Control of Apple Clearwing Moth, *Synanthedon myopaeformis*, with Tree-trunk Applications of Reduced-risk Insecticides, Nematodes and Barriers

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ABSTRACT

Apple clearwing moth (ACM), *Synanthedon myopaeformis* (Borkhausen) (Lepidoptera: Sesiidae), was discovered in an apple orchard in Cawston, British Columbia, in 2005. This xylophagous, European species has become a serious pest in high-density apple orchards where size-controlling rootstocks are attacked by the wood-boring larvae. Seven screening trials with reduced-risk insecticides, including seven conventional treatments and three organic treatments, were established in two commercial, high-density, mixed-variety apple plantings in Cawston. Objectives were: (1) to screen several new synthetic insecticides having novel chemistries that purportedly have reduced risks; (2) to evaluate use of several organically approved spray materials, including nematodes; and, (3) to compare the efficacy of various products when applied at different times during the growing season. Single, handgun sprays delivering treatments in 2000 L of water ha^{-1} at 200 psi were applied as curative sprays targeting mature larvae in rootstock–scion graft unions in May and October 2008, and in June 2009. Among seven treatments tested, only the insect growth regulator, Rimon® 10 EC (10% novaluron), at 2.8 L of product ha^{-1}, consistently reduced adult emergence compared with untreated control trees in all experiments. When applied twice as *preventative* treatments during flight of male ACM in 2008, Altacor®, Belt®, Delegate™, Entrust® and Rimon all caused significant reductions in adult emergence the following year; the Rimon treatment exhibited the greatest reduction (–96.4%). In a similar 2009 trial, only Rimon reduced populations the following year. One curative application of the organic materials, Entrust®, Crocker's Fish Oil®, or Purespray Green Oil™, at any spray timing, did not control ACM. Applying *Steinernema feltiae* (Filipjev) at 1×10^5 infective juvenile nematodes / 100 ml of water / tree provided significant control of ACM in one spring 2008 trial. In two 2009 nematode-only experiments, a sawdust paste tree-trunk barrier applied over nematode treatments made either in May or August caused significant reductions in emergence of ACM adults. Curative tree-trunk sprays of Rimon 10 EC at the tested rate are recommended for control of ACM in conventional apple orchards. Tree-trunk barriers and nematodes warrant further study as possible organic controls for ACM.

Key Words: Lepidoptera, Sesiidae, clearwing borer, invasive species, apples, Rimon, novaluron, curative sprays, preventative sprays, tree-trunk barriers,

INTRODUCTION

Synanthedon myopaeformis (Borkhausen) (Lepidoptera: Sesiidae), the apple clearwing moth (Alford 2007), sometimes called small red-belted clearwing borer (Ateyyat and Al-Antary 2006), is a xylophagous, European insect that commonly infests species of *Rosacea* (Špatenka *et al.* 1999). The first North American detection of *S. myopaeformis* occurred in 2005 (Philip 2006), when a moth was collected in an organic apple orchard in the Similkameen Valley, near Cawston, British Columbia (B.C.). In 2006, the Centre for Plant Quarantine Pests at the Canadian Food Inspection Agency (CFIA; www.inspection.gc.ca) conducted pheromone trapping surveys of most commercial apple growing areas within Canada. These surveys detected *S. myopaeformis* at several locations in B.C.: near Cawston and Keremeos in the Similkameen Valley, in Oliver,

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Osoyoos and the Ellison suburb of Kelowna in the Okanagan Valley, and near Langley, Abbotsford, and Yarrow in the Fraser Valley (Canadian Food Inspection Agency 2006). One moth catch in Fingal, Ontario, was the only Canadian detection outside B.C. (Beaton and Carter 2006). By 2008, the insect was officially established in areas of Washington State, USA (LaGasa *et al.* 2009), adjacent to the Fraser Valley detections. Tree surveys in 2008 confirmed the species had invaded 97% of all apple orchards within the Similkameen Valley, and in 39% of the affected orchards more than 80% of the trees were infested (Cossentine *et al.* 2013).

Apple clearwing moth (ACM) can be a destructive pest of commercial apple trees, *Malus domestica* Borkhausen (*Rosacea*), particularly when grown on clonal, size-controlling rootstocks in high-density plantings (Dickler 1976). Damage from ACM has increased throughout Eurasia wherever apple industries have implemented this more intensive apple-production technology (Abd Elkader and Zaklama 1971; Dickler 1976; Blaser and Charmillot 1984; Castellari 1987; Balázs *et al.* 1996; Sahinoglou *et al.* 1999; Ateyyat 2006; Kutinkova *et al.* 2006). An identical situation occurred in eastern North America, where the congeneric, native dogwood borer, *Synanthedon scitula* (Harris), became a serious pest after the apple industry converted to high-density plantings (Riedl *et al.* 1985; Kain and Straub 2001).

The heightened pest status of these apple-infesting sesiids has occurred because clonal rootstocks promote formation of adventitious root primordia (burr knots) near the rootstock–scion graft union. These above-ground burr knots are either preferred oviposition sites or susceptible points of entry for neonate larvae (Dickler 1976; Bergh and Leskey 2003). Repeated infestation and feeding by sesiid larvae eventually depletes burr knot tissue, and this leads to feeding in the cambial layer, which ultimately girdles the bark and provides sites for infections that weaken or kill the tree (Dickler 1976; Iren *et al.* 1984; Weires 1986).

Given the European experience with ACM, the potential for severe damage seemed likely after its introduction to the Similkameen Valley. Most apple orchards in this production region had been converted to high-density plantings in the preceding decade (personal observation and unpublished Okanagan Tree Fruit Authority reports), at least 50% of the apples were under organic production (Mullinix 2005), and an area-wide programme controlling codling moth had virtually eliminated use of synthetic insecticides in apples (Judd and Gardiner 2005). An expectation of impending damage stimulated pest management research on several fronts (Judd 2008; Cossentine *et al.* 2010; Aurelian 2011; Eby 2012; Kwon 2013), including chemical controls that are still a primary method of managing many sesiid pests of woody trees and shrubs (Johnson and Lyon 1991).

Traditional insecticidal sprays are effective against most borers only when lethal residues are present on bark during a brief period between egg deposition and initial entry of neonate larvae into the tree (Potter and Timmons 1983). Control of *S. myopaeformis* with many short-lived insecticides is difficult because adults emerge and oviposit from June to August (Judd 2008) and larvae spend the majority of life feeding beneath the bark—up to two years in some areas (Dickler 1976). The extended field life of organochlorines (e.g., endosulfan) and organophosphates (e.g., chlorpyrifos), especially when applied to tree trunks using large volumes of water (drenches), provides levels of efficacy that led to their global use for controlling apple-infesting sesiids for more than four decades (Abd Elkader and Zaklama 1971; Frankenuyzen 1979; Warner and Hay 1985; Balázs *et al.* 1996; Ateyyat 2005). With these insecticidal classes under review or being deregistered in Canada in 2008, largely a result of the 1996 USA *Food Quality Protection Act*, urgent need arose for controls to address the problem facing many Similkameen apple producers, particularly organic producers.

The objectives of this study were: (1) to screen a number of new synthetic insecticides having novel chemistries that purportedly have reduced risks; (2) to evaluate the use of several organically approved spray materials, including live nematodes; and, (3) to compare the efficacy of these various products when applied at different times during the growing season.

MATERIALS AND METHODS

Test Sites. Screening trials for control of ACM with synthetic insecticides and nematodes were established on two conventionally managed commercial apple orchards in Cawston, B.C. (49.15 N and –119.74 W). Three screening trials in 2008 and one in 2009 were conducted on Farm 1, in a 14-row, 12-year-old, slender-spindle planting of 'Gala' apple cultivar grafted to M9 rootstock (Block 1). One summer 2009 trial was conducted in a six-row, eight-year-old, slender-spindle planting of 'Fuji' apple cultivar grafted on Ottawa-3 rootstock (Block 2), also on Farm-1, about 50 m from Block 1. In both blocks 1 and 2, the alley spacing between tree rows was 3 m, and tree spacing within rows was 0.75–1.0 m.

Two nematode-only screening trials were conducted on Farm 2, located on Barcello Road about two kilometres south of Farm 1, in a mature, double-row, slender-spindle planting of 'Gala' apple cultivar grafted to M26 rootstock (Block 3). The alley and tree spacing in Block 3 was 3×1 m.

Spray Materials and Rates. Three insecticides tested as possible organic chemical control products included: (1) Entrust® 80W (80% spinosad) at 109 g of product ha $^{-1}$ [Dow AgroSciences, Calgary, Alberta]; (2) Crocker's Fish Oil® [Crocker's Fish Oil Inc., Quincy, Washington State, USA]; and (3) Purespray Green™ Spray Oil 13E [Petro-Canada Lubricants Inc., Mississauga, Ontario]. Both oils were applied as 1% (volume / volume) suspensions in water.

Four synthetic insecticides, each with a novel chemistry and some recently registered for use by conventional apple producers in Canada (British Columbia Ministry of Agriculture 2010), included: (1) Altacor® (35% chlorantraniliprole) at 285 g of product ha^{-1} [DuPont™ Canada Company, Mississauga, Ontario]; (2) Belt® (39% flubendiamide) at 300 and 350 ml of product ha^{-1} in 2008 and 2009, respectively [Bayer CropScience, North Carolina, USA]; (3) Delegate™ WG (25% spinetoram) at 420 g of product ha^{-1} [Dow AgroSciences, Calgary, Alberta]; and, (4) Rimon® 10EC (10% novaluron) at 2.8 L of product ha^{-1} [Chemtura Canada Company, Elmira, Ontario].

Nematode Products and Rates. Three species of nematodes were tested as possible biological control products for organic apple producers: (1) *Steinernema feltiae* (Filipjev) (1×10^5 infective juvenile [IJ] nematodes in 100 ml of water / tree [May 2008 source: L. Lacey, USDA, Wapato, USA; October 2008 source: Westgro Sales Inc., Delta, B.C.]), (2) *Heterorhabditis bacteriophora* Poinar (1.5×10^5 IJ [May 2009] and 5×10^5 [August 2009] nematodes in 100 ml of water / tree [(Biobest Biological Systems, Leamington, Ontario]), and (3) *Steinernema carpocapsae* (Weiser) 7×10^3 IJ [May 2009] and 3.9×10^3 IJ nematodes [August 2009] in 100 ml of water / tree [The Bugfactory Ltd., Nanoose Bay, B.C.].

Spray Techniques. Unless noted otherwise, all insecticide sprays were applied using a calibrated, hand-held spray gun (Wheaton Gunjet, Spraying Systems Company, Wheaton, Illinois, USA) equipped with a Teejet D6 nozzle and attached to a truck-mounted sprayer (Rittenhouse, St. Catharines, Ontario) that operated at 200 psi and was calibrated to deliver 2,000 L ha^{-1}. All sprays were applied to the base of individual trees from soil level to a height of the lowest scaffold limbs; in general, this corresponded to the height of the lowest wire on the trellis system and was approximately 50 cm above ground.

Spray Timing. A total of seven screening trials—three in 2008 and four in 2009, including two nematode-only trials—were conducted to evaluate the various control products when applied during three different seasons: (1) spring, (2) summer, and (3) autumn. The spring post-bloom spray timing was considered *curative* and primarily targeted mature larvae as they expelled frass from feeding galleries, prepared cocoons, and pupated near their gallery entrances. Each year, spring applications were made following an examination of all trees in all test blocks (Block 1 on 15 May 2008; Block 2 on 10 May 2009; Block 3 on 21 May 2009). These examinations determined there was a 100% level of tree infestation, based on the presence of larval frass having been expelled from feeding galleries near the rootstock–scion graft unions. This expulsion of frass in spring is commonly observed in B.C. whenever burr knots on dwarfing apple trees are infested by ACM.

The in-season, mid-summer spray timing was considered *preventative*, because it targeted eggs and neonate larvae before they gained entry to the tree. The timings for these preventive summer sprays were based on a preliminary phenology model that attempted to predict 50% and 95% adult emergence (Judd 2008). Phenology of moth emergence was approximated by catches of males in traps containing the female sex pheromone 3Z,13Z-octadecadienyl acetate (Judd *et al.* 2011). Two all-yellow Unitraps® (AgBio Inc., Westminster, Colorado, USA) were hung at 1.5 m above ground in the middle of each test block. Traps were baited with grey halobutyl rubber septa (West Co., Lyonville, Pennsylvania, USA) that were impregnated with 10 mg of 3Z,13Z-octadecadienyl acetate (Pherobank, Wageningen, The Netherlands; > 95% isomeric purity) dissolved in 200 µL of HPLC grade hexane (Aldrich Chemical Co., Milwaukee, Wisconsin, USA). We placed a 2.5×5.0 cm insecticidal strip containing 10% dichlorvos (Vaportape™ II, Hercon Environmental, Emigsville, Pennsylvania, USA) inside the bucket of each composite Unitrap to improve capture (Judd and Eby 2014). Traps were checked weekly, and all apple clearwing moths were counted and removed. A single pheromone lure lasted the entire season.

Hourly air temperatures throughout the study were recorded at a centrally located orchard in Cawston, B.C., from 1 January through 31 December each year. Temperature readings were made using a HOBO® data logger (Onset, USA) housed in a 1-m high Stevenson screen. Daily degree-day (DD) summations above an arbitrary 10° C developmental base temperature ($DD_{10°C}$) and below a 31° C upper developmental threshold were calculated by fitting a sine wave (Allen 1976; case 4) to daily air temperature minima and maxima using the computer program described by Higley *et al.* (1986).

The late-summer and early-autumn post-harvest sprays targeted late-season hatching eggs and larvae that may not have gained deep entry beneath the bark. All post-harvest sprays were applied after catches of male moths in traps had ceased.

Experimental Trials and Assessments. In Experiments 1 to 5, all treatments were assigned to test plots using a randomised complete block design with 4 to 10 replicates depending on the trial. Each replicate block consisted of a single 6-metre-long tree-row containing 7 to 9 trees, depending on the exact tree spacing. Data in experiments 1 to 5 were collected only from the five central trees in each test block. One to two trees on either end of each 6-m row served as guard trees to separate adjacent treatments.

Experiment 1 (2008) had five replicates and evaluated single spring applications of Altacor, Belt, Delegate, Rimon, Entrust, Crocker's Fish Oil, a nematode treatment, and water-only control. All treatments were applied on 27 May 2008 (Fig. 1). The nematode treatment in this experiment contained *S. feltiae* and was applied with a backpack sprayer at a rate of $1×10^5$ IJ nematodes in 100 ml of water / tree. After applying the nematode treatment, a water-soaked piece of burlap was wrapped around the treated rootstock–scion graft union of each tree and then covered with wet cardboard that was stapled in place. The purpose of wraps was to slow desiccation and promote nematode efficacy (Lacey *et al.* 2010; Shapiro-Ilan *et al.* 2010; Cottrell *et al.* 2011).

The efficacy of the spring 2008 treatments in Experiment 1 was assessed on 5 August 2008 and again on 13 August 2009. Efficacy was measured by counting the numbers of pupal exuviae that protruded from the bark within a 25-cm zone from the ground up. This zone usually included the rootstock–scion graft union. Pupal exuviae are evidence of adult emergence and often remain attached to the tree for several weeks to months.

Experiment 2 (2008) had 10 replicates and evaluated two summer applications of Altacor, Belt, Delegate, Rimon, Entrust, and Crocker's Fish Oil, compared to a water-only control. The two summer sprays were applied on the 8 and 22 July 2008 (Fig. 1). The nematode treatment was excluded from Experiment 2, because it was assumed that extreme summer temperatures would eliminate its efficacy. Pupal exuviae were counted and removed from all test trees with fine forceps on 5 August 2008. This count confirmed the level and uniformity of the infestation that must have existed before summer treatments were applied, because these pupal exuviae would have arisen from larvae feeding in the tree since 2007, well before our controls were applied. The efficacy of the summer 2008 treatments in Experiment 2 was assessed by counting pupal exuviae on 13 August 2009.

Experiment 3 (2008) had five replicates and evaluated single autumn applications of Altacor, Belt, Delegate, Rimon, Entrust, and a nematode treatment, compared to a water-only control. The nematode treatment in this experiment also contained *S. feltiae* applied with $1×10^5$ IJ nematodes in 100 ml of water / tree, but unlike the spring nematode treatment (Experiment 1), nematodes were not covered with burlap or cardboard to prevent desiccation. As before, all pupal exuviae

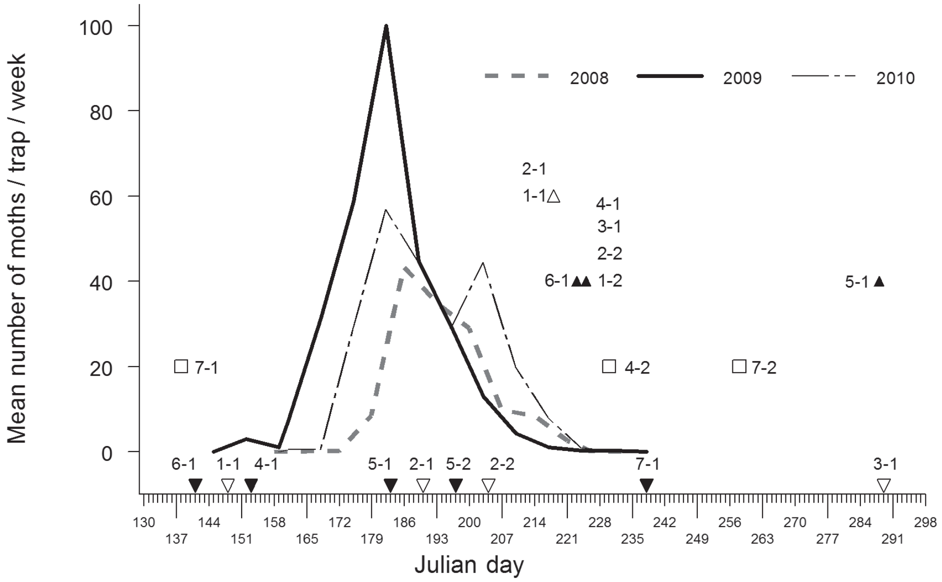

Figure 1. Treatment application dates in each of three 2008 experiments (open inverted triangles with associated experiment - spray numbers) and four in 2009 (solid inverted triangles with associated numbers), with follow-up population assessments in 2008 (open triangles with associated experiment - assessment numbers), 2009 (solid triangles with associated numbers), and 2010 (open squares with associated numbers), in relation to seasonal catches of male *S. myopaeformis* in pheromone-baited all-yellow Unitraps® at Cawston B.C., 2008–2010.

were counted and removed from test trees on 5 August 2008. These counts served as a pre-treatment assessment to ensure the levels of infestation were uniform across all treatments and replicates. All treatments in Experiment 3 were applied on 15 October 2008, and their efficacy was assessed as before on 13 August 2009.

Experiment 4 (2009) had four replicates and evaluated single spring applications of Altacor, Belt, Delegate, Rimon, Purespray Green Oil, Belt *plus* Purespray Oil, and a Rimon plus Purespray Oil treatment, compared to a water-only control. The Belt plus oil and Rimon plus oil treatments were tested using the same insecticide product rates as used in Experiment 1, but materials were tank-mixed with the 1% oil in water suspension (volume to volume). All treatments in Experiment 4 were applied on 2 June 2009, and their efficacy was assessed on 13 August 2009 and again on 18 August 2010.

Experiment 5 (2009) had five replicates and evaluated two summer applications of Altacor, Belt, Delegate, Rimon, Entrust, and Purespray Green Oil, compared to a water-only control. The two summer sprays were applied on 2 and 16 July 2009 (Fig. 1). On 13 August 2009, we counted and removed all the pupal exuviae from our test trees as we had done in Experiment 2. This provided an assessment of the level of infestation that existed before treatments were applied.

Our original intention was to assess the efficacy of sprays applied in Experiment 5 one year after treatment, in August 2010, as we had done in Experiment 2. However, in August 2009, the grower informed us that he intended to remove our test block in October 2009. We switched our assessment method and took the opportunity to examine the harvested trees and count the numbers of larvae using a destructive sample. Two test trees in the centre of each treatment block were cut 30 cm above ground and pulled from the ground with an excavator, exposing the roots. All roots more than 30 cm from the tree trunk were removed with pruning shears. Pruned tree sections were returned to the laboratory, where they were washed with a low-pressure water hose. All bark 25 cm above and below ground level was removed with a knife, and exposed larvae were counted and classified as being found above or below ground. Chilled larvae were measured with a small ruler and classified as either ≤ 9 mm or > 9 mm. The smallest larvae were expected to have arisen from eggs laid in 2009; thus, their reduction should represent the impact of summer 2009 treatments. The largest larvae may have arisen from oviposition in 2008 before our treatments were applied.

Nematode *plus* Barrier Experiments. These nematode-only experiments were conducted in Block 3 located on Farm 2, about 2 km south of Farm 1. Experiment 6 (2009) used a split-plot design with five replicate blocks to evaluate the efficacy of two different species of nematode when applied to tree trunks as a single spring application, alone or in combination with different barrier wraps that help to prevent desiccation of nematodes (Lacey *et al*. 2010; Shapiro-Ilan *et al*. 2010; Cottrell *et al*. 2011). On 21 May 2009, two nematode treatments, *S. carpocapsae* (7×10^3 IJ nematodes [Sc] in 100 ml of water / tree) and *H. bacteriophora* (1.5×10^5 IJ nematodes [Hb] in 100 ml of water / tree), and a 100-ml water-only control were each applied to 30 different trees within each of five replicate blocks. All sprays were applied with a calibrated backpack sprayer. Air temperature during application was 15° C but reached >19° C on the day of application. Immediately following these three applications, each group of 30 trees was further subdivided into three groups of 10 trees. One group of 10 nematode- or water-treated tree trunks was wrapped with a sawdust mixture (0.8 L of sawdust: 0.55 L vermiculite : 0.4 L perlite : 10 ml white glue [Elmer's white] : 1 L of tap water) that was moulded onto trees by hand (SDW). A second group of 10 treated trees was wrapped with wet cardboard that was stapled in place (CBW). The third group of 10 treated trees was left unwrapped (UW). Thus, there were nine nematode-wrap treatment combinations in total: (1) Sc-SDW, (2) Sc-CBW, (3) Sc-UW, (4) Hb-SDW, (5) Hb-CBW, (6) Hb-UW, (7) water-SDW, (8) water-CBW, and (9) water-UW. All CBW were removed on 5 June 2009. The SDW were left in place to erode naturally from the effects of irrigation and rain, but all remaining sawdust material was completely removed on 11 August 2009. The original plan was to use higher and comparable numbers of nematodes in each nematode treatment; however, laboratory counts of live nematodes were lower than the estimated counts on labelled commercial packages. Nematode infectivity for each treatment was confirmed in the laboratory using infection rates on third-instar oblique-banded leafroller, *Choristoneura rosaceana* (Harris). The efficacy of nematode and barrier treatments (SDW and CBW) was subsequently measured by counting numbers of empty pupal exuviae that protruded from the bark within a 25-cm zone from the ground up. Counts of pupal exuviae were made on all trees on 11 August 2009 (Fig. 1).

Experiment 7 (2009) was also conducted in Block 3 on Farm 2, but used a different set of trees than in Experiment 6. Experiment 7 employed a split-plot experimental design with five replicates to evaluate the efficacy of a single late-summer application of two different species of nematode when applied to tree trunks, alone or in combination with the SDW. On 26 August 2009, two nematode treatments, *S. carpocapsae* (3.9×10^3 IJ nematodes [Sc] in 100 ml of water / tree) and *H. bacteriophora* (5×10^5 IJ nematodes [Hb] in 100 ml of water / tree), and a 100 ml water-only control were each applied using a calibrated backpack sprayer to the bottom 45 cm of each of 20 trees within each of five replicate blocks. Immediately after the nematode treatments were applied, each group of 20 trees was subdivided into two groups of 10 trees. One group of 10 nematode- or water-treated tree trunks was left uncovered (Sc-UW, Hb-UW, and Water-UW, respectively), and the other groups of 10 treated trees were wrapped with a SDW as described in Experiment 6 (Sc-SDW, Hb-SDW and Water-SDW, respectively). Air temperature was above 15° C at the time all nematode treatments were applied, but reached 27° C later that day. Any SDW still remaining on trees on 18 May 2010 was removed before any moths emerged (Fig. 1). The efficacy of the August 2009 nematode treatments was measured by counting pupal exuviae protruding from the trunks and on the soil around all treated trees on 29 September 2010.

Statistical analyses. Pupal count data generated in Experiments 1 through 5 were subjected to two-way randomised block analyses of variance (ANOVA), with repeated measures in 2008 and 2009 (Experiments 1 through 3), or in 2009 and 2010 (Experiment 4). Larval count data from harvested trees in Experiment 5 were analyzed by a two-way randomised block ANOVA. Mean numbers of pupal exuviae (Experiments 1 through 4) or mean numbers of larvae (Experiment 5) in treatment trees were compared to counts from control trees using the *post hoc* Dunnett test and an experiment-wise error rate set at $\alpha = 0.05$ (Zar 1984). All insect count data were tested for normality (Kolmogorov-Smirnov Test) and equality of variances (Levine's Median Test) to ensure they met the assumptions of the ANOVA. All of these analyses were performed using SigmaPlot®-12 (Systat Software Inc., San Jose, California, USA).

In Experiments 6 and 7, the effects of nematode treatments and tree trunk wraps were tested using a two-way split-plot ANOVA, with replication and barriers as the main effects (SAS 2008). Mean numbers of pupal exuviae in each treatment were compared *post hoc* using Tukey's HSD test and an experiment-wise error rate set with $\alpha = 0.05$.

RESULTS and DISCUSSION

Seasonal pheromone trap catches indicate that ACM had a single flight period that started in late-May and culminated by mid-August during 2008 – 2010 in Cawston, B.C. (Fig. 1). By overlaying our experimental spray dates on catch curves, we were able to compare spray timings in various experiments with seasonal phenology of ACM. In 2008, spring treatments in Experiment 1 were applied at 201 $DD_{10°C}$ from 1 January 2008, almost three weeks before the first moth was caught (Fig. 1)—meaning many larvae had likely not yet formed cocoons or pupated. Among the treatments applied in spring 2008, Rimon, Belt, and nematodes all caused a significant reduction in emergence of moths in the summer of 2008, relative to emergence from the control trees (Table 1). This indicates that a single spring application of these materials can be curative in action, because they kill mature larvae in their feeding galleries or exit holes before pupation.

A single spring application of Rimon may contribute to mortality over two seasons because trees treated with Rimon in spring 2008 had a statistically significant year-over-year reduction (–66.7%) in pupal exuviae counts in 2009 that was more than twice that seen in water controls (Table 1). We are uncertain whether ACM has a one- or two-year lifecycle in B.C. (Judd 2008); therefore, it remains unclear whether the reduced adult emergence in 2009 from trees treated in 2008 (Table 1) is the result of a curative action in spring 2008 or a carry-over preventative action in summer 2008. If ACM has a one-year life cycle and Rimon has a long residual period, the product could prevent further infestation by killing eggs and neonate larvae appearing on trees in summer 2008. However, if ACM has a two-year lifecycle, then immature larvae present in spring 2008 but destined to emerge in 2009 could have been killed by Rimon through a curative action. Nothing precludes both things happening. Either way, control of ACM with Rimon applied in spring appears promising. Adult emergence from trees treated with Belt in spring 2008 was significantly different than the control trees in summer 2009 (Table 1), but there was no significant year-over-year reduction from the spring Belt treatment—a reduction similar to that seen on the control trees was evident (Table 1).

Summer 2008 treatments in Experiment 2 were applied at 579 and 764 $DD_{10°C}$ after 1 January 2008, which corresponded to 51% and 95% cumulative moth catch, respectively (Fig. 1). Among the insecticide treatments applied twice in summer 2008, Altacor, Belt, Delegate, Entrust, and Rimon all caused significant reductions in adult emergence in 2009 (Table 1). The summer 2008 Rimon treatment exhibited the greatest year-over-year reduction (–96.4%) in pupal exuviae counts (Table 1).

Autumn 2008 treatments in Experiment 3 were applied at 1445 $DD_{10°C}$ after 1 January 2008, about seven weeks after the last moths were caught (Fig. 1). Rimon was the only treatment applied once in autumn 2008 (Experiment 3) that caused a significant reduction in adult emergence in 2009 compared with emergence from the control trees (Table 1). Pupal counts on Rimon-treated trees in 2009 were 89.2% lower than the pre-test counts made in summer 2008 (Table 1). It should be noted that several autumn treatments in Experiment 3, including the control, exhibited significant year-over-year reduction in pupal counts (Table 1). These generalized reductions may indicate that eggs and neonate larvae can be damaged or dislodged by high-pressure or high-volume handgun sprays, but lack of a non-treatment control prevents us from making definitive conclusions on these year-over-year results.

Spring treatments in Experiment 4 were applied on 2 June 2009, with an accumulation of 288 $DD_{10°C}$ after 1 January 2009, and almost one week after the first moth was caught (Fig. 1). This means that many of the late-instar larvae this spray timing was targeting in 2009 had accumulated

Table 1

Control of apple clearwing moth with reduced-risk insecticides and nematodes when applied as spring post-bloom and autumn post-harvest *curative* treatments or as summer *preventative* treatments in Cawston, B.C., Canada, in 2008.

Experiment no. and replicates with treatment timings	Treatments[1]	Product rate ha^{-1}	Mean (± SE) number of pupal exuviae / tree / assessment year[2]		Percent change in exuviae counts year-to-year[3]
			2008	2009	
Exp. 1 (n = 5)	Water control	2000 L	2.43 ± 0.49 a	1.81 ± 0.29 a	– 25.5
27 May 2008	Crocker's Fish Oil	20 L	1.78 ± 0.17 a	1.61 ± 0.24 a	– 9.6
	Nematodes	105 IJs	1.17 ± 0.23 b	1.80 ± 0.34 a	+ 53.8
	Altacor	285 g	1.73 ± 0.32 a	1.05 ± 0.16 a	– 39.3
	Belt	300 mL	1.08 ± 0.13 b	0.83 ± 0.18 b	– 23.1
	Delegate	420 g	1.59 ± 0.31 a	1.57 ± 0.15 a	– 1.3
	Entrust	109 g	2.05 ± 0.43 a	1.51 ± 0.27 a	– 26.3
	Rimon	2.8 L	0.71 ± 0.13 b	0.06 ± 0.03 b	– 66.7*
Exp. 2 (n = 10)	Water control	2000 L	2.58 ± 0.32 a	2.16 ± 0.21 a	– 15.4
8, 22 July 2008	Crocker's Fish Oil	20 L	1.86 ± 0.27 a	2.14 ± 0.32 a	+ 10.5
	Altacor	285 g	2.42 ± 0.45 a	1.22 ± 0.27 b	– 50.0*
	Belt	300 mL	2.61 ± 0.37 a	0.62 ± 0.17 b	– 76.9*
	Delegate	420 g	2.27 ± 0.32 a	1.09 ± 0.11 b	– 52.2*
	Entrust	109 g	2.69 ± 0.48 a	1.35 ± 0.26 b	– 51.8*
	Rimon	2.8 L	2.78 ± 0.41 a	0.13 ± 0.05 b	– 96.4*
Exp. 3 (n = 5)	Water control	2000 L	4.13 ± 0.64 a	1.90 ± 0.41 a	– 53.9*
15 October 2008	Nematodes	10^5 IJs	2.93 ± 0.51 a	1.23 ± 0.13 a	– 58.0*
	Altacor	285 g	3.14 ± 0.64 a	1.84 ± 0.59 a	– 41.4
	Belt	300 mL	3.80 ± 0.32 a	1.20 ± 0.22 a	– 68.4*
	Delegate	420 g	3.57 ± 0.47 a	1.65 ± 0.37 a	– 53.8*
	Entrust	109 g	2.93 ± 0.38 a	2.05 ± 0.39 a	– 30.0
	Rimon	2.8 L	3.53 ± 0.24 a	0.38 ± 0.16 b	– 89.2*

[1] All treatments except nematodes were applied using a handgun and delivered in water at a rate of 2000 L ha^{-1} to each rootstock scion–graft union. All *Steinernema feltiae* nematode treatments (IJs = infective juvenile nematodes) were applied using a back sprayer and delivered in 100 ml of water.

[2] Treatment means within a column for each experiment followed by the same letter as the control group are not significantly different (Dunnett's test, $\alpha = 0.05$) following significant randomised block ANOVA ($P < 0.05$), with repeated measures in 2008 and 2009.

[3] Percentages followed by an asterisk (*) denote significant change in counts between yearly assessments based on two-tailed paired *t*-tests, $P < 0.05$.

87 DD$_{10°C}$ more than the same larval stages in 2008. Many of these late-instar larvae had probably cocooned or pupated at the time this spray was applied. This late spray timing likely explains why none of the spring 2009 treatments in Experiment 4, including Rimon, had any impact on adult emergence in summer 2009 (Table 2). Rimon is an insect-growth regulator that must be absorbed by eggs or ingested by larvae to be effective. Its primary mode of action is disruption of cuticle formation and deposition when insects change from one developmental stage to another, resulting in death at moulting. Due to this mode of action, a late-spring Rimon treatment in Experiment 4 would have no effect on insects that have cocooned, completed moulting, or pupated. However, this late-spring 2009 Rimon treatment did have an impact on emergence in 2010 (Table 2). Once

Table 2

Control of apple clearwing moth with reduced-risk insecticides when applied once as spring post-bloom curative treatments in Cawston, B.C., Canada, in 2009.

Experiment no. and replicates with treatment timings	Treatments[1]	Product rate ha^{-1}	Mean (± SE) number of pupal exuviae / tree / assessment year[2] 2009	2010	Percent change in exuviae counts year-to-year[3]
Exp. 4 (n = 4)	Water	2000 L	3.20 ± 0.97 a	3.85 ± 1.87 a	+ 20.3
2 June 2009	Oil	20 L	2.50 ± 0.57 a	3.15 ± 1.45 a	+ 26.0
	Altacor	285 g	3.50 ± 1.60 a	2.80 ± 1.28 a	– 20.0
	Belt	350 ml	2.30 ± 0.46 a	1.60 ± 0.37 a	– 30.4
	Belt plus Oil	350 ml + 20 L	2.30 ± 0.88 a	0.55 ± 0.26 b	– 76.1*
	Delegate	420 g	1.40 ± 0.32 a	2.00 ± 1.23 a	+ 42.9
	Rimon	2.8 L	2.40 ± 1.43 a	0.50 ± 0.26 b	– 79.2*
	Rimon plus Oil	2.8 L + 20 L	2.35 ± 0.79 a	0.60 ± 0.45 b	– 74.5*

[1] All treatments were applied using a handgun and delivered in water at a rate of 2000 L ha^{-1} to each rootstock scion–graft union. Oil is Purespray Green.

[2] Treatment means within a column followed by the same letter as the control group are not significantly different (Dunnett's test, $\alpha = 0.05$) following significant ($P < 0.05$) randomised block ANOVA with repeated measures in 2009 and 2010.

[3] Percentages followed by an asterisk (*) denote significant change in counts between yearly assessments based on two-tailed paired *t*-tests, $P < 0.05$.

again, the effects of Rimon that manifest in 2010 could be due to a curative or preventative action. Late-spring applications of Rimon could control populations of ACM by killing immature larvae already in the tree or by killing eggs and neonate larvae appearing on trees in summer 2009. Apparently, Altacor, Belt, and Delegate either do not penetrate tree bark sufficiently to reach immature larvae or their residual activity is significantly less than Rimon, as none of these insecticides when applied in late-spring 2009 had any effect on emergence of adults in summer 2010 (Table 2). The addition of oil to an application of Belt did appear to increase its efficacy, because the Belt *plus* Oil treatment applied in late-spring 2009 caused a significant reduction in adult emergence in summer 2010 (Table 2). The Rimon *plus* Oil treatment was no more effective than Rimon applied alone (Table 2).

Summer 2009 treatments in Experiment 5 were applied at 583 and 759 $DD_{10°C}$ after 1 January 2009, corresponding to 71% and 94% cumulative moth catch in 2009, respectively (Fig. 1). Given the grower's decision to remove this test block in autumn 2009, we were forced to assess the impact of our summer 2009 sprays before they would likely show their greatest efficacy. Sprays applied in summer likely have their greatest impact on ACM populations by killing eggs and neonate larvae before they enter the bark. On trees harvested in autumn 2009, we expected to see the greatest impact of summer 2009 sprays on a younger, smaller-size class of larvae. Rimon was the only insecticide treatment in summer 2009 that caused a significant reduction in larval counts compared with those from control trees (Table 3). Whether we compared counts of larvae found on above- or below-ground parts of trees, the effect of Rimon was greatest on the smallest larval class (Table 3). We were somewhat surprised to find ACM larvae on below-ground tree parts, as we have found no literature reference to this species being subterranean. The occurrence of subterranean larvae may be because the densities of this invasive species are much greater in the Similkameen Valley than anywhere in its natural range (Špatenka *et al.* 1999).

Nematode plus Barrier Experiments. Although effective in one spring 2008 trial (Table 1), nematodes had little impact on controlling larval populations of ACM. Efforts to improve their efficacy focused on preventing desiccation at the time of application. Spring 2009 applications of nematodes in Experiment 6 were applied at 157 $DD_{10°C}$ after 1 January 2009, three weeks before the first moths were caught (Fig. 1) and well before larvae had pupated. At this spray timing, neither the *H. bacteriophora* nor the *S. carpocapsae* nematode treatments appeared effective in suppressing the number of ACM that emerged from treated trees in 2009 (Fig. 2). These results

Table 3

Control of apple clearwing moth with reduced-risk insecticides when applied as summer *preventative* treatments in Cawston, B.C., Canada, 2009 (Exp. 5, n =5).

Treatment[1]	Product rate ha^{-1}	Mean (±SE) number of pupal exuviae / tree before harvest[2]	Mean (±SE) number of larvae in different size classes and parts of harvested trees[3]				Mean total number of larvae / tree
			0-25 cm above ground		0-25 cm below ground		
			Larva length		Larva length		
			≤9 mm	>9 mm	≤9 mm	>9 mm	
Water	2000 L	4.6 ± 1.1 a	10.2 ± 2.1 a	2.8 ± 0.5 a	1.5 ± 0.5 a	0.4 ± 0.2 a	14.9 ± 2.5 a
Oil	20 L	4.5 ± 1.2 a	9.7 ± 1.7 a	4.5 ± 0.9 a	1.4 ± 0.4 a	0.8 ± 0.4 a	16.4 ± 1.6 a
Altacor	285 g	4.0 ± 0.9 a	5.2 ± 0.9 a	3.0 ± 0.6 a	1.9 ± 0.7 a	1.1 ± 0.5 a	11.2 ± 1.6 a
Belt	300 mL	5.9 ± 1.2 a	5.5 ± 1.8 a	3.9 ± 1.2 a	2.8 ± 1.4 a	1.1 ± 0.3 a	12.5 ± 3.1 a
Delegate	420 g	4.6 ± 0.4 a	5.0 ± 1.0 a	3.9 ± 0.9 a	0.4 ± 0.4 a	0.7 ± 0.3 a	10.0 ± 1.7 a
Entrust	109 g	4.2 ± 0.6 a	9.4 ± 2.1 a	3.9 ± 0.9 a	0.3 ± 0.2 a	0.4 ± 0.3 a	13.8 ± 2.6 a
Rimon	2.8 L	4.5 ± 1.5 a	2.9 ± 0.9 b	1.0 ± 0.3 b	0.0 ± 0.0 b	0.0 ± 0.0 a	4.0 ± 1.1 b

[1] All treatments were applied on 2 July and again on 16 July 2009 using a handgun and delivered in water at a rate of 2000 L ha^{-1} to each rootstock scion–graft union.

[2] Mean pupal exuviae counts within this column were not significantly different by randomised block ANOVA ($F_{6,24} = 0.326$, $P = 0.918$).

[3] Treatment means within a column followed by the same letter as the control group are not significantly different (Dunnett's test, $\alpha = 0.05$) following significant randomised block ANOVAs ($P < 0.05$). Two trees were harvested from each treatment replicate on 15 October 2009.

could be due, in part, to a low number of IJ nematodes in each of these commercial nematode products: there were large numbers of dead nematodes in both suspended products.

The efficacy of commercial nematode treatments applied in spring 2009 was not impacted by wrapping tree trunks in wet cardboard (CBW) for one week after nematode application (Fig. 2), but was improved by the SDW that remained in place from May to August. Trees receiving the SDW had significantly less ACM emergence than UW or CBW trees ($F_{2,429} = 39.7$; $P < 0.0001$). The effect of the SDW appears independent of the nematode treatment because significantly fewer pupal exuviae were found on water-treated control trees receiving the SDW than on water-treated trees that received no wrap (see UW, Fig. 2). Although the SDW deteriorated over time, especially on trees hit by irrigation water, much remained in August and a significant inverse correlation existed between the percentage of the sawdust barrier remaining at the end of the adult emergence period and the number of pupal exuviae on each tree (n = 192; r = -0.34, $P < 0.0001$). It is important to note that any impact the SDW might have had on oviposition during summer 2009 would not have contributed to the smaller number of pupal exuviae counted in autumn 2009, because pupae arising from 2009 eggs would not appear until 2010 at the earliest.

The August 2009 application of nematodes with and without SDW in Experiment 7 was made at 1303 $DD_{10^\circ C}$ after 1 January 2009, at least one week after the last moths were caught in 2009 (Fig. 1). The SDW, which remained in place from 26 August 2009 to 18 May 2010, was removed well before moths emerged in 2010 (Fig. 1). August 2009 nematode treatments without SDW appeared to have no effect on the emergence of ACM in summer 2010 (Fig. 3), whereas the number of ACM emerging from trees that received nematodes with SDW was significantly lower ($F_{1,285} = 25.31$; $P < 0.0001$) than the number emerging from trees left unwrapped over the winter months (Fig. 3). Again, a significant inverse correlation was found between the percentage of the

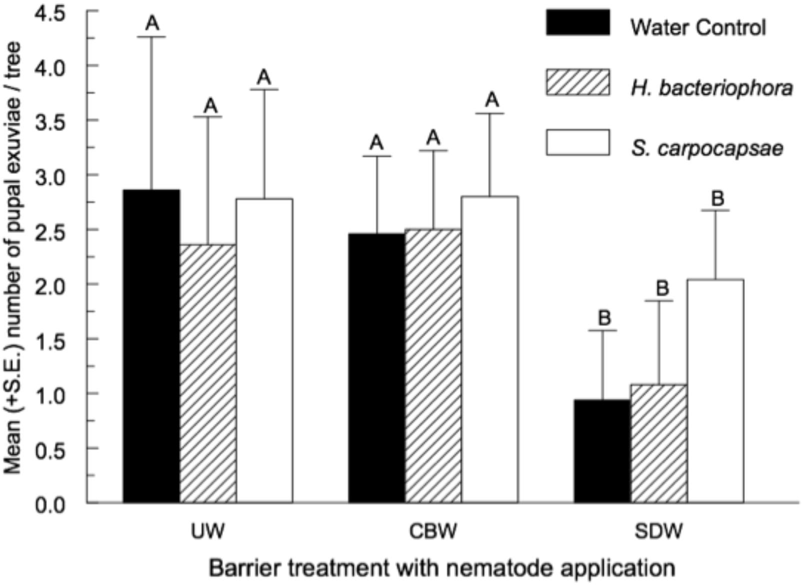

Figure 2. Mean numbers of ACM pupal exuviae recovered from tree trunks on 11 August 2009 after applying water or two nematode treatments, *Heterorhabditis bacteriophora* and *Steinernema carpocapsae*, on 21 May 2009 and left unwrapped (UW), wrapped with cardboard (CBW) for one week, or wrapped with a sawdust mixture (SDW) from 21 May 2009 to 11 August 2009 after application. A significant ($F_{2,\ 429} = 39.7$; $P < 0.0001$) difference between barrier treatments is indicated by different letter superscripts above bars. There were no significant treatment effects within each barrier treatment ($P > 0.05$).

SDW that remained in May—before ACM emergence had begun (Fig. 1)—and the number of pupal exuviae recovered from each tree in late summer 2010 (n = 192, r = -0.24, $P = 0.0006$).

Although the ANOVA indicated that nematode treatments applied in autumn 2009 did not have a significant ($F_{2,\ 285} = 0.52$; $P = 0.5949$) independent impact on the number of ACM emerging in 2010, there was a significant wrap × treatment interaction ($F_{2,\ 285} = 4.98$; $P = 0.0075$) that affected the number ACM that emerged. When the data were partitioned and only those trees receiving SDW were compared, treatment with both nematode species was found to significantly ($F_{2,\ 142} = 5.39$; $P = 0.0056$) lower the number of ACM that emerged compared to the control group (Fig. 3). This result is promising and should be followed up, as it suggests nematodes applied in autumn could be efficacious if combined with the correct physical barrier. The temperature maximum on the day nematodes were applied in August 2009 was higher than the maximum in spring 2009; this may have increased the ability of both nematode species to find and infect hosts in the August study (Fig. 3). It also seems possible that the SDW increases survival of nematodes and/or affects movement of ACM larvae in their feeding tunnels, both of which may increase the efficacy of entomopathogenic nematodes.

ACM is becoming a pest of increasing importance to the B.C. apple industry, especially as the industry becomes economically dependent on replanting new varieties on dwarfing root stocks using high-density planting systems with relatively short rotation times. Our studies suggest conventional apple producers have more options for managing ACM than organic producers as this invasive pest spreads through B.C. (Cossentine *et al.* 2103). Rimon 10 EC appears to be an effective control product for ACM, and its mode of action appears to provide apple producers with varied and flexible spray timing. Spring or autumn applications outside the fruiting season may be the best times to apply Rimon, because these likely have the least impact on beneficial organisms. There are some unpublished reports that Rimon can lead to mite outbreaks if used during the summer months. The most interesting aspect about using Rimon outside the fruiting season is that,

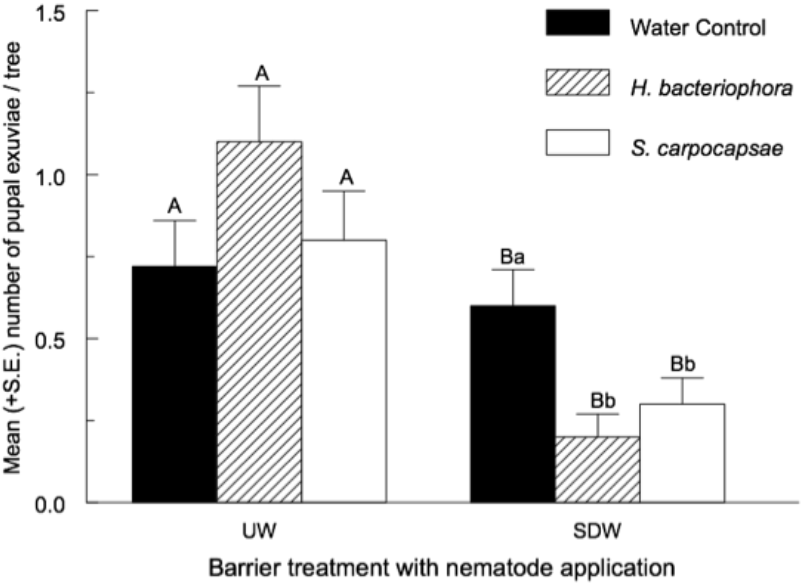

Figure 3. Mean numbers of ACM pupal exuviae recovered from tree trunks on 29 September 2010, after applying water or two nematode treatments, *Heterorhabditis bacteriophora* and *Steinernema carpocapsae*, on 26 August 2009 and left unwrapped (UW) or wrapped with a sawdust mixture (SDW) from 26 August 2009 to 18 May 2010 after application. Bars above each barrier treatment label having different uppercase letter superscripts are significantly different ($F_{1, 285}$ = 25.31; $P < 0.0001$), and bars within the SDW barrier treatment with lower-case letter superscripts are significantly different (Tukey's HSD test $\alpha = 0.05$).

when used at these times, it appears to be curative in action and effective against cohorts from two seasons.

Several other insecticides show promise for control of ACM when applied as preventative sprays in summer; some of these are already registered on apples in Canada (Altacor and Delegate). Summer sprays may even be more efficacious when more is known about the seasonal phenology of female ACM and their oviposition patterns in relation to temperature summations. It should be noted that the efficacy of Rimon and other insecticides described in these trials is based on tree-trunk sprays using a handgun with high pressure and high volumes of water. This application method makes sense while infestations of ACM remain restricted to the rootstock graft-union regions of apple trees. Similar results cannot necessarily be expected when ACM infests other parts of the tree or when insecticides are applied as dilute or low-volume sprays typical of air-blast spray techniques used against leafrollers or codling moth (British Columbia Ministry of Agriculture 2010). Recent observations in the Similkameen Valley, where populations of ACM are most extreme (Cossentine *et al.* 2013), have revealed that the pest is beginning to infest limbs higher in the tree, top-grafted scion–tree-trunk unions, and is even entering and killing pruned tree leaders as producers attempt to manage tree height (GJ personal observations). More research will be needed to determine if ACM can be controlled effectively with any insecticides when applied using an air-blast sprayer to these aerial tree limbs.

Our screening trials did not reveal many effective organic options for controlling ACM. Oils and Entrust have become mainstays of integrated pest management for organic apple production in B.C. (British Columbia Ministry of Agriculture 2010), but when used as described herein, these materials had limited impact on infestations of ACM (Tables 1, 3). Some organic apple producers have resorted to applying as many as six trunk sprays of Entrust annually for suppression of ACM (GJ personal observation). This approach is likely uneconomical and unsustainable in the long term, because a lack of alternative insecticides with which to rotate use of Entrust means resistance may develop, not to mention, the many adverse effects Entrust has on important parasitoids (Williams *et al.* 2003) and predators like lacewings and European earwigs (Mandour 2009; Shaw 2010).

The general ineffectiveness of nematodes in the absence of barriers is disappointing because this would seem to be an excellent organic approach. More research is needed to determine if there are conditions under which nematodes could be made more efficacious. Suboptimal application temperatures and desiccation in dry environments may make nematodes impractical for use in the interior of B.C., but infestations in wetter, cooler coastal areas (Cossentine *et al.* 2013) may be controlled by nematodes.

Although we did not set out to test the efficacy of physical barriers as a method to control ACM, their use in combination with nematodes did lead to some interesting observations. The SDW appeared to be particularly effective at reducing emergence of ACM, especially when applied in spring (Fig. 2). Other studies have found that physical barriers can significantly reduce infestations of *Synanthedon* species. Ateyyat and Al-Antary (2006) found that mounding soil over apple rootstock-scion graft unions or wrapping tree trunks in cheese cloth prevented subsequent adult emergence. Kain *et al.* (2010) used polyethylene fabric, veterinary gauze, and sprays of ethylene vinyl acetate to prevent dogwood-borer infestations. The reduction in emergence of ACM from trees receiving a SDW in spring was not the result of any oviposition-deterring effect, because the emergent adults were already larvae within the trees before the barrier was applied. It is possible some pre-pupal ACM larvae were deterred from chewing through the SDW, but some pupae did successfully exit through the SDW. In an unpublished laboratory study (JC personal observation), the presence of a SDW for seven weeks did not significantly reduce emergence of ACM adults from infested tree trunks that had been harvested and wrapped compared with those that had not been wrapped. It is possible that the SDW modified larval development time. If SDW insulated tree trunks, it may have delayed ACM development to the point where we may not have seen emergence during a single test season. Unfortunately, the same trees were not re-examined the following year to test this hypothesis.

In conclusion, if infestations of ACM remain restricted to the graft-union areas of dwarfing apples trees, then our research suggests use of physical barriers for control of ACM populations in organic orchards warrants further study. A better understanding of the barriers' mode of action, either as oviposition deterrents or as physical deterrents to larval development and pupal formation or exit from trees, should be sought. With ACM now infesting multiple locations on apple trees, particularly pruned apical stems (GJ personal observations), use of physical barriers and even tree-trunk sprays of Rimon may be limited to situations where populations have not grown to high levels and are restricted to rootstock graft unions. It seems clear from this study that a search for alternative organic methods of controlling ACM is warranted.

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