The impact on fruit is, however, greater, and on a tree with more than 15 apples, aphid feeding in the current year can reduce fruit growth by 25%. Deformation of the fruit following aphid feeding also makes some fruit unmarketable.

Rosy apple aphids are piercing-sucking insects that feed on the phloem of the plant. On apple trees, they inject a toxin into the leaf which causes the leaves to curl and the fruit to develop abnormally. As a result, the leaves do not function to their full potential, the fruit is not marketable, and the aphids are difficult to control with insecticides because they are protected inside the curled leaf (Gardner, 2003). Eggs hatch with bud burst on the leaves or stems of apple trees in the spring and these fundatrices, or stem mothers, feed on flower or leaf buds. This feeding also affects the next year's flower buds which are developing during this time and thus affects the crop the following year (Blommers *et al.* 2004). The phenology of egg hatch and bud burst has proven to be important, as Minarro and Dapena (2007) have shown that the earlier flowering apple varieties receive the most damage. Towards the end of May, the aphids begin to produce alate (winged) morphs which migrate to their obligate alternate (summer) hosts, broad and narrow leaf plantain, *Plantago major* and *P. lanceolata*, where they remain for the summer. These two hosts are quite common in the irrigated areas of the Okanagan and Similkameen Valley of British Columbia (BC). Once on the new host, the aphids complete several generations during the summer (Blommers *et al.* 2004).

In the autumn, gynoparae (alate females), are produced and migrate back to the apple trees. This production of alates seems to be triggered by decreasing daylength, but the rate of production of alates is affected by temperature (Lees, 1966; Blommers *et al.*, 2004). On the apple trees, sexual females, called oviparae, are produced by the gynoparae, generally within the first 24 hrs of arriving (Blommers *et al.*, 2004). During this time, alate males are produced on the plantain, which also migrate to the apple trees to mate with the oviparous females. Small black eggs are laid on the branches at the base of buds to complete the lifecycle (Wyss and Daniel, 2004).

This life cycle provides several opportunities for aphid control. Once the aphids have begun feeding, control is difficult because they are protected by the leaves which curl around the colony. In the spring after egg hatch and before feeding, however, at 140 degree days over the thermal constant of 4°C (Graf *et al.*, 2006), the aphids can be targeted with oils as the aphids are not yet protected by the curled leaves. During the spring and early summer, beneficial insects attack the colonies, leaving opportunities for augmentative biological controls. Finally, in the fall, the migration back to apple provides another period in which populations are vulnerable. The aphids can be targeted on the apple trees during migration but before mating and egg laying (Wyss and Daniel, 2004, Cross *et al.*, 2006).

The research focus in the past 10 years has been on autumn chemical control of this insect using a range of both organic and conventional products (Surround® WP [kaolin clay], garlic oil, pyrethrum, rotenone, Assail 70 WP® [acetamiprid], potassium soap

[Savona], Admire [imidacloprid], and Aphox [pirimicarb])) with varying levels of success. Kehrli and Wyss (2001) tested pyrethrum applications and found that three, four and five applications in late autumn (September 29, October 8, 13 and 28, November 9) had a significant effect, reducing the number of aphids per tree in the spring by between 91 and 98% compared to untreated controls, but that single applications did not reduce aphid numbers compared to controls. Helsen (2001) and Helsen and Simonse (2002) showed that single applications of imidacloprid and pirimicarb in the second week of October gave between 90 and 100% control the following spring compared to untreated controls.

In this study, I have proposed two alternate approaches to autumn control. Just prior to migration, the aphids could be targeted on the plantain by removing their host from the system. The first method was flail mowing which cuts the orchard floor vegetation down to soil level, leaving nothing for the aphids to feed on, and potentially killing them. The second method was rotavating the orchard floor in early September, also killing the plantain and any rosy apple aphids not yet in the adult winged form.

There are two essential pieces of information necessary for designing an autumn control system for the rosy apple aphid: timing of alate aphid flight back to the apple trees, and efficacy of the chemical products or mechanical control methods being used. All of the research conducted on autumn control of the rosy apple aphid has occurred in Europe and is invaluable in deciding which products provide the best control. It does not, however, provide information on the correct application timing, as climatic conditions, latitude and

photoperiod, are different. Local research must be done to demonstrate efficacy of control procedures.

The goals of this study were to 1) conduct an assessment of the economic losses caused by the rosy apple aphid to justify the cost of management options, 2) to determine the timing of the autumn migration of rosy apple aphids in southern BC 3) to assess the efficacy of three chemical products in the autumn (kaolin clay, Superior dormant oil, and PureSpray Green summer oil) and one spring application (PureSpray Green summer oil) 4) assess the efficacy of two mechanical control methods for reducing aphids on the summer secondary hosts prior to migration.

3.2 Methods

3.2.1 Study Area

The study areas were located in the vicinity of Cawston and Keremeos in the Similkameen Valley of BC, Canada (49°09', 119 °44'). The twenty four apple orchards chosen for sampling to determine harvest losses were all planted with the apple variety 'Ambrosia' and the orchards used for chemical and mechanical control trials were a mixture of 'Ambrosia', 'Gala' and 'Sunrise' apple varieties. All were managed organically according to Certified Organic Association of British Columbia (COABC) standards.

3.2.2 Harvest Loss Analysis

To assess the economic damage caused by this pest, I compared the marketable apple crop on highly infested trees and uninfested trees in August 2007. In each of 24 orchards, between 30 and 40 trees were selected (half infested and half uninfested) by sampling

every 20th tree and categorizing it as uninfested if it had zero aphid colonies, and as infested if it had any infested colonies. The number of apples were counted and categorized into marketable (large apples >6.5cm) and unmarketable apples (small apples < 6.5cm – only suitable for juicing and deformed apples). The mean difference in marketable apples per tree between infested and uninfested trees per orchard was determined for infested and uninfested trees (Orchard A: mean # apples from uninfested trees – mean # apples from infested trees = mean difference). This difference was considered to be the ‘harvest loss’ and was combined with the percent infestation level of the orchard [(mean harvest loss per infested tree) X (% of infested trees in an orchard) = # apples lost per 100 trees]. The conversion was made, based on planting density, of apples lost per acre and then bins lost per acre. The average number of apples per bin (2000 apples/bin) was obtained from the Cawston Cold Storage packing house, Cawston, BC, which is where all the orchards in the study sold their apples. A linear regression of the number of bins lost compared to the percent trees infested per orchard was performed so that the relationship could be used to calculate economic losses and an economic threshold for the potential management strategies employed against the rosy apple aphid.

Herbivory by rosy apple aphids is reported to affect the developing flower/fruit buds for the following season. To determine the impact of this damage, I assessed the 2008 spring blossom count for trees severely infested in the summer of 2007. In 2007, ten severely infested trees (> 20 infested clusters) were flagged. In the spring of 2008, prior to blossom thinning, the number of blossom clusters produced on those trees was compared to that of a sample of ten unflagged trees. Unflagged trees were selected by sampling the

tree at a distance of 10 trees from the flagged tree. Thus, this sample of unflagged trees includes both infested and uninfested trees and represents the average blossom set for the orchard. These data were analyzed using linear mixed model with 'Orchard' as a random factor, Infestation level of the tree as a fixed factor, and the average number in fruit per orchard as the response variable. The raw data for each orchard were used in Wilcoxon rank tests to determine which orchards showed a significant difference between infested and uninfested trees. All analyses were performed in R (Version 2.7.2).

3.2.3 Pheromone Trapping

To determine the timing of the autumn rosy apple aphid migration, pheromone traps containing rope impregnated with the female sex pheromone (1*R*,4*aS*,7*S*,7*aR*-nepetalactol and 4*aS*,7*S*,7*aR*-nepetalactone in a 5:1 ratio) (Stewart-Jones *et al.*, 2007) were placed in the 24 orchards to catch the alate morphs as they migrated from the plantain to the apple trees. Traps were checked every three days between Sept 24 and Oct 21, 2007 and alate rosy apple aphids identified according to a key to alate aphids of Western North America (Pike *et al.*, 2003). Samples of positively identified alates and alates of unknown identification were sent to Dr. R. Foottit and E. Maw at Agriculture and Agri-food Canada, Ottawa, ON, for confirmation of identification. The daylength for peak migration times were calculated using an Online Photoperiod Calculator. (Lammi, 2008)

3.2.4 Monitoring Aphid Populations

Apterous aphid populations on the apple trees were assessed in treatment and control sites for all experiments on the first week of June, 2008 to determine the effects of the autumn and spring chemical applications and the autumn physical control methods. This timing was determined based on sampling done in 2007, which showed that this sampling

time corresponds with the peak in apterous aphid populations and with 650 to 750 degree days according to the lower threshold of 4.5°C determined by Graf *et al.* (1985) for nymph development. Aphid infestation level was assessed in each orchard by counting the number of infested spurs or terminals (termed clusters) on twenty trees per treatment. The total number of clusters on the tree was also recorded to calculate the percent of infested clusters per tree to remove the effect of tree size from the data. The orchard rows were chosen in the centre of the treatment site to avoid including any effects of spray drift from neighbouring treatments

3.2.5 Chemical Controls

The three products applied in the autumn of 2007 were kaolin clay (Surround® WP), dormant oil (Bartlett Superior Oil®), and summer oil (PureSpray™ Green). PureSpray Green is not currently registered for use in Canada, but summer oils are included in the Permitted Substances List (Canadian General Standards Board, 2006) for organic production in Canada, and PetroCanada is expected to pursue registration in the near future, and approval for experimentation was granted by the Pesticide Management Regulatory Agency. The only product applied in the spring was PureSpray Green. The applications were done by each grower using a Turbo Mist sprayer and were done on trees that had already been harvested and consisted of the Sunrise and Gala varieties.

Table 3. 1: Autumn and spring chemical application rates of kaolin clay, dormant oil and summer oil to apple trees.

	Application Rate	Amount Applied / Acre
Autumn Applications		
Kaolin Clay (SurroundWP®)	32g/L	12.5kg in 400L water
Dormant Oil (Bartlett's Superior® Oil)	2%	8L in 400L water
Summer Oil (PureSpray™ Green)	2%	8L in 400L water
Spring Applications		
Summer Oil (PureSpray™ Green)	4%	40L in 1000L water

Treatments involved different application schedules (timing and number of applications).

Kaolin clay and Superior oil received the same treatments, but PureSpray Green was applied later in the autumn because of a delay in the product delivery. The following tables outline all treatments.

Table 3. 2: Experiment 1: Treatment descriptions including the number of applications and dates of those applications of Surround WP and Superior Oil

Treatment	Number of Applications	Application Start Date	Subsequent Treatment Dates
5-Early-Sept	5	Sept. 12, 2007	Sept. 18, 25, Oct 4, 11, 2007
4-Early-Sept	4	Sept 12, 2007	Sept 18, 25, Oct 4, 2007
4-Mid-Sept	4	Sept. 18, 2007	Sept. 25, Oct. 4, 11, 2007
3-Late-Sept	3	Sept. 25, 2007	Oct. 4, 11, 2007
2-Early-Oct	2	Oct. 4, 2007	Oct 11, 2007
1-Mid-Oct	1	Oct. 13, 2007	N/A
Control	None	N/A	N/A

Table 3. 3: Experiment 2: Treatment descriptions including the number and dates of applications of PureSpray Green to apple trees in the autumn and spring of 2007 and 2008.

Treatment	Number of Applications	Application Start Date	Subsequent Treatment Dates
Mid-Oct	1	Oct. 15, 2007	N/A
Mid & Late-Oct	2	Oct. 15, 2007	Oct 25, 2007
Late-Oct	1	Oct. 25, 2007	N/A
Mid-Oct, Mid-April	2	Oct. 15, 2007	April 17, 2008
Mid-April	1	April 17, 2008	N/A
Control	0	Control	N/A

Treatment	Pesticide Coverage Maintained on Crop				
	Sept 12	Sept 18	Sept 25	Oct 4	Oct 11
5 Early Sept					
4 Early Sept					
4 Mid Sept					
3 Late Sept					
2 Early Oct					
1 Mid Oct					
Control					

Figure 3. 1: Pesticide coverage maintained in the kaolin clay and Superior oil treatments applied to apple trees in the autumn of 2007.

3.2.6 Mechanical Controls

Two approaches were taken to mechanical control: flail mowing and rotavating and reseeding of the orchard floor. The flail mower cuts vegetation down to ground level and the rotavator turns the top layer of the soil. Both methods remove the above ground portion of the alternate host. Flail mowing was done 3 times during the autumn migration period (Sept. 5, 9, and Oct. 4, 2007) to maintain an environment without plantain, since plantain can re-grow from the roots left in the soil. Rotavating was done once at the beginning of the autumn migration on Sept. 5, 2007, and once at the end of the migration Oct. 5, 2007, before reseeding with an orchard grass mix.

3.2.7 Data Analysis

Linear mixed models, with ‘Orchard’ as a random factor were used to determine the efficacy of the mechanical and chemical methods by comparing the differences between the mean percent of infested clusters of the treated plot and its associated control (the

change in infestation level). For experiment 1: kaolin clay and superior oil, the data from each treatment was pooled and the overall efficacy of each chemical product. Significant difference from zero indicated a significant difference from the control plots, since the subtracted difference between treatments and controls standardizes the data around zero. A two factor linear mixed model was then used to analyze the data for experiment 1. The two products (Factor A) and the six treatments of application date and timing (Factor B) were compared to each other using the difference in the mean percent of infested clusters between each treated plot and its associated control. This is to account for the different background levels of infestation in different orchards. A single factor linear mixed model was used for experiment 2: PureSpray Green and the five treatments were compared using the difference in the mean percent of infested clusters between each treated plot and its associated control. The percent reduction of statistically significant treatments was calculated by dividing the mean infestation level of the treatment plots by the mean infestation level of the controls.

To calculate the mean percent of clusters infested per treatment or control block, the number of clusters infested per tree were sampled and converted to a percentage by comparing to the total number of clusters per tree. The mean of these percentages were calculated for the block. To account for differences between sites, the mean percent of clusters infested was subtracted from the mean of the control plot to give the change in infestation.

The difference between the mean percent of clusters infested in the treatment and control was used for the linear models to determine whether or not differences between treatments were significant. The log of this difference plus a constant was used to meet

the assumptions of normality and equality of variance for experiment 1. The residuals of the untransformed difference for experiment 1 were not normal according to a Shapiro-Wilk normality test ($W = 0.9145$, $p\text{-value} = 0.01134$), whereas the residuals of the log of the difference plus three are normal ($W = 0.9645$, $p\text{-value} = 0.33$).

3.3 Results

3.3.1 Harvest Loss Assessment

The economic damage caused by rosy apple aphid infestations was assessed in the autumn of 2007, two days prior to harvest. The levels of harvest loss ranged from 0.4 bins (3.4% of the total bins produced) to 33.7 bins (75.8% of the total bins produced) (Figure 2). This addresses the direct loss in harvest in the form of deformed, unmarketable fruit.

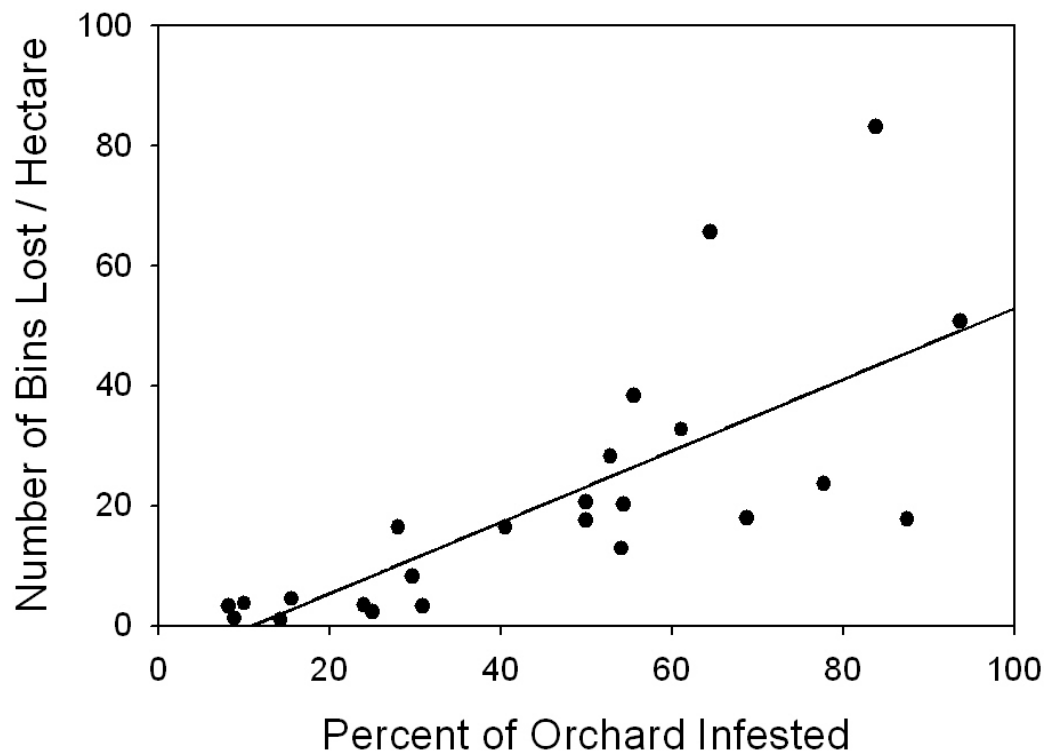


Figure 3.2: Number of bins lost per hectare, by orchard, in 2007 as a function of the percentage of the trees in the orchard infested with rosy apple aphids (Adj. $R^2 = 0.52$, $F = 26.19$, $df = 1, 22$, $p < 0.001$).

There was a linear relationship between the percentage of trees in an orchard that were infested and the number of bins lost. The percent of the orchard infested (x-axis) was used in the calculation of the number of bins lost per acre (y-axis) making the statistics of the regression trivial. This relationship is useful, however, for calculating the economic losses associated with each level of infestation and for determining the economic thresholds of the potential control strategies.

In this study two autumn applications and a single spring application of PureSpray Green application gave an 83.4% and 73.4% reduction, respectively, and making the assumption that this reduction would remain constant in years with high aphid population pressure,

these values were applied in developing economic thresholds. The cost of one application per hectare would be approximately \$100.00 CAD (J. Bartlett, South Valley Sales, Pers. comm..) and the price received per bin on average is \$400 CAD (B. Potash, Cawston Cold Storage, pers. comm.). By applying the following equations we can solve for the number of bins lost and then the infestation level at which the control method is justified.

(1) % reduction of control method X bins lost per acre X value per bin = cost of control method

(2) Regression Equation: $Y = 0.60X - 6.49$ where Y is the square root of bins lost/hectare and x is the % infestation of the orchard.

Two autumn applications of oil reduce losses by approximately 83% (see section 3.2.2 below) and thus, given the cost of \$200 for this treatment, are justified when the loss is expected to be over 0.60 bins (equation 1). The infestation level at which this occurs is 11.82 ± 6.05 (SE) percent of the trees in an orchard infested (equation 2). One spring oil application reduces losses by approximately 73% (see section 3.2.2 below) and given the cost of \$100 for this treatment, is justified at 0.34 bins. The infestation level that this occurs at is 11.38 ± 6.05 (SE) percent of the trees in an orchard infested. These control methods are economically viable between approximately 5.3% and 17.9% infestation, if it performs consistently at different aphid densities and if it is applied at the correct time.

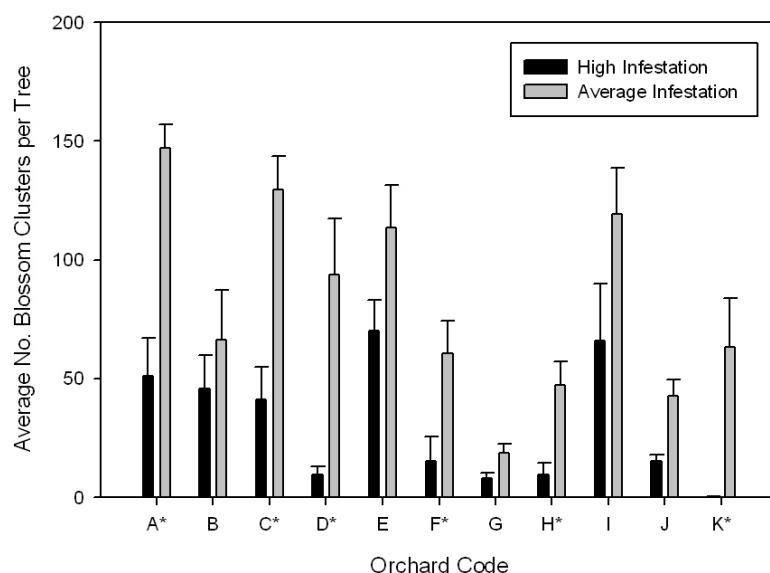


Figure 3. 3: Average number of blossom clusters per tree in spring 2008 (one SE). Black bars represent trees that were flagged in 2007 as being highly infested (>20 infested clusters) and grey bars represent unflagged trees and show the average blossom production of each orchard. An asterix beside the Orchard Code denotes a significant difference for that orchard.

Significantly fewer blossom clusters are found on trees with a high infestation level the previous summer than trees with an average infestation level ($F = 31.85$, $df = 1,8$, $p < 0.001$). A significant decrease was seen, in nine of eleven orchards, in the number of blossoms produced on trees that experienced a high level of rosy apple aphid infestation in the previous year (Figure 3). The average number of blossom clusters of highly infested flagged trees for all orchards was 28.78 ± 2.10 (SE) compared with 81.70 ± 3.76 (SE) in average unflagged trees.

3.3.2 Pheromone Traps

Trap catches of rosy apple aphids in the autumn of 2007 were very low (Figure 4). The by-catch in the traps was significant, with 12 other aphid species and many non-aphid

species being captured in the traps. The number of non-target aphid species per trap was not recorded due to limited time and the difficulties of identifying alate aphids. The most common aphid species in the traps was identified as *Capitophorus elaeagni* (del Guercio). Male and female alate rosy apple aphid captures occurred from September 24th to October 21st, 2007 (Figure 12). The peak of female flight occurred between the 24th and the 27th of September at 11:56 hours daylength (2524 degree days from spring nymph development) and the peak of male flight occurred between the 9th and the 12th of October at 11:02 hours daylength (2610 degree days).

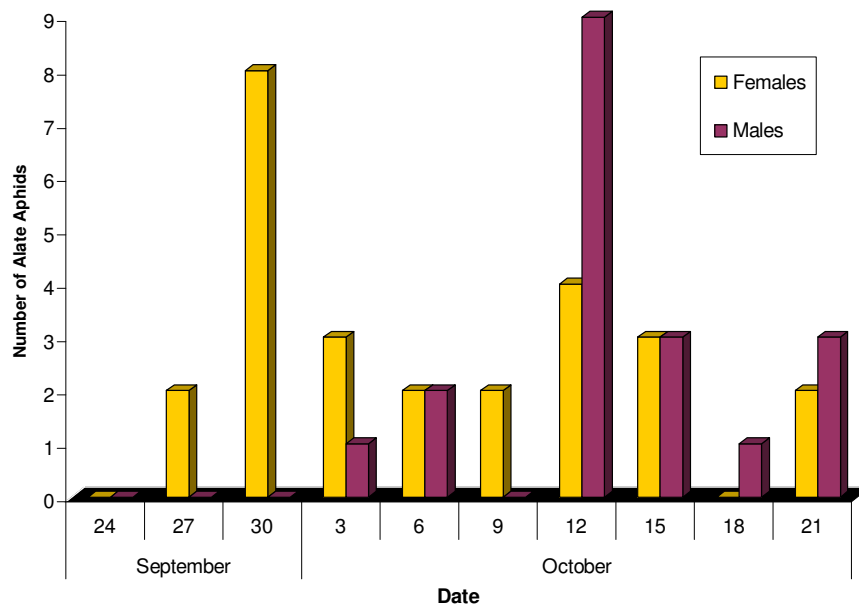


Figure 3. 4: Autumn migration period of male and female rosy apple aphids in the Similkameen Valley of Southern British Columbia, Canada based on pheromone trap captures. The y-axis shows the total number of rosy apple aphids caught for each date in 24 orchards.

3.3.3 Chemical Controls

Spring aphid population levels in 2008 were very low and as a result differences between treatments and controls were small and difficult to detect. No significant differences between treatments, by product used or by the timing of the applications, were observed for kaolin clay or superior oil. Two autumn applications and one spring application of PureSpray Green summer oil did show a significant reduction in the percent of clusters infested.

Experiment 1: Kaolin clay and Superior oil

Across all treatments, no significant difference was seen between the two control products (Figure 5).

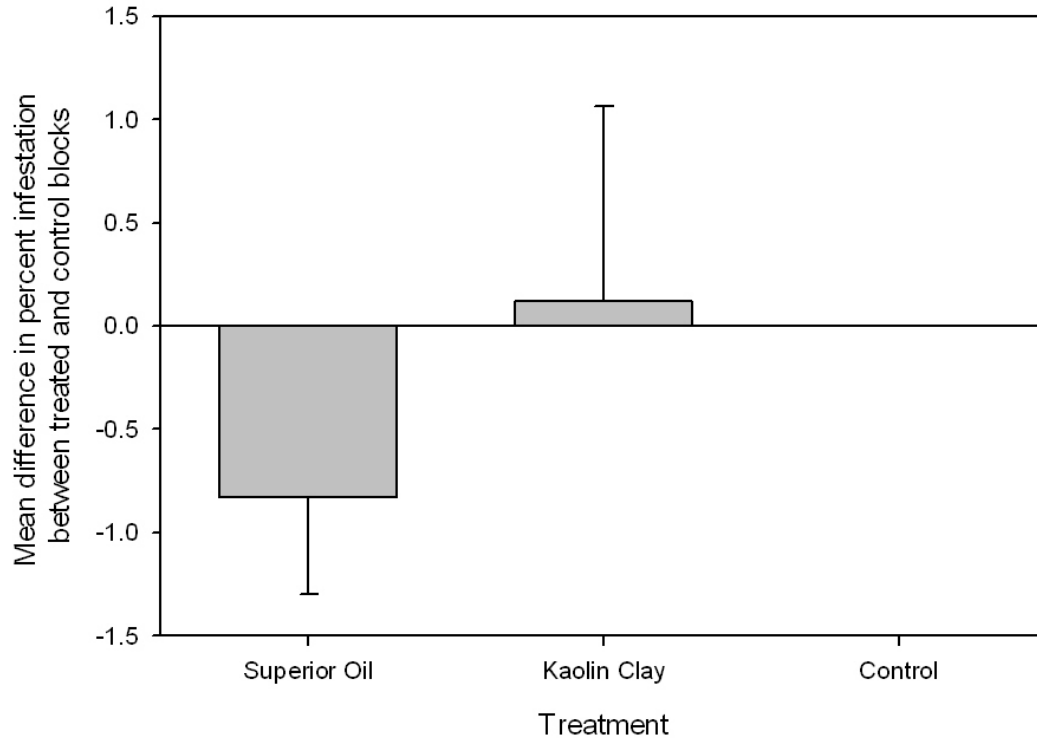


Figure 3.5: The difference in mean percent of clusters infested for plots treated with either Superior oil or kaolin clay from the control plots ($F = 2.13$, $df = 1, 24$, $p = 0.16$). Error bars show one standard deviation.

The analysis of variance (ANOVA) using the difference between the control and treatment percent of clusters infested and including Orchard as a random effect shows that the effects of product (kaolin clay or Superior oil) used ($F = 1.92$, $d = 1, 14$, $p = 0.19$) application timing and date ($F = 0.50$, $d = 5, 14$, $p = 0.77$) and the interaction between the two ($F = 0.55$, $d = 5, 14$, $p = 0.74$) were not significant.

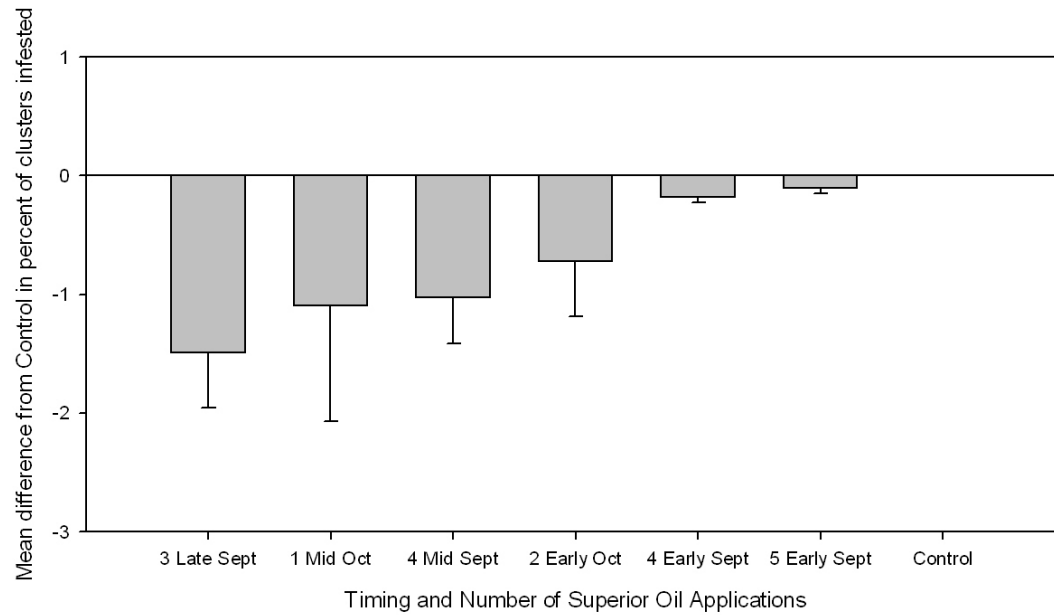


Figure 3. 6: Mean (one SE) difference in percent infestation of the apple trees (measured June 9 to 14, 2008) between autumn treatments and untreated control for six Superior oil treatments.

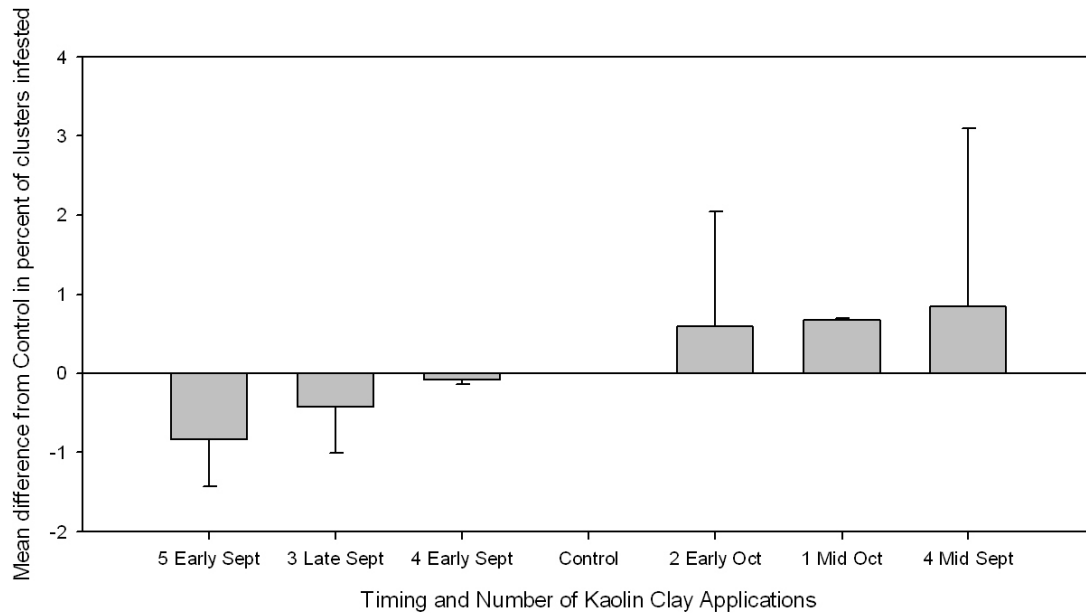


Figure 3. 7: Mean (one SE) difference in percent infestation of the apple trees (measured June 9 to 14, 2008) between autumn treatments and untreated control for six kaolin clay treatments.

Experiment 2: Purespray Green

When treatments were pooled, the PureSpray Green treatment blocks did not result in a significant difference from the untreated control blocks ($F = 0.5816$, $df = 6,6$, $p = 0.69$).

However, the PureSpray Green treatments of Mid and Late Oct ($t = -2.59$, $df = 6$, $p = 0.04$) and mid April ($t = -2.46$, $df = 6$, $p = 0.05$) showed a significant difference from the control (Difference between treatment and control is significantly different from 0) (Figure 8). These two treatments gave a percent reduction of 83% and 73%, respectively.

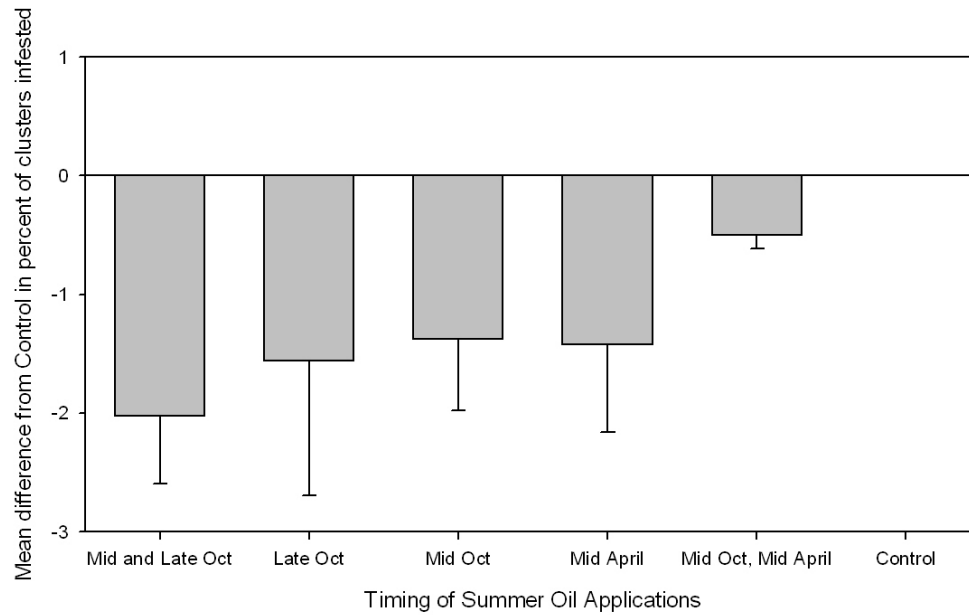


Figure 3.8: Mean (one SE) difference in percent infestation of the apple trees (measured June 9 to 14, 2008) between autumn treatments and untreated control for five PureSpray Green treatments.

3.3.4 Mechanical Controls

Infestation levels between mowed, rotavated and control plots were not significantly different ($F = 1.30$, $df = 2,6$, $p = 0.32$) (Figure 9).

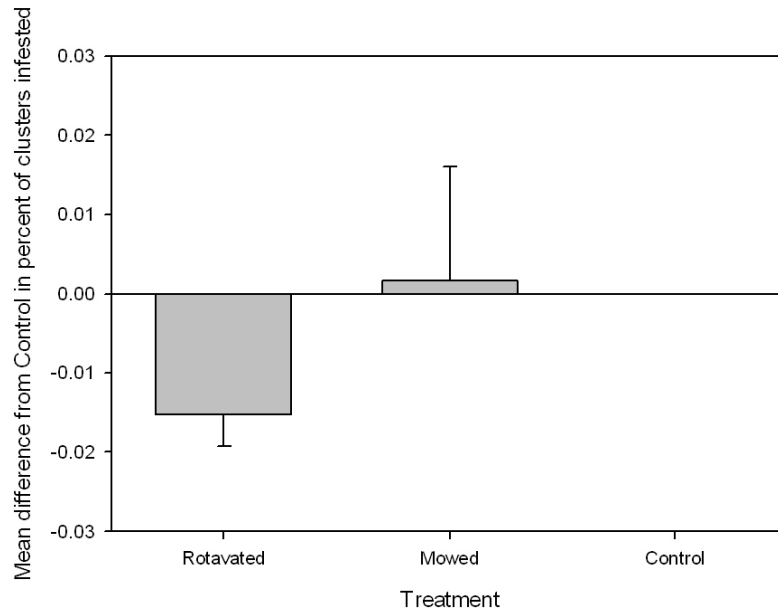


Figure 3.9: Mean (one SE) difference in percent infestation of the apple trees (measured June 9 to 14, 2008) between autumn treatments and untreated control for two mechanical control methods.

3.4 Discussion

3.4.1 Harvest Loss Assessment

The average value of a bin of organically produced Ambrosia apples in British Columbia is between \$350 and \$450 depending on apple size. An average “high density” orchard produces 40 to 45 bins per acre and the cost of production per acre is \$3000 to \$4000 CAN (B. Potash, Cawston Cold Storage, pers. comm.). This means that at a loss of about 80%, the orchard is no longer profitable. The results of this study show substantially higher potential losses than the 25% reduction in fruit growth predicted by the model created by Minarro *et al.* (2005) based on orchards in Spain. This could be explained by the fact that the Spanish orchards were not managed organically and because the pest is introduced in North America and may not be under as much pressure from natural

enemies as it is in Europe. This study took into account losses due to stunted fruit growth, but also the simultaneous effect of apple deformation and marketability. The percent of bins lost increases linearly with the percent infestation of the orchard and this relationship can be used to determine the economic feasibility of treatment options.

The indirect damage of reduced blossom production the year following the infestation is somewhat harder to quantify since there are many factors involved, including stress of the previous year's fruit load. However, by comparing blossom production on heavily infested trees with the average blossom count per tree for the orchard, some of those other factors should be accounted for. The 36% decrease seen in blossom clusters in trees heavily infested may translate into a significant loss of apple production in the year following the infestation meaning that a grower actually pays twice for the rosy apple aphid infestation. Apple blossoms are thinned in the spring; however, since only one to three apples can be produced to a marketable size on one spur, the loss of entire clusters will equal fruit loss as the remaining clusters cannot compensate for the loss by producing more apples themselves.

3.4.2 Pheromone Traps

The pheromone trap by-catch showed that the sex pheromone alone (without plant volatile compounds) at a ratio of 5:1 was not species specific in British Columbia. As a result, it could not be used as a practical trap for BC growers to be able to predict their spring aphid populations due to the required aphid species identification skills. Second, it showed that flight patterns were very consistent, with the data collected in England (Cross *et al.*, 2007), confirming that migration is highly dependent on daylength and less

so on temperature. The peak of female flight occurred between the 24th and the 27th of September at 11:56 hours daylength (2524 degree days from spring nymph development) and the peak of male flight occurred between the 9th and the 12th of October at 11:02 hours daylength (2610 degree days). When compared to average catches of *Dysaphis* sp. in the Rothamsted Insect Survey suction trap at Wye in Kent (Cross *et al.*, 2007) over a period of 39 years and using the 2007 calendar as a reference, the peak in female flight occurred in Kent, England at 11:59 hours daylength and the peak in male flight occurred at 11:04 hours daylength. Finally, although they have not been compared with a second year of data, the trap catches were very low, consistent with the low aphid population seen the following spring of 2008. It may be possible, with a more species-specific trap, to predict spring populations based on trap catch numbers the previous autumn. This information also gives growers in Cawston, BC the appropriate timing for chemical applications, as the most effective time to apply chemical treatment is at the peak of the female migration, according to Cross *et al.* (2007)

3.4.3 Chemical Controls

Experiment 1: Kaolin clay and Superior oil

The goal of these trials was to identify which product and combination of application timing and number is most effective at reducing spring aphid population size. The Superior oil and kaolin clay products applied during the autumn migration of 2007 did not result in a significant decrease in rosy apple aphid population size in the following spring of 2008. Aphid populations were very low in 2008, including in the control blocks, making significant differences difficult to detect and the differences would not have been meaningful in terms of management since the aphid population levels that year did not require any intervention.

Testing various application timings and numbers was meant to investigate whether a reduction in the number of applications was possible, while maintaining an acceptable level of control. Although not statistically significant, the kaolin clay treatments showing the most promise began on Sept. 12 and involved 4 and 5 applications (Treatment #1 and 2 – Table 2). This treatment spans almost the entire migration period of the rosy apple aphid and so was expected to be most effective. Wyss and Daniel (2004) found that gynoparae are the most susceptible to the kaolin clay and that coverage during the early migration is crucial for its efficacy. Other studies have shown an increase in rosy apple aphid populations as a result of kaolin clay applications (Knight et al., 2000; Knight et al., 2001).

In keeping with IPM principles, the effect of these management strategies on the natural enemies must also be considered. Kaolin clay applications at ten day intervals from March 25 to August 5, 1997 showed a significant decrease in the number of natural enemies present in the apple tree canopy. Spiders, earwigs (*Forficula auricularia*), predatory mites (*Allothrombium fuliginosum*), and pine ladybirds (*Exochomus quadripustulatus*) were reduced compared with untreated control blocks on all nine sample dates throughout the summer (Marko et al., 2006). It was not only the accumulation of these multiple summer sprays causing the decline, since the same reduction was seen early in the season. The effect of autumn applications of kaolin clay on beneficial insects in apple orchards has not been tested. However, many researchers have shown high levels of overwintering aphid egg mortality, ranging from 65% to 83% (Gange and Llewelyn, 1988; Leather, 1980 and Dunn and Wright, 1955), and Leather

(1981) has demonstrated that the majority of an 81% decline can be attributed to arthropod and bird predators.

The Superior oil application schedule treatments show no trends in effectiveness.

Although not statistically significant, they potentially show more promise than the kaolin clay treatments, as the mean percent of infested clusters were lower than the control in all six treatments.

Experiment 2: Purespray Green

Purespray Green was used to test the efficacy of late autumn and spring applications.

Two sprays in the autumn and one in the spring showed a statistical difference from the untreated controls.

The statistically significant reductions seen in chemical control treatments in this particular season is not meaningful in terms of management since the untreated spring population was so low that no treatment was needed to begin with. However, if the percent reduction in aphid populations remains constant regardless of the untreated spring population level then these treatments would be of significant value to growers in seasons with high aphid population levels of economic importance.

Percent reduction is commonly used to determine the impact of an insecticide, however, since the initial population was so low, percent reduction would have magnified the difference between control and treatment and potentially resulted in misleading results.

In a season with high initial populations, this experiment should be repeated to reassess the efficacy of these potentially useful products. Due to the timing of the applications it

is very difficult to know whether autumn treatment will be required or not and applications will be wasted if there is no method of predicting the population size of the following spring. This brings to light a very important consideration for research. If studies continue to be conducted on the efficacy of autumn applications, then a reliable and grower-friendly autumn alate trapping system must be developed at the same time so that the extent of the spring damage can be predicted in September and early October of the previous year.

3.4.4 Mechanical Controls

The mechanical controls tested in the autumn of 2007 did not result in significant reductions in rosy apple aphid populations in the spring in 2008. These approaches are meant to remove or disturb the alternate host before and during the migration. In management terms, they are both time-intensive and occur during apple harvesting. Rotavating appeared to be the more effective treatment with less variability in the results than mowing, but would be much less practical as machinery must be able to pass through the rows to move apple bins, which would cause compaction of the freshly turned soil. Mowing is a more appealing option as it does not leave the ground bare, potentially increasing the risk of sunburn and creating muddy alleys when pickers and tractors need to enter the area. In economic terms, the option of mowing would be very worthwhile as it requires less time and money than oil applications and ecologically, the disturbance to non-target insects is minimal. The mowing trial should be repeated in a year with higher aphid populations because if this strategy can be proven effective in future research, this option may prove to be the most feasible and environmentally benign option.

3.4.5 Other Potential Opportunities for Aphid Management

Conservation of the natural enemy populations (conservation biological control) through reduced pesticide use and habitat provision, is often effective for control for aphids, but only at relatively low population densities, and is not able to prevent extensive damage in bad years (Weires and Leeper, 1980).

Research on augmentative biological control using aphidophagous predators (*Adalia bipunctata*, *Aphidoletes aphidimyza*, and *Episyrphus balteatus*) has shown that high ratios of predators to aphids (5:1) are required to bring populations of rosy apple aphids down significantly (Wyss *et al.* 1999b). The effectiveness of this method for reduction in crop damage has not been assessed, which is important since the aphid population causes damage very early in the spring, possibly prior to the effect of biological controls. The timing of release is also very important and early May was shown to be more effective than early April for egg releases (Wyss *et al.*, 1999). When larvae were released in April they achieved the same level of control as the May release, but the time required to clean up the aphid populations was six days longer for the April release. This may indicate a need for accurate timing of release with aphid egg hatch and / or at temperatures that allow for increased survival and activity of the predators. Another predator genus, *Aphidoletes*, has both naturally occurring and commercially available species in Canada, however, they are adversely affected by cold temperatures and only appear in the orchards later in the summer (end of May) (Veronica Cervantes, The Bug Factory; pers. comm.). *Aphidoletes aphidimyza* has an egg development threshold of 10.5 °C and a mean developmental period of 25.5 heat units above the lower threshold. Larval development has a lower temperature threshold of 8.1 °C and developmental period of

65.5 heat units. Based on data collected in this study in Cawston, BC in 2007, this means that the eggs produced by these biological controls would only hatch at the end of April, after the rosy apple aphids have already been feeding for three weeks. However, this does not rule *Aphidoletes* out as a potentially effective agent and future work on this option would be welcomed by growers.

3.4.6 Conclusions

This study has shown that in the Similkameen Valley of British Columbia, organic apple growers suffer significant economic losses as a result of the rosy apple aphid in some years. Further research on the efficacy of oils and mowing should be conducted to attempt to reduce these losses; however, in order for an autumn control program to be effective, an alate trapping system must be developed that will allow growers or crop consultants to predict the spring population size and determine whether or not an autumn treatment is necessary. This is especially the case if future research shows chemical applications to be effective. Based on one year of pheromone trap data collected in the Similkameen Valley and comparisons with pheromone trap data from England, the timing of the autumn applications can be based on daylength, with the peak of female flight occurring at about 11:56 hours daylength and the peak of male flight occurring at 11:02 hours daylength. Fall and spring applications of PureSpray Green showed the most promise and should be repeated to ensure efficacy at high aphid populations. According to the current study, the economic threshold, when using this product, is very low, making it a feasible option at any level of infestation.

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Chapter 4

The Rosy Apple Aphid: Economic damage, Insect Host Interactions and Options for Control

4.1 Summary and Conclusions

Although many pests of organic fruit production in north western North America such as codling moth, leaf rollers and mites are well understood and controlled with organically acceptable techniques such as mating disruption sterile insect release, *Bt*-based insecticides, and the manipulation of natural enemy populations (L. Edwards, Personal communication), two pests remain without available control strategies. The rosy apple aphid is one of these and this species has recently been occurring with increasing intensity and frequency (L. Edwards, Pers. comm.).

This study was developed to achieve four basic goals: 1) to determine the economic impact of rosy apple aphids in organic orchards and the economic thresholds associated with potential control strategies, 2) to determine the environmental factors associated with high aphid populations, 3) to study the interactions between the aphid and its alternate host, and 4) to evaluate the efficacy of several chemical and mechanical control strategies.

Rosy apple aphids present a complex problem for growers of organic apples. They have a heteroecious lifecycle, alternating between the primary host, *Malus domestica*, in the autumn, winter and spring and the secondary hosts, *Plantago spp.*, in the summer and early fall (Blommers *et al.* 2004). One of these alternate summer hosts, *Plantago major*,

being an invasive weed, is widespread in orchards in the Similkameen Valley of British Columbia, Canada (A. Brown, Personal observation). Spring populations of rosy apple aphids on the apple trees are well protected from natural enemies in leaves that curl once the aphids begin feeding, and the natural enemy populations build up too late to prevent damage (Weires and Leeper, 1980). Some conventional insecticides have achieved 100% reduction in spring aphid populations when applied once in the autumn, and organically acceptable insecticides have in some cases achieved 98% reduction with five autumn applications (Cross *et al.*, 2007). There is, however, no prediction method for determining in the autumn, the following spring's population level. Autumn aphid flight can be monitored using traps baited with the sex pheromone of the rosy apple aphid, identified by Stewart-Jones *et al.*, (2007), but the trap is not entirely species specific and the identification of alate aphids is too time consuming to be practical for growers. Potential lies in the development of a more specific trap using plant volatiles, combined with the pheromone monitoring of traps however, currently this technology is not available to growers.

4.2 Economic Thresholds

The current research has demonstrated that the economic losses, in a year with high rosy apple aphid populations, can be significant, reaching \$29,050 CAD per hectare, using a conservative estimate of \$350 CAD per bin at a level of 84% of trees infested in an orchard. The economic threshold for this pest in the past has been reported to be low at one fundatrix female in 50 leaf bud clusters in early spring (Anonymous, 1977) or one fundatrix in 100 buds (Blommers, 1994). For organic apple production in the Similkameen Valley of BC, I have found that based on two autumn oil applications and

one spring oil application, any percentage of trees infested in an orchard is above the economic threshold. This threshold of 0% of the orchard infested is consistent with Blommers (1994). The single spring and double autumn oil application schedules were chosen because they are the most economical, showed a significant reduction in spring aphid density, and are products that are available to organic orchardists. Many of the products tested in Europe are not registered for use in Canada and are unlikely to be. The spring application is also more environmentally friendly as the grower is able to make the application based on spring sampling rather than spraying prescriptively each autumn. In many conventional orchards the rosy apple aphid is considered a secondary and sporadic pest and prescription spraying of a sporadic pest is not in accordance with the principles of IPM (Croft and Hoyt, 1983).

4.3 Environmental Factors of Population Size Variability

Populations of rosy apple aphids vary widely between orchards, and I hypothesized that the abundance of the alternate host or other factors of the orchard environment might be correlated with the rosy apple aphid populations. The abundance of the alternate host plant, *Plantago* spp., was not significantly correlated with aphid population size, and neither was the planting density of apple trees in the orchard. The leaf nitrogen levels and age of the trees, as well as the interaction between the two, were significant factors and explained 27% of the variation seen in aphid population sizes. Aphid populations increased with decreasing nitrogen levels and tree age. Although this seems contradictory to the literature that suggests that higher nitrogen better supports aphid growth, generally this is referring to nitrogen that is more available during translocation

(Dixon, 1985). Foliar samples were taken in July 2007 and at this point in the growing season, this nitrogen would not necessarily be available to the aphids. It is plausible that trees with increased levels of nitrogen also had increased levels of plant defense compounds. Herbivory by leaf miners on apple leaves has been shown to produce much higher levels of triterpene squalene ($C_{30}H_{50}$), and this in turn increased the host finding ability and increased the probing behaviour of the generalist parasitoid, *Pholetesor bicolor* (Dutton *et al.*, 2002). Increasing age of the tree relates to reduced vigour and new growth in the spring, reducing the amount of nitrogen being translocated to these tissues.

Rosy apple aphid populations also vary from year to year in individual orchards and a Pearson's rank correlation analysis showed that the rank of the aphid density in an orchard in spring 2007 as highest, second highest, or lowest is not correlated with the rank of the orchard in spring 2008. This indicates that it is not the same orchards that experience high aphid populations from year to year, and that it is not entirely fixed, within-orchard characteristics that are determining this variation.

4.4 Alternate Host – Aphid Interactions

The summer generations of the rosy apple aphid on its alternate host, *P. major*, were sampled in July, August and September 2007 and observation during sampling revealed that presence of alate aphids and apterous aphid colony development was related to the architecture of the host plant. Analysis of plantain abundance data showed a 20% decrease in aphid population size on the apple trees in orchards containing only small plants ($<0.013m^2$). Colony size on plantain was 25 times larger on leaves with an angle

to the ground of $\leq 15^\circ$, than leaves with an angle of 15° to 90° . A regression also showed that low leaf angle, increase leaf length and an increased difference in temperature above and below the leaf were correlated with higher aphid population size on the plantain.

Experimental manipulations of plantain answered the following questions: 1) Do more alates select, survive and reproduce and do more apterae survive and reproduce on large or small leaves, with a low or high angle to the ground? 2) Does mowing alter the characteristics of plantain leaf length and angle to the ground? 3) Does mowing prior to migration result in larger population size of rosy apple aphids on the plantain in the summer?

I found that significantly more alatae and apterae are found on large leaves with a low angle to the ground, that mowing creates significantly shorter leaves by 1.5cm and lower angle leaves by 20° . Mowing prior to migration resulted in significantly higher numbers of aphids on the plantain compared with an adjacent unmowed control.

4.5 Control Strategies

As a result of very low population densities in the spring of 2008, differences between treatments and controls may not have been detectable, and these trials should be repeated in a year prior to a spring with higher population densities. In this study, autumn chemical applications of Superior oil and kaolin clay did not cause significant differences between products and control blocks or between application schedule treatments. The summer oil application did result in a significant reduction of aphid populations compared to controls when applied twice in the autumn (mid and late October) and when applied once in the spring (mid April). The mechanical plantain removal treatments of

flail mowing, which cuts the vegetation down to ground level, and rotavating, which turns the soil over, were both intended to remove the host plant from the system prior to and during autumn migration. Neither of these resulted in significant differences between the treatments and controls.

4.6 Management Implications

The results of the current study indicate that the architecture of the plantain may influence the survival of aphids during the summer. Mowing frequently or just prior to aphid migration creates a habitat conducive to aphid survival in the hot, dry, summer conditions of the Similkameen Valley. Postponing mowing until after migration has occurred may reduce the summer aphid population size and potentially the fall migratory population, although this still needs to be tested. Removal of plantain from the orchard system may be extremely difficult given the ubiquitous nature of this weed, but rotavating and reseeding with an orchard grass mix may reduce plantain through competition. Finally, the autumn flail mowing trials should be repeated as it would provide a cost effective and environmentally benign strategy. In terms of all autumn controls, further research is also needed on the pheromone lures used for trapping rosy apple aphids to make them more species specific and autumn economic thresholds must be developed so that they could be used to predict spring populations and determine the level of threat to production. The spring oil application shows the most promise and should also be repeated to confirm the efficacy in a year with higher population pressure as well as low population pressure, as was the case in this study.

Future research could tackle such gaps in knowledge such as how far aphids migrate during both spring and autumn migration periods, and what the correlation is between summer population size on plantain, autumn migrant population size, and spring population size on apple.

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Appendix A

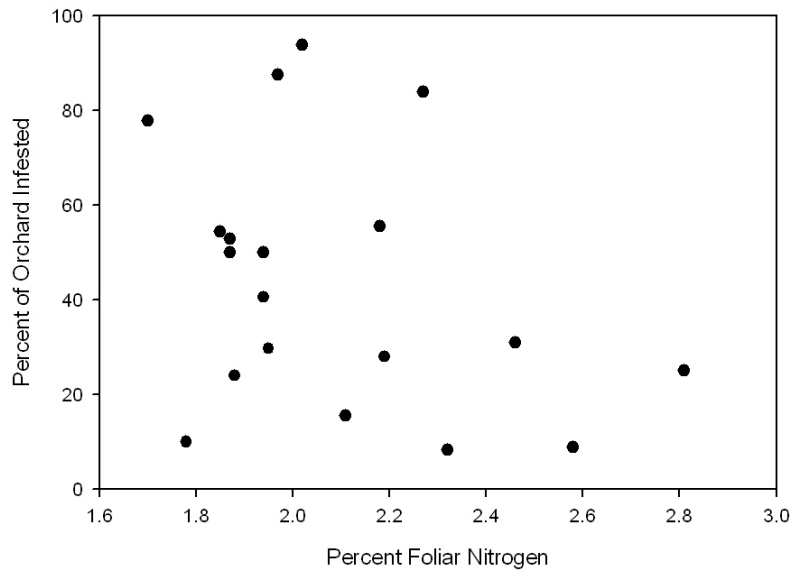


Figure 5. 1: Percent of trees in an orchard infested in 2007 as a function of the percent foliar nitrogen content of the trees, in 19 of the 24 Ambrosia orchards sampled.

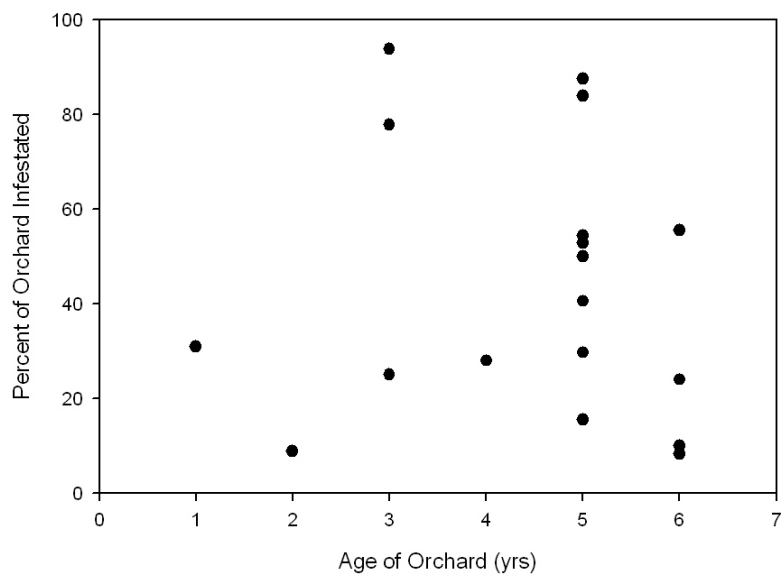


Figure 5. 2: Percent of trees in an orchard infested in 2007 as a function of the orchard age, in 19 of the 24 Ambrosia orchards sampled.