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Integrated Pest Management Programs for Pear Psylla, *Cacopsylla pyricola* (Förster) (Hemiptera: Psyllidae), Using Kaolin Clay and Reflective Plastic Mulch

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Abstract

Pear psylla, *Cacopsylla pyricola* (Förster) (Hemiptera: Psyllidae), is the most economically important pest of pears grown in Washington State. Standard conventional management programs involve season-long broad-spectrum insecticide sprays. Although the industry uses some tools that are not disruptive to biological control, such as kaolin clay and selective insecticides, they are additions to broad-spectrum insecticides instead of replacements. Conventional sprays suppress pear psylla through the spring and early summer; however, disruption of biological control leads to pear psylla outbreaks near harvest. In 2018 and 2019, we tested two season-long programs that used only selective approaches. The programs began with either kaolin clay or reflective plastic mulch and were followed by identical spray programs using only selective insecticides. Programs were compared with an industry standard conventional program that used numerous broad-spectrum insecticides throughout the season, and a check program with no insecticides for pear psylla. Experiments were conducted using replicated 40-tree plots in a research orchard near Wenatchee, WA with high pear psylla pressure. In both years, selective programs had similar pear psylla densities to the industry standard program and all had lower pear psylla densities and fruit injury than the check. Both selective programs had lower fruit injury than the industry standard in the first year, and similar injury to the industry standard in the second year. Our results suggest kaolin clay and reflective mulch can effectively suppress pear psylla populations and injury in the early season and support season-long selective management programs without the use of broad-spectrum insecticides.

Key words: *Cacopsylla pyricola*, pear psylla, reflective plastic mulch, kaolin, selective

Pear psylla, *Cacopsylla pyricola* (Förster) (Hemiptera: Psyllidae), has been the primary economic pest of pears grown in Washington, the top pear producing state in the United States, since the 1940s (Smith 1940, Burts 1976, Riedl et al. 1981, DuPont et al. 2021). Nymphs feed on phloem and excrete large amounts of honeydew, which drips onto fruit and causes superficial marking and growth of sooty mold (Burts 1970, Murray et al. 2021). High pear psylla pressure can lead to 'psylla shock,' a condition in which excessive nymph feeding and honeydew production causes leaf abortion, stunted growth, and yield loss (Burts 1970). Pear psylla overwinter as adults (winterforms) on various plant hosts, within and outside pear orchards. In late winter or early spring as trees break dormancy, migrant winterforms recolonize orchards to mate and begin laying eggs on developing fruiting buds (Fye 1983). First generation nymphs develop on flowers and leaves around young fruit (Horton 1999). The proximity of the first immature generation to developing fruit is thought to give them greater injury potential than summer nymphs, which survive on vegetative shoots (Burts 1983). Therefore, 'early season' (from dormant to petal fall) management is considered a critical time to achieve pear psylla suppression.

Growers generally use multiple broad-spectrum insecticide sprays to prevent early season injury and limit densities of the summer generations (Burts 1983, Beers et al. 1993, Murray and DeFrancesco 2014, Murray et al. 2020). Early season sprays are more effective than summer sprays for immediate pest population reductions due to compromised spray penetration through denser summer foliage (Westigard et al. 1986). Predatory and parasitic arthropods (natural enemies) are also in lower abundance in the early season, so biological control is less reliable than in the summer (Beers et al. 1993). However, as spray effectiveness decreases, biological control becomes critical for the suppression of pear psylla (Madsen and Wong 1964, Burts 1983, Westigard et al. 1986, Booth 1992, Edwards 1993, DuPont et al. 2021). Unfortunately, the multitude and frequency of broad-spectrum sprays through the spring and early summer disrupt the potential for biological control, leading to pear psylla outbreaks near harvest (DuPont et al. 2021). In the growing regions of central Washington, early season pear psylla pressure is high nearly every year, so psylla management from dormant through petal fall usually involves three to four applications of tank-mixed broad-spectrum insecticides (Dupont et al. 2021). Selective materials like mineral oil, insect growth regulators, and kaolin clay can suppress psylla with lower impacts to natural enemies (Madsen and Williams 1967, Burts 1983, Alway 2001, Glenn et al. 1999, DuPont and Strohm 2020, DuPont et al. 2021), but these tools are commonly used in addition to broad-spectrum sprays instead of as substitutes, negating their potential to conserve biological control (Dupont et al. 2021). Research suggests that the optimal approach for season-long pear psylla management involves using selective techniques only to suppress pear psylla below injury thresholds through the early season while conserving natural enemies for the summer (Burts 1983, Westigard et al. 1986, DuPont et al. 2021). However, industry practitioners currently lack confidence that selective tools can suppress pear psylla without supplemental broad-spectrum insecticides (Beers 2014, Murray et al. 2020).

Two selective approaches, kaolin clay sprays (herein: 'kaolin') and reflective polyethylene ground covers (herein: 'reflective mulch'), were the focus of this study due to their demonstrated potential for early season pear psylla management (Glenn et al. 1999, Puterka et al. 2005, Nottingham and Beers 2020). Kaolin has been used commercially for pear psylla management since the early 2000s, whereas reflective mulch has not been widely adopted in commercial pear orchards. Kaolin is a 'particle film', a wettable powder that is sprayed on trees leaving a white particulate residue (Glenn and Puterka 2005). Kaolin residues primarily deter pear psylla adults from landing and laying eggs on trees and, to a lesser extent, reduce the survivability of nymphs (Glenn et al. 1999, Puterka et al. 2005). Washington pear growers commonly use one or two kaolin sprays before bloom in conjunction with broad-spectrum insecticides such as malathion, chlorpyrifos (before deregistration), lambda-cyhalothrin, tolfenpyrad, acetamiprid, or novaluron (DuPont et al. 2021, Murray et al. 2021). Reflective mulch is metalized (aluminum infused) polyethylene sheets laid beneath trees to reflect light back into the canopy. Reflected light is known to disrupt insects' host finding behavior and create an unfavorable environment due to increased ultraviolet light (Shimoda and Honda 2013), which has led to its occasional use in agriculture for pest management. Nottingham and Beers (2020) demonstrated that reflective mulch significantly reduced pear psylla winterform adults from colonizing orchards and laying eggs in proof-of-concept experiments using replicated single-tree plots. In addition to insect disruption, reflective mulch has other horticultural and pest management benefits including increased fruit production (Bertelsen 2005, Einhorn et al. 2012), weed suppression (Croxton and Stansly 2014), and improvements to soil moisture and temperature (Nottingham and Beers 2020). Although empirical studies have demonstrated that kaolin and reflective mulch can suppress pear psylla, none have examined them as components of season-long pear integrated pest management (IPM) programs. Therefore, pest management decision makers are lacking specific details for implementation; particularly, whether these tools can stand alone without supplemental broad-spectrum insecticides.

The goal of this study was to determine if kaolin and reflective mulch can serve as early season components to season-long pear psylla IPM programs that avoid broad-spectrum insecticides. The broader goal was to challenge the presumption that selective tools, in general, cannot suppress pear psylla effectively without supplemental broad-spectrum insecticides. We evaluated two season-long IPM programs, one using kaolin and the other reflective mulch during the early season (dormant to petal fall), followed by full season programs that excluded broad-spectrum insecticides. These IPM programs were compared with a standard conventional program using broad spectrum insecticides (herein, 'industry standard') and a 'check' program using no insecticides targeting pear psylla. The selective insecticides used after petal fall were shown to be compatible with pear psylla biological control in past studies by Alway (2001), DuPont and Strohm (2020), and DuPont et al. (2021). Transitioning to selective spray programs instead of continuing with kaolin or reflective mulch was due to the following factors: kaolin is less effective in the summer due to reduced spray coverage (L. Nottingham unpublished) and it can be disruptive to biological control if used too frequently (Knight et al. 2001, Tacoli et al. 2019). Reflective mulch also loses efficacy following petal fall, likely due to shading by trees (Nottingham and Beers 2020). We hypothesized that kaolin and reflective mulch IPM programs would provide similar or improved suppression of pear psylla across the entire season compared with the industry standard program. We discuss outcomes of pear psylla population densities, injury, and natural enemies, as well as implications for pest management.

Methods

Experiments were conducted in 2018 and 2019 in a pear orchard at Washington State University's Sunrise Research Orchard (47°18′31.6″N 120°03′51.5″W) near Rock Island, WA. Experimental plots were established within a 1.5 ha (4 acre) block of d'Anjou and Bartlett pears planted in 2007. Sixteen plots were established. Each plot (hereafter called 'main plot') was 0.08 ha (0.2 acre) and consisted of 4 rows × 10 trees (40 trees total). Main plots consisted of two rows of Bartlett and two of d'Anjou trees (Fig. 1) which were sampled separately (hereafter called 'cultivar subplots'). Main plots were separated from each other by at least two untreated trees within and between rows (Fig. 1).

Four treatment programs were tested in 2018 and 2019. Products and rates used are specified in Table 1, treatment programs in Tables 2 and 3, and sprays applied to the whole orchard for codling moth and mites as well as fungicides and herbicide sprays in Table 4. Programs were: (1) industry standard, a full-season conventional spray program reflecting commercial management programs in central Washington; (2) kaolin, two prebloom kaolin clay (Surround CF, NovaSource, Phoenix, AZ) sprays followed by selective sprays after petal fall; (3) reflective mulch, sheets of 1.2 m wide × 30.3 m long × 1 mil (0.0254 mm) thick polyethylene film with aluminum-infused top layer and black bottom layer (Star Metallizing Escondido, CA) laid over herbicide strips on both sides of experimental trees before bloom, followed by selective sprays after petal fall (Fig. 2); and (4) check, limited to sprays used across the entire orchard for basic maintenance. The entire orchard (including all study plots) received standard management practices for nutrients and suppression of weeds, diseases, codling moth, mealybug, and pest mites (Table 4). Additionally, the entire orchard

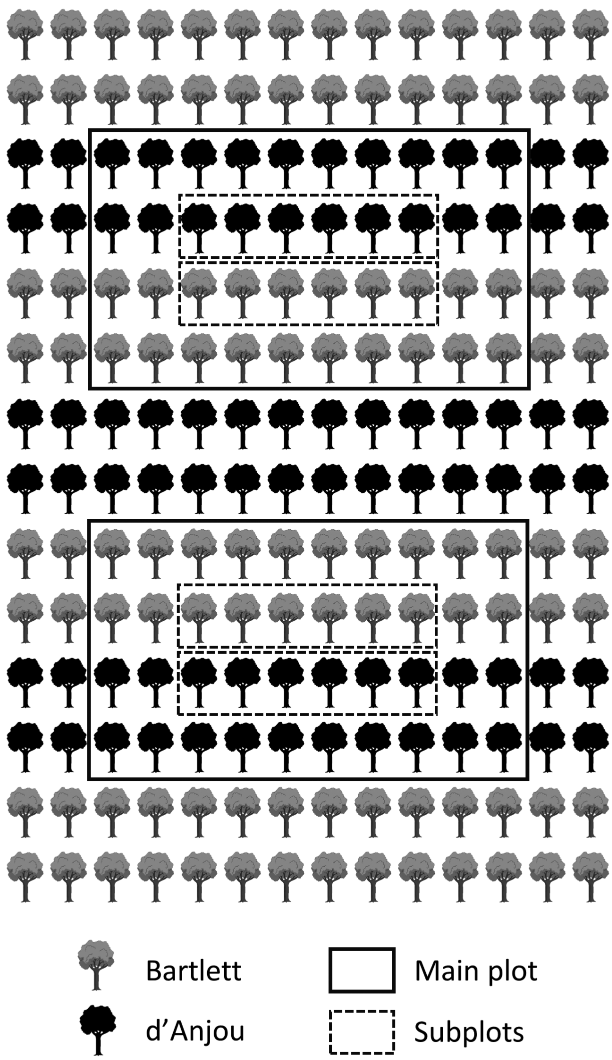

Fig. 1. Experimental plot diagram demonstrating two main plots (of 16 total across the experiment) and four cultivar subplots. Each main plot consisted of 40 trees total, with 20 d'Anjou and 20 Bartlett trees in two rows each. There were 16 main plots (four treatments × four replicates), with 32 subplots. Separate samples were performed on each subplot.

received one to three selective sprays for pear psylla to suppress densities below levels that could harm untreated trees (i.e., psylla shock), which only occurs when densities are very high. This included two summer sprays of azadirachtin in 2018 and one spring spray of kaolin in 2019 specifically. At least one prebloom kaolin spray is standard in all conventional and organic orchards, so the addition of kaolin in the whole orchard in 2019 increased the relevance of the study to commercial orchards.

Light Measurements

Because spray residues from kaolin or other materials could inhibit the reflectivity of reflective mulch, we measured photosynthetic active radiation (PAR) intensity (SQ-110 pyranometer, Apogee Instruments, Logan, UT) in reflective mulch and check plots. Sensors were attached to metal stake 1.0 m above the ground and facing down. Stakes were driven into the ground within tree rows halfway between two trees. Pyranometers were deployed in the field from 17 April through 3 May 2019 when mulch was removed, taking light intensity readings every five minutes.

Insect Sampling

Pest and beneficial insects were sampled via beat trays, fruiting bud examination, leaf brushing, yellow sticky cards, and corrugated cardboard earwig shelters following VanBuskirk et al. (1999) and Nottingham and Beers (2020). Beat tray counts were performed the entire season to sample adult pear psylla and natural enemies: *Deraeocoris brevis* (Hemiptera: Miridae), *Trechnites insidiosus* (Hymenoptera: Encyrtidae), lady beetles (Coleoptera: Coccinellidae), anthocorids (Hemiptera: Anthocoridae), and spiders (Arachnida: Araneae). Beat tray samples involved using a hard rubber hose to make three consecutive strikes to a horizontal tree limb, dislodging arthropods onto a 45 × 45 cm white cloth tray held ca. 18 cm underneath the limb (VanBuskirk et al. 1999). Following three strikes, all arthropods on the sheet were visually counted to gain a composite sample referred to as one 'tray.' Five trays were taken in each cultivar subplot on all sample dates. A pretreatment beat tray sample was conducted each year, before installation of reflective mulch and first spray treatments. Natural enemies were analyzed by species or groups occurring in significant densities. We also calculated and analyzed all natural enemies into a single value (labeled as 'combined' in Tables 6 and 7), which included less common species that were not analyzed separately.

Before petal fall (March through early May), psylla eggs and nymphs were sampled by collecting five fruiting buds per cultivar subplot and returning them to the lab for evaluation under a stereoscope. Following petal fall (early May through late August or early September), pear psylla eggs and nymphs were sampled by collecting 25 leaves from each cultivar subplot for leaf brushing. A leaf-brushing machine (Leedom Mfg., Mi-Wuk Village, CA) was used to dislodge arthropods from leaves onto a revolving glass plate, where the composite sample was counted under a stereoscope (VanBuskirk et al. 1999, DuPont et al. 2021). Pear psylla nymphs were separated into two categories: young (instars 1–3) and old (instars 4 and 5). Other arthropods counted included parasitized psylla nymphs ('mummies'; likely *Trechnites insidiosus*), twospotted spider mites (*Tetranychus urticae* [Acari: Tetranychidae]), pear rust mites (*Epitrimerus pyri* [Acari: Eriophyidae]), and predatory mites (Acari) in the family Phytoseiidae were also counted. *Galendromus occidentalis* (Acari: Phytoseiidae) is thought to be the primary phytoseiid mite in Washington pears, but species ID was not confirmed in this study. Yellow sticky cards (10 × 12.5 cm, Alpha Scents, Inc., West Linn, OR) were used after petal fall as an additional method to sample pear psylla adults, *T. insidiosus* adults, and *D. brevis* adults. One card was hung in a center tree of each cultivar subplot, and collected ca. every 14 d. European earwigs (*Forficula auricularia* [Dermaptera: Forficulidae]), generalist predators known to feed on pear psylla (Unruh et al. 2008), were sampled via rolled cardboard traps (11 × 35 cm) secured to tree trunks ca. 0.5 m above the ground (Orpet et al. 2019, Nottingham and Beers 2020). Earwigs were shaken out of traps and counted in the field ca. every 14 d.

Fruit Injury

Fruit injury was assessed once per year within the commercial harvesting time frame for both Bartlett and d'Anjou, on 20 August 2018 and 26 August 2019. Ten fruits per cultivar subplot were visually assessed for amount of surface area with pear psylla injury, defined as black markings or brown russeting. Injury measurements were scored on an ordinal rating scale (1 = 0 to 1%, 2 = 1 to 5%, 3 = 5 to 20%, 4 = 20 to 40%, 5 = >40%). Ratings of 1 through 3 reflect commercial grading (1 = highest quality, no psylla injury, 'US 1'; 2 = lower quality due to slight psylla injury, 'downgrade'; 3 =

Table 1. Spray product information and rates: product name, active ingredient, concentration (a.i./liter [H_2O]), and amount of formulated product per unit area. All sprays volumes were 946.3 liter/ha (100 gal/acre)

Product	Active Ingredient (a.i.)	Concentration (a.i./liter [H_2O])	Product/ha.	Product/acre
Actara 25WDG	Thiamethoxam	103.0 mg	0.390 kg	5.5 oz
Altacor	Chlorantraniliprole	118.0 mg	0.320 kg	4.5 oz
Assail 70WP	Acetamiprid	178.3 mg	0.241 kg	3.4 oz
Aza-Direct 1.2L	Azadirachtin	44.36 mg	2.360 liter	32 fl oz
Bexar 1.34L	Tolfenpyrad	338.7 mg	1.996 liter	27 fl oz
Celite 610	Diatomaceous Earth	47.94 g	45.36 kg	40 lb
Centaur 70WDG	Buprofezin	1.809 g	2.445 kg	34.5 oz
Cinnerate	Cinnamon Oil	(60%)	2.957 liter	40 fl oz
Delegate 25WG	Spinetoram	131.1 mg	0.496 kg	7 oz
Dimilin 2L	Diflubenzuron	898.8 mg	3.548 liter	48 fl oz
Esteem 35 WP	Pyriproxyfen	131.1 mg	0.354 kg	5 oz
FujiMite 5XLO	Fenpyroximate	119.8 mg	2.365 liter	32 fl oz
IAP 440 (Oil)[1]	Mineral Oil	(100%)	2.366 liter	120 fl oz
Malathion	Malathion	1.498 g	2.365 liter	32 fl oz
Neemix 4.5L	Azadirachtin	58.42 mg	0.888 liter	12 fl oz
Rimon 0.83EC	Novaluron	248.7 mg	2.365 liter	32 fl oz
Surround CF/WP	Kaolin Clay	59.92 g	56.70 kg	50 lb
Ultor 1.25L	Spirotetramat	163.8 mg	1.035 liter	14 fl oz

Table 2. 2018 insecticide and miticide materials by date in industry standard, kaolin, reflective mulch, and check treatment programs

Season	Date	Industry Standard	Kaolin	Reflective Mulch	Check
Pre-petal fall	16 Mar.	Surround CF Oil 4% Malathion	Surround CF Oil 0.5%	–	–
	20 Mar.	–	–	Refl. mulch installed	–
	12 April	Oil 0.5% Assail Rimon	Oil 0.5% Surround CF	–	–
Post-petal fall	2 May	Oil0.5% Actara Rimon	–	Refl. mulch removed	–
	21 May	Oil 0.5% Ultor Rimon	Oil 0.5% Surround WP –	Oil 0.5% Surround WP –	–
	30 May	Oil 0.5% Delegate	Oil 0.5% Surround WP Aza-Direct Esteem	Oil 0.5% Surround WP Aza-Direct Esteem	–
	6 June	–	Oil 0.5% Centaur Aza-Direct	Oil 0.5% Centaur Aza-Direct	–
	18 June	–	Oil 0.5% Dimilin Aza-Direct	Oil 0.5% Dimilin Aza-Direct	–
	8 July	Oil 0.5% Delegate Assail	Oil 0.5% Aza-Direct	Oil 0.5% Aza-Direct	–
	20 July	Oil 0.5% Aza-Direct	Oil 0.5% Aza-Direct	Oil 0.5% Aza-Direct	Oil 0.5% Aza-Direct
	10 Aug.	Oil 0.5% Aza-Direct Altacor	Oil 0.5% Aza-Direct Altacor	Oil 0.5% Aza-Direct Altacor	Oil 0.5% Aza-Direct Altacor
	29 Aug.	Oil 0.5% Altacor	Oil 0.5% Altacor	Oil 0.5% Altacor	Oil 0.5% Altacor

unmarketable due to significant injury, 'cull'). We included ranking categories of 4 and 5 to add greater detail about psylla levels, past the cut-off for culls. Individual fruit rankings were averaged for each subplot; subplot average values were used for statistical analysis.

Statistical Analysis

Statistical analyses were performed in SAS 9.4 (SAS 2021a). Measurements of insect density and fruit injury averages in each cultivar subplot by sample date were response variables. The most

Table 3. 2019 insecticide and miticide materials by date in industry standard, kaolin, reflective mulch, and check treatment programs

Season	Date	Industry Standard	Kaolin	Reflective Mulch	Check
Pre-petal fall	2 April	–	–	Refl. mulch installed	–
	5 April	Oil 4% Malathion	Oil 0.5% Surround CF	–	–
	11 April	Surround CF	Surround CF	Surround CF	Surround CF
	15 April	Oil 0.5% Assail Bexar Rimon	Oil 0.5% Surround CF	–	–
Post-petal fall	2 May	–	–	Refl. mulch removed	–
	16 May	DelegateOil 0.5% Actara Rimon Ultor	Oil 0.5% Surround WP Cinnerate	Oil 0.5% Surround WP Cinnerate	–
	30 May	Oil 0.5% Delegate	Oil 0.5% Surround WP Aza-Direct Esteem	Oil 0.5% Surround WP Aza-Direct Esteem	–
	6 June	Oil 0.5% Celite Delegate FujiMite	Oil 0.5% Celite Cinnerate Neemix	Oil 0.5% Celite Cinnerate Neemix	–
	21 June	Oil 0.5% Assail	Oil 0.5% Celite Cinnerate Neemix	Oil 0.5% Celite Cinnerate Neemix	–
	2 July	Oil 0.5% Esteem	Oil 0.5% Esteem	Oil 0.5% Esteem	Oil 0.5% Esteem
	10 July	Oil 1% Cyd-X Intrepid	Oil 1% Cyd-X Intrepid	Oil 1% Cyd-X Intrepid	Oil 1% Cyd-X Intrepid
	26 July	Oil 0.5% Delegate	Oil 0.5%	Oil 0.5%	Oil 0.5%
	20 Aug.	Oil 0.5%	Oil 0.5%	Oil 0.5%	Oil 0.5%
	4 Sept.	Oil 1% Altacor	Oil 1% Altacor	Oil 1% Altacor	Oil 1% Altacor

appropriate distribution was selected for each response variable (Gaussian, Poisson, negative bionomical, or log-normal) based on random spread in residual/predicted plots, linear pattern in residual/quantile plots, and low AICc values. For insect and mite density comparisons, seasons were broken into two sections: pre-petal fall and post-petal fall. Repeated measures were performed using the Glimmix procedure to compare effects on each insect group and sampling method over time. Fixed variables were management program, date, and their interaction. Cultivar was initially included as a fixed effect, but it did not significantly affect any response variable in either year, so it was removed from all models. Autoregressive AR(1) repeated structure occurred on subplots nested within main plots (SAS 2021b). Fruit injury differences among management programs were analyzed using generalized linear mixed models in Glimmix for each year. For all analyses, treatment separation was determined by Tukey's HSD, differences accepted when $P < 0.05$.

Results

Light Measurements

In 2019, average mid-day reflected PAR was 514.9 μmol/m²s (±31 SEM) in reflective mulch plots and 145.1 μmol/m²s (±5.9 SEM) in check plots.

Insect Sampling, Pre-Petal Fall

In 2018 and 2019, there were no significant differences among treatments in pretreatment beat tray samples of pear psylla adults (Table 5). Following initiation of treatments, one generation of pear psylla eggs and young nymphs developed before petal fall; old nymphs were not found until after petal fall. For both years, there was a significant effect of treatment on pre-petal fall averages of pear psylla adults, eggs, and young nymphs (Table 5, Figs. 3 and 4A–C). Kaolin, reflective mulch, and industry standard treatments had similar reductions in psylla life-stages relative to the check, except in 2018 when reflective mulch young nymph counts were similar to the check (Fig. 3C), and in 2019 when the industry standard treatment had similar egg numbers as the check (Fig. 4B). Too few natural enemies of any group were collected before petal fall in either year to make meaningful comparisons.

Insect Sampling, Post-Petal Fall

Two post-petal fall generations of pear psylla immatures occurred based on egg and nymph density peaks in 2018 (Fig. 3E–G). In 2019, only one summer generation was clearly seen (Fig. 4E–G).

In both years, significant treatment effects occurred for post-petal fall densities of all pear psylla life-stages, except eggs in 2019 (Table 5). In 2018, industry standard, kaolin, and reflective mulch treatments had lower pear psylla densities than the

Table 4. Sprays made across all orchard trees, including industry standard, kaolin, reflective mulch, and check plots in 2018 and 2019; spray volumes were 946.3 liter/ha (100 gal/acre)

Year	Date	Chemical (Purpose)
2018	07 Mar.	Oxyfluorfen (weeds)
	16 Mar.	Copper, zinc, *Aureobasidium pullulans* (fire blight)
	17 April	Copper, *Bacillus subtilis* (fire blight)
	24 April	Copper, *Bacillus subtilis* (fire blight)
	27 April	Oxytetracycline,kasugamycin (fire blight)
	02 May	Magnesium (nutrition)
	07 May	Magnesium (nutrition); oxytetracycline,kasugamycin (fire blight)
	15 May	Methoxyfenozide (codling moth)
	30 May	Methoxyfenozide, 440 mineral oil (codling moth); spirodiclofen (mites); zinc,penthiopyrad (fire blight and fungal diseases)
	05 July	Cyantraniliprole,440 mineral oil (codling moth)
	20 July	Cyantraniliprole,440 mineral oil (codling moth);buprofezin (mealybug)
	10 Aug.	Chlorantraniliprole,440 mineral oil (codling moth)
	29 Aug.	Chlorantraniliprole,440 mineral oil (codling moth)
	08 Nov.	Indaziflam,glyphosate (weeds)
2019	28 Mar.	Oxyfluorfen,glyphosate (weeds)
	11 April	Fenbutatin-oxide (mites); copper (fire blight)
	22 April	Zinc,boron (nutrition); streptomycin (fire blight)
	24 April	Copper, *Bacillus subtilis* (fire blight)
	30 April	Oxytetracycline,kasugamycin (fire blight)
	13 May	Oxytetracycline (fire blight); chlorantraniliprole (codling moth)
	29 May	Zinc (nutrition); fluopyram (fungal diseases); chlorantraniliprole,440 mineral oil (codling moth)
	02 July	Bifenazate (mites)
	10 July	Codling moth granulovirus, methoxyfenozide, 440 mineral oil (codling moth)
	08 Aug.	Pyraflufen-ethyl,glufosinate-ammonium (weeds)
	20 Aug.	Potassium (nutrition)
	04 Sept.	Mineral oil,chlorantraniliprole (codling moth)

Fig. 2. Photo of one reflective mulch plot. The two left rows are Bartlett, the two right rows are d'Anjou.

check program for all pear psylla life-stages (Table 5, Fig. 3D–G). Industry standard, kaolin, and reflective mulch treatments had similar densities of eggs, young and old nymphs in 2018 (Figs. 3E–G), but adults from beat trays were lowest in the kaolin treatments (Fig. 3D). Pear psylla adult counts on sticky cards were similar among reflective mulch, kaolin, and check treatments while the industry standard program had significantly higher adults than all three (Table 6). Significantly more spider mites (leaf brushing) were found in kaolin and reflective mulch plots than the check, while the industry standard program had similar densities to the check (Table 6).

In 2019, psylla adults in the industry standard and kaolin treatments were similar and significantly lower than in the reflective mulch and check; the reflective mulch treatment had significantly fewer adults than the check program (Fig. 4D). Psylla eggs were lower in the kaolin than industry standard treatment (Fig. 4E). Young nymphs were significantly different among all treatments; the check had the most followed by reflective mulch, kaolin, and industry standard, respectively (Fig. 4F). The industry standard program had significantly fewer old nymphs than all other treatments; the kaolin and reflective mulch programs had significantly fewer old nymphs than the check (Fig. 4G). Sticky card counts differed

Table 6. 2018 season-long average densities for natural enemies, mites, and pear psylla in industry standard, kaolin, reflective mulch, and check plots, for sampling type. Values beneath treatments are season-long averages ± SEM. 'Combined' stands for the cumulative sum of all natural enemies captured in beat trays, including those not in individual rows. Repeated measures multiple comparison results and distribution used are displayed to the right of insect category

Method and taxon	Season-long average density				$F_{3,21}$	P	Dist
	Industry Standard	Kaolin	Reflective	Check			
Beat tray (per tray)							
Combined	1.16 ± 0.17 b	1.39 ± 0.12 b	1.97 ± 0.14 b	5.17 ± 0.31 a	5.79	**0.005**	Pois
T. insidiosus	0.16 ± 0.04 b	0.17 ± 0.05 b	0.45 ± 0.09 b	1.38 ± 0.15 a	41.4	**<0.001**	logn
D. brevis	0.16 ± 0.04 b	0.31 ± 0.04 b	0.41 ± 0.10 b	1.51 ± 0.21 a	29.4	**<0.001**	logn
Spiders	0.63 ± 0.13 b	0.70 ± 0.08 b	0.95 ± 0.08 b	1.47 ± 0.27 a	9.68	**<0.001**	Gaus
Coccinellidae	0.03 ± 0.02 b	0.04 ± 0.03 b	0.01 ± 0.01 b	0.20 ± 0.06 a	5.51	**0.006**	Gaus
C. verbasci	0.00 ± 0.00 b	0.01 ± 0.01 b	0.00 ± 0.00 b	0.17 ± 0.03 a	22.1	**<0.001**	logn
Sticky card (per card)							
Pear psylla adults	99.58 ± 16.17 a	57.85 ± 10.80 b	66.15 ± 8.09 b	63.30 ± 16.17 b	15.3	**<0.001**	Pois
T. insidiosus	1.85 ± 0.24 c	5.13 ± 1.19 b	6.03 ± 0.80 b	21.53 ± 3.97 a	23.5	**<0.001**	logn
D. brevis	1.13 ± 0.40 a	1.17 ± 0.42 a	1.44 ± 0.48 a	1.42 ± 0.33 a	0.21	0.889	Pois
Chrysopidae	0.06 ± 0.03 a	0.03 ± 0.02 a	0.06 ± 0.03 a	0.19 ± 0.08 a	0.73	0.545	Pois
Leaf brush (per leaf)							
Psylla mummies	0.04 ± 0.02 b	0.02 ± 0.01 b	0.09 ± 0.04 b	2.07 ± 0.24 a	102	**<0.001**	logn
Spider mites	0.77 ± 0.24 ab	2.39 ± 0.73 a	2.32 ± 0.73 a	0.30 ± 0.18 b	8.14	**0.001**	logn
Cardboard (per trap)							
Earwigs	0.02 ± 0.02 a	0.02 ± 0.02 a	0.07 ± 0.07 a	0.13 ± 0.09 a	0.06	0.970	Pois

Values within a row not sharing a letter are significantly different according to Generalized Mixed Model Analysis and Tukey's HSD ($P < 0.05$).

Table 7. 2019 season-long average densities for natural enemies, mites, and pear psylla in industry standard, kaolin, reflective mulch, and check plots, for sampling type. Values beneath treatments are season-long averages ± SEM. 'Combined' stands for the cumulative sum of all natural enemies captured in beat trays, including those not in individual rows. Repeated measures multiple comparison results and distribution (Dist.) used are displayed to the right of insect category

Method and taxon	Season-long average density				$F_{3,21}$	P	Dist.
	Industry Standard	Kaolin	Reflective	Check			
Beat tray (per tray)							
Combined	0.47 ± 0.07 b	0.36 ± 0.06 b	0.54 ± 0.06 b	1.02 ± 0.13 a	13.9	**<0.001**	Gaus
T. insidiosus	0.01 ± 0.01 a	0.02 ± 0.01 a	0.04 ± 0.01 a	0.03 ± 0.01 a	1.33	0.290	logn
D. brevis	0.16 ± 0.03 b	0.14 ± 0.04 b	0.23 ± 0.04 b	0.54 ± 0.11 a	10.2	**<0.001**	logn
Spiders	0.14 ± 0.03 a	0.13 ± 0.04 a	0.11 ± 0.02 a	0.12 ± 0.03 a	0.19	0.902	logn
Coccinellidae	0.07 ± 0.03 ab	0.03 ± 0.02 b	0.06 ± 0.01 b	0.22 ± 0.06 a	5.83	**0.005**	logn
C. verbasci	0.00 ± 0.00 a	0.01 ± 0.01 a	0.01 ± 0.01 a	0.03 ± 0.01 a	1.54	0.235	logn
Sticky card (per card)							
Pear psylla adults	167.4 ± 10.5 b	265.6 ± 27.4 a	273.1 ± 31.5 a	89.86 ± 11.14 c	62.6	**<0.001**	logn
T. insidiosus	16.71 ± 0.82 c	25.00 ± 2.16 b	21.69 ± 3.12 bc	47.27 ± 7.60 a	31.5	**<0.001**	Pois
D. brevis	2.28 ± 0.55 a	2.05 ± 0.55 a	1.80 ± 0.44 a	2.39 ± 0.32 a	0.18	0.909	Pois
Chrysopidae	0.64 ± 0.16 ab	0.34 ± 0.08 b	0.67 ± 0.20 ab	0.97 ± 0.22 a	5.77	**0.005**	logn
Leaf brush (per leaf)							
Psylla mummies	0.01 ± 0.00 b	0.04 ± 0.02 b	0.07 ± 0.03 b	0.67 ± 0.16 a	32.4	**<0.001**	logn
Spider mites	0.01 ± 0.00 a	0.10 ± 0.06 a	0.07 ± 0.04 a	0.04 ± 0.02 a	3.38	0.034	logn
Cardboard (per trap)							
Earwigs	0.26 ± 0.07 a	0.65 ± 0.22 a	0.65 ± 0.21 a	0.61 ± 0.18 a	1.47	0.252	Pois

Values within a row not sharing a letter are significantly different according to Generalized Mixed Model Analysis and Tukey's HSD ($P < 0.05$).

between years and from beat tray results: in 2019, kaolin and reflective mulch programs had significantly more psylla adults than industry standard and check programs, and the check had significantly fewer psylla adults than all other programs (Table 7). There were fewer spider mites overall in 2019 and no differences were observed. Very few pear rust mites were found in either year, so no analyses were performed for this species.

There were usually more natural enemy arthropods found in the untreated check program than industry standard, kaolin, and reflective mulch programs in both years (Tables 6 and 7). Natural enemy counts were similar among industry standard, kaolin, and reflective mulch programs, except for significantly fewer *T. insidiosus* found in industry standard programs on sticky cards in both years (Tables 6 and 7). Natural enemies that were not affected by any program include *D. brevis* on sticky cards (both years), Chrysopidae on sticky cards (2018), *T. insidiosus* on beat trays (2019), spiders on beat trays (2019), *C. verbasci* on beat trays (2019), and earwigs in cardboards (both years).

Table 5. Pear psylla life stage means comparisons tests among check, kaolin, reflective mulch, and industry standard programs and distribution (Dist.) used. Tests were performed for three seasonal timeframes in 2018 and 2019: pretreatment (single sample before experimental treatments), pre-petal fall (treatment initiation to petal fall), and post-petal fall (samples following petal fall until experiment termination after harvest)

		Pretreatment			Pre-petal fall			Post-petal fall		
Year	Life stages	$F_{3,21}$	P	Dist.	$F_{3,21}$	P	Dist.	$F_{3,21}$	P	Dist.
2018	Adults	2.13	0.127	logn	38.6	<0.001	Pois	230.9	<0.001	Pois
	Eggs	–	–	–	104.5	<0.001	Pois	18.5	<0.001	Gaus
	Instars 1–3	–	–	–	29.2	<0.001	logn	35.6	<0.001	logn
	Instars 4–5	–	–	–	–	–	–	86.5	<0.001	logn
2019	Adults	0.62	0.620	logn	13.5	<0.001	logn	39.2	<0.001	Gaus
	Eggs	–	–	–	14.1	<0.001	Pois	2.87	0.061	logn
	Instars 1–3	–	–	–	25.3	<0.001	Pois	105.1	<0.001	logn
	Instars 4–5	–	–	–	–	–	–	52.2	<0.001	logn

'–' indicates no sample conducted (for Pretreatment), and none found (for Pre-petal fall).
[a]Distribution abbreviations: logn = log normal, Pois = Poisson, Gaus = Gaussian.

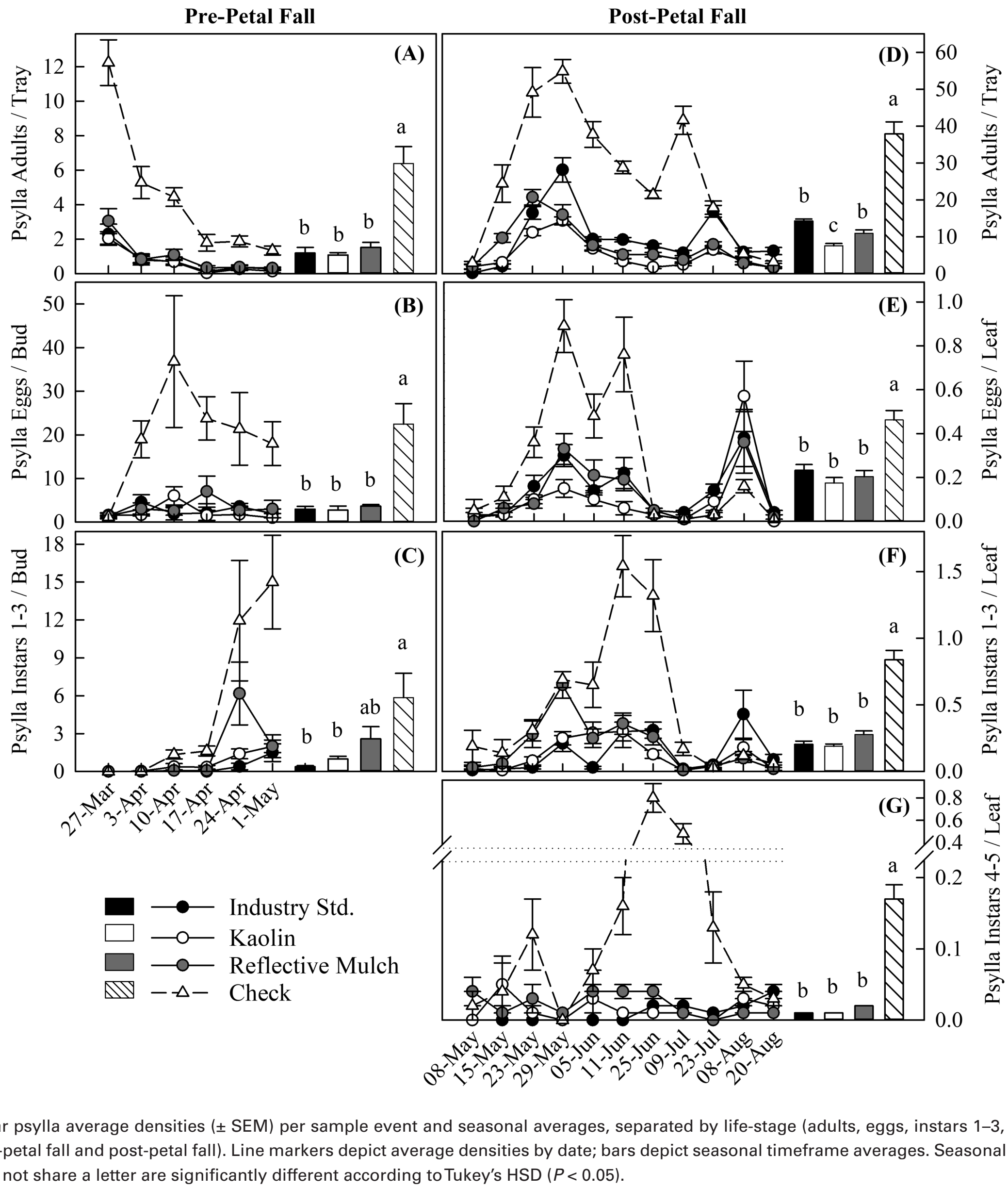

Fig. 3. 2018 pear psylla average densities (± SEM) per sample event and seasonal averages, separated by life-stage (adults, eggs, instars 1–3, instars 4–5) and timeframe (pre-petal fall and post-petal fall). Line markers depict average densities by date; bars depict seasonal timeframe averages. Seasonal averages within a panel that do not share a letter are significantly different according to Tukey's HSD ($P < 0.05$).

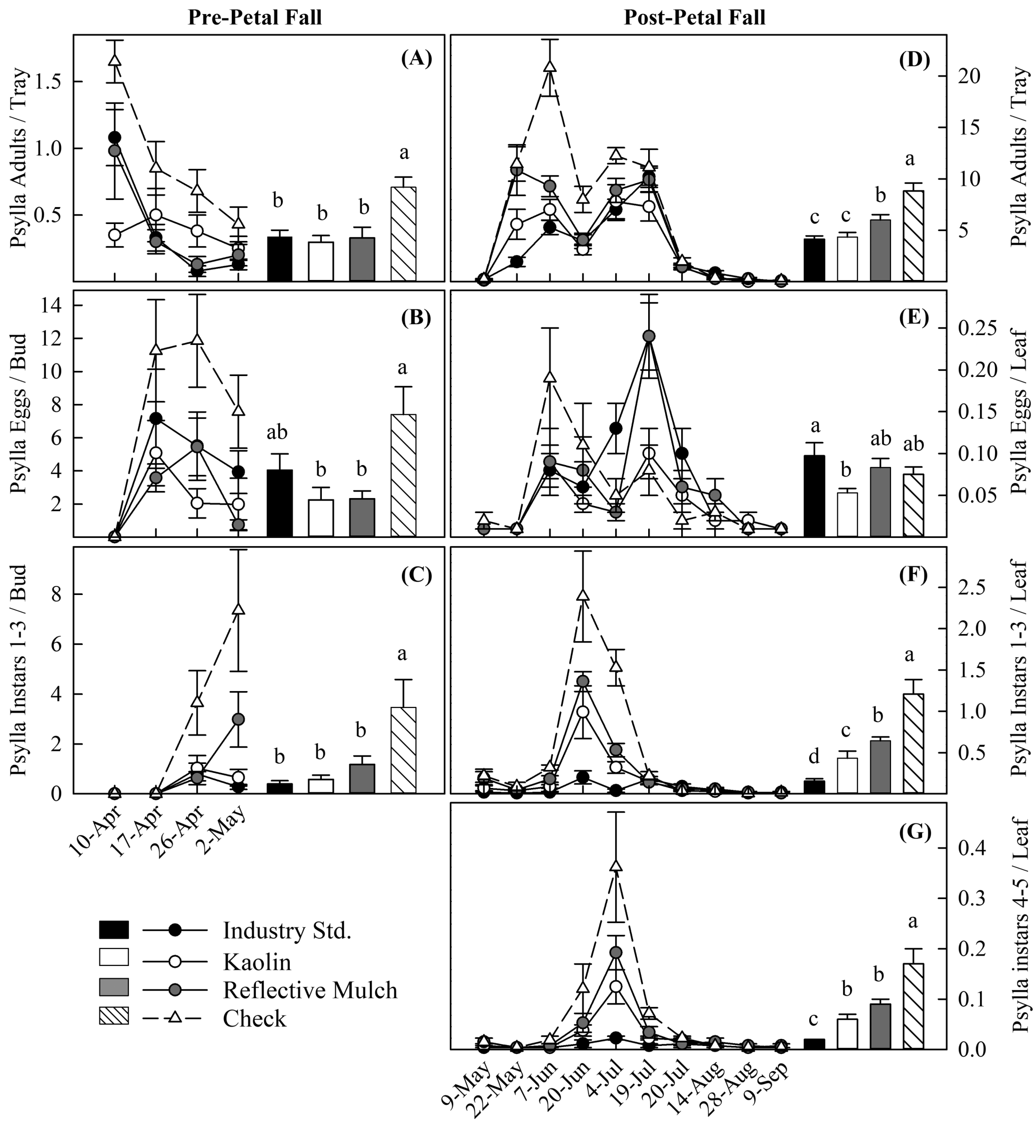

Fig. 4. 2019 pear psylla average densities (± SEM) per sample event and seasonal averages, separated by life-stage (adults, eggs, instars 1–3, instars 4–5) and timeframe (pre-petal fall and post-petal fall). Line markers depict average densities by date; bars depict timeframe averages. Seasonal averages within a panel that do not share a letter are significantly different according to Tukey's HSD ($P < 0.05$).

Fruit Injury

Pear psylla injury (% of fruit surface area marked by honeydew) was significantly affected by management program in both years (2018: $F_{3,21} = 90.1$, $P < 0.001$; 2019: $F_{3,21} = 50.1$ $P < 0.001$). Average injury was significantly higher in the check than all other treatments in both years (Fig. 5). Kaolin and reflective mulch treatments had significantly lower average injury levels than the industry standard treatment in 2018; injury averages were not different among kaolin, reflective mulch, and industry standard treatments in 2019 (Fig. 5). Re-interpreting rating scale data as commercial grading categories showed that no inspected fruits in the check plots were free of russeting or black marking, therefore, most would be graded as culls (94% in 2018 and 84% in 2019), and the rest would be downgraded (Fig. 6). Most fruit in the treatment plots were scored as marketable, and across the two years, the kaolin program averaged the most US 1 fruit and the fewest culls, followed by reflective mulch, then industry standard (Fig. 6).

Discussion

This study has two primary conclusions: (1) kaolin and reflective mulch can provide similar early-season suppression of pear psylla as industry standard programs, and (2) full-season management programs using only selective approaches can have similar or better results as those using broad-spectrum insecticides. Relative densities of pear psylla life-stages among kaolin, reflective mulch and the industry standard were not different for most evaluations, and fruit injury was either similar or reduced in kaolin and reflective mulch programs compared with the industry standard. Pear psylla densities and fruit injury levels were significantly and substantially greater in check plots than the other three treatments, demonstrating that all approaches were challenged with high pest pressure. Psylla densities in the reflective mulch treatment trended higher than kaolin and industry standard programs (although often not significantly different), but this treatment was likely disadvantaged due to more experimental errors and less institutional knowledge to guide our methods (discussed further below). Spider mites were only different in 2018, with higher densities in kaolin and reflective mulch than the check and industry standard. Some evidence suggests that spider mites can be increased when particle films are used frequently within a season (Knight et al. 2001, L. Nottingham unpublished), as occurred in these treatments. Natural enemies were highest in check plots, presumably because of the higher psylla densities, and mostly similar among kaolin, reflective mulch, and industry standard programs.

Spraying kaolin prior to bloom is a common practice throughout the Washington pear industry; however, it is mostly used in addition to insecticides to manage pear psylla (Murray et al. 2021). This practice was reflected in the industry standard program by applying one kaolin spray before bloom (at delayed dormant) alongside the organophosphate insecticide, malathion, and followed by a tank mix of multiple broad-spectrum insecticides. In recent years since this study, multiple kaolin sprays are becoming more common before and after bloom; however, similar amounts of broad-spectrum materials are used alongside these sprays suggesting that confidence in kaolin sprays alone remains low. Further complicating the issue is the rising use of alternative (cheaper) particle film products that are not registered for use against pear psylla, such as alternative kaolin products (for sunburn only) and a calcium carbonate film. The cost of Surround (about US$150/ha [US$60/acre]) is higher than many available insecticides, but some of the most popular conventional insecticides for pear psylla are similar or even more expensive (Delegate [spinetoram], Rimon [novaluron] and Nexter [pyridaben] are each between US$170 and 220/ha [US$70–90/acre]); therefore, the cost of Surround is not prohibitive. There is also a diatomaceous earth product that is registered for pear psylla management (Celite 610), however, it is similar in cost to Surround, so its potential to replace Surround seems low. Research into alternative particle films, such as calcium carbonate, has been conducted (Glenn and Puterka 2005), and more is underway (Nottingham and Beers 2022).

Reflective mulch is rarely used in the Washington pear industry, if at all. Our results suggest that this strategy has potential utility as an IPM strategy for pear psylla and should be considered for further examination. Reflective mulch plots had lower pear psylla injury than industry standard plots in the first year and the same in the second year; injury was the same among reflective mulch and kaolin plots in both years. Reflective mulch's ability to suppress pear psylla populations was occasionally less than kaolin and industry standard treatments, but it was likely at an experimental disadvantage due to a lack of prior research. Reflective mulch has only been experimentally tested for pear psylla management in one study, which determined it suppressed the first generation of pear psylla relative to black plastic and bare ground on single tree plots (Nottingham and Beers 2020). Two other studies, Bertelsen (2005) and Einhorn et al. (2012), examined horticultural benefits of a reflective geotextile, Extenday (Extenday USA Inc., Union Gap, WA), in pears; however, this material and application are quite different (Extenday is laid across the drive row and attached with cords to trees, allowing it to hover over the ground). Using reflective mulch in pears is a novel practice relative to kaolin and pesticide sprays, so experimental execution of the reflective mulch treatment involved more unguided choices, including sheet thickness, width, backing colors (clear, metalized, white, or black), placement (covering weed strips, drive rows, or both), and securing method (buried perimeter, partial burial with dirt scoops, or landscape staples). We experienced multiple failed attempts to keep the mulch secured to the ground, resulting in sections of mulch being blown out of place and, thus, areas of plots were unprotected from pests for up to 48 h until the mulch could be replaced. In 2018 we secured the mulch with landscape staples, and in 2019 switched to shoveling individual clumps of dirt over the mulch. Both methods worked when enough staples or clumps were used; however, staples were less ideal due to the added material cost, labor for removal, and potential to lose staples in the field which can be a hazard to mowing or cultivation equipment. The optimal strategy to keep the mulch in place involved weighing the mulch down with one scoop of dirt every meter or more (Fig. 2).

The potential implementation of reflective mulch depends not only on its ability to suppress psylla, but also on factors adding to or reducing its value. Value-enhancing factors include interdisciplinary benefits like weed suppression (Croxton and Stansly 2014), increasing pear yields (Bertelsen 2005, and Einhorn et al. 2012), improving fruit set in the lower canopy (Einhorn et al. 2012), and providing more consistent soil moisture and temperature (Nottingham and Beers 2020). Value-reducing factors of reflective mulch include added costs and inconveniences mostly related to deployment. Laying mulch in the dormant to delayed dormant time overlaps with pruning schedules for most growers, so pruning would have to occur in the fall or mid-winter. Due to the physically challenging nature of

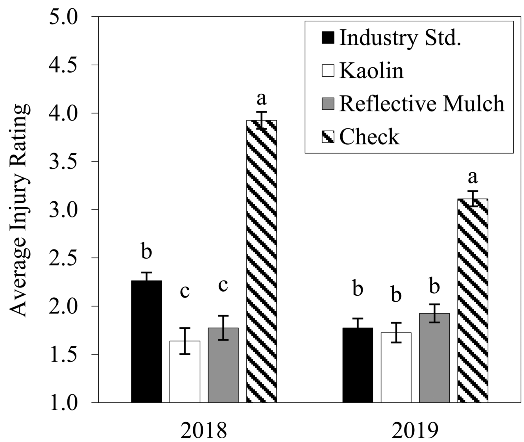

Fig. 5. Fruit injury from pear psylla honeydew in 2018 and 2019. The subplot average injury was gained from 10 individual fruit per subplot rated on an ordinal scale of 1–5 representing the percentage of fruit surface area with honeydew marking (1 = not detectable, 2 = 1 to 5%, 3 = 5 to 20%, 4 = 20 to 40%, 5 = >40%). Bars depict the average rating (± SEM) among all subplots for the industry standard, kaolin, reflective mulch, and check treatments. Bars not sharing a letter within a panel are significantly different according to Tukey's HSD ($P < 0.05$).

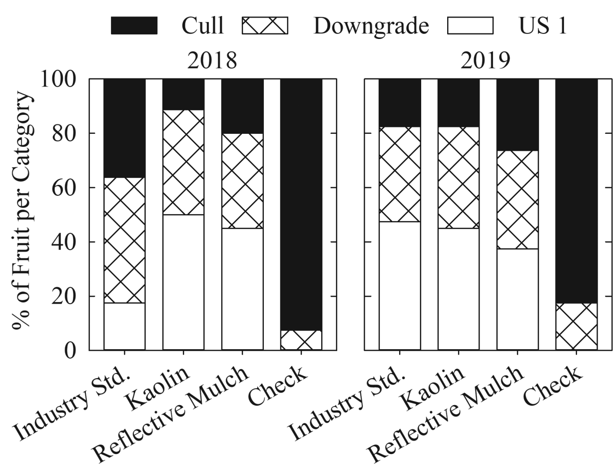

Fig. 6. Percentage of fruit in each commercial fruit grade category in 2018 and 2019. Stacked bars depict the percentage of fruit, from the total harvested, in each grading category for industry standard, kaolin, reflective mulch, and check plots. Commercial grading categories are 'US 1' (no honeydew marking [can be sold at a highest market price]), 'downgrade' (1–5% honeydew marking, [sold at a reduced market price]), and 'cull' (>5% honeydew marking [discarded]).

pruning, coupled with weather constraints and limited workforce, it can take months to complete pruning across larger operations, constituting a serious roadblock to the implementation of reflective mulch. Early season sprays where mulch is present may also be a challenging factor. Airblast sprayers can easily dislodge mulch if not secured effectively, and some sprays, such as kaolin and copper, can leave residues that alter the color of the mulch which may reduce its reflectivity (kaolin residues on mulch are further discussed below). Reflective mulch also has material and deployment costs that are likely to be greater than sprays. As with most novel strategies, costs and inconvenience may appear prohibitive in the early stages, but further research may lead to improvements that increase efficiency and lower costs. A project testing reflective ground covers on commercial orchards and with applications performed by growers is currently underway to further examine the technique at implementation scale (Nottingham et al. in prep).

The compatibility of kaolin and reflective mulch used together is an important future research direction. Both strategies appear to be most effective before bloom, and they have the potential to impact each other if overlapped. For example, kaolin sprayed after reflective mulch is deployed creates a kaolin film layer over the mulch, potentially reducing reflectivity. In the 2019 experiment, kaolin was sprayed over reflective mulch and PAR measurements were conducted in reflective mulch and check plots. Our measurements showed that reflective mulch remained reflective relative to the check; however, kaolin residues likely reduced reflectivity from its maximum potential. Nottingham and Beers (2020) measured PAR in reflective mulch plots where no kaolin was sprayed using similar methods and equipment, but a longer period of time (from March through June). They reported average daily highs of 829 μmol/m²s, which was 38% greater than the 602 μmol/m²s seen in this study when kaolin was sprayed over mulch. Still, suppression of pear psylla relative to other treatments was similar to 2018 when kaolin was not sprayed over reflective mulch. Probably the more important topic is the cost effectiveness of using both treatments. Since this study demonstrated that kaolin is highly effective on its own, the additional benefits of reflective mulch (weed suppression and increased yields) must be great enough to justify added costs.

Compared to kaolin, reflective mulch's post-petal fall averages of pear psylla life-stages were either the same or greater depending on the year and life-stage. This may be due to kaolin having lasting residues, whereas the effect of reflective mulch likely ends immediately after removal. Reflective mulch can also increase vegetative vigor (Croxton and Stansly 2014), which can promote pear psylla population growth (McMullen and Jong 1972). Nottingham and Beers (2020) reported that although reflective mulch suppressed first generation pear psylla, later generations of pear psylla were greater in reflective mulch than check plots. Risk of pear psylla rebound in reflective mulch plots following removal should be considered in future studies.

A goal of this study was to document differences in biological control, via natural enemy counts, between selective and broad-spectrum programs. The only instance where natural enemies were fewer in the industry standard treatment than kaolin or reflective mulch, in both years, was *Trechnites insidiosus* adults on sticky cards. Sticky cards caught far more *Trechnites insidiosus* adults than beat trays, providing a more robust sample for comparison. Otherwise, no meaningful differences in natural enemy densities among the industry standard, kaolin, and reflective mulch treatments. The lack of differences may have been due to poor ability to gain high enough numbers from the beat tray sampling method. Despite the lack of differences in biocontrol between the two selective treatments (kaolin and reflective mulch) and the industry standard treatment, there were other indicators of biological control being compromised in the industry standard program. In 2018 after petal fall, psylla nymph averages were not different among the industry standard, kaolin, and reflective mulch treatments, but kaolin and reflective mulch had significantly lower fruit injury than the industry standard. In 2019, the industry standard treatment had significantly fewer pear psylla nymphs than kaolin and reflective mulch after petal fall, but pear psylla injury to fruit was not different among those three treatments. These results may have been the result of sublethal effects of pesticides, which would be difficult to see by counts alone. Sublethal pesticide effects have been documented for many of the insecticides used in an industry standard program on key natural enemies of pear psylla including *D. brevis* (Kim et al. 2006, Amarasekare and Shearer 2013) and earwigs (Campos et al. 2011). Kaolin, reflective mulch, and/or selective summer sprays are less likely to harm natural enemies than conventional sprays (Burts 1983, Alway 2001, Puterka et al. 2005, DuPont and Strohm 2020, Nottingham and Beers 2020, DuPont et al. 2021, Nottingham and Sater 2021); however, a few studies have reported nontarget effects from kaolin clay (Knight et al. 2001, Tacoli et al. 2019) and the selective insecticide, diflubenzuron (Sauphanor et al. 1993). Future studies should consider using larger plots and/or additional methods to document sublethal effects, should they occur.

Below are rudimentary cost comparisons of materials for early season treatment programs as a starting point for future economic analysis. We did not include labor costs for treatments, which certainly differ among sprays and installing reflective mulch, but because laying reflective mulch is uncommon in pears a true labor cost is not available. It should be noted that material costs can differ based on many factors such as product formulation, supplier pricing differences, amount purchased, etc. Furthermore, comparing the material cost of reflective mulch to sprays is imperfect. Reflective mulch does not have a per area amount limit (e.g., rate per acre) like insecticide sprays; instead, the amount used will depend on the number of rows, which will differ due to row spacing. Material cost comparisons also do not consider cost savings and value-added factors likely to result from reflective plastic mulch, such as reduction in herbicide spray needs and increased yields, respectively. The reflective mulch used in this experiment cost US$260 per 1,220 m (4,000 ft) roll. The pre-petal fall reflective mulch program cost US$437 per 0.4 ha (1.0 acre) for the 4 m (13 ft) row spacing in this trial. However, the more common row spacing of pears in the central Washington is 6 m (20 ft) (R. Schmitten, grower and packing house representative, personal communication), which would cost US$283 per 0.4 ha (1.0 acre). Like insecticides, there are different reflective mulch products with varying prices, so further testing to compare efficacy among different mulch types will be useful. Kaolin (Surround) costs about US$60 per 0.4 ha (1.0 acre). The kaolin-only pre-petal fall program was the least expensive (aside from the check) at about US$130 per 0.4 ha (1.0 acre) in 2018, and US$190 in 2019. The industry standard pre-petal fall program, including kaolin and insecticides, cost US$230 per 0.4 ha (1.0 acre) in 2018 and US$300 in 2019. Therefore, the kaolin only treatment was the least expensive in both years, while reflective mulch and industry standard were similar.

In summary, reliance on broad-spectrum insecticides for pear psylla management in central Washington has become ineffective and excessively expensive. The results of this study demonstrated that selective methods (kaolin or reflective mulch) can be substituted for broad-spectrum insecticides before petal fall, followed by selective insecticides after petal fall, creating full-season selective programs. This not only demonstrates the potential utility of kaolin and reflective mulch, but it verifies that selective tactics, in general, can control pear psylla without supplemental broad-spectrum insecticides. Although implementation of reflective mulch will require further assessment to determine commercial practicality, the kaolin-focused programs tested in this study were less expensive, similarly or more effective, and convenient compared with the industry standard, and therefore should be considered for immediate implementation by the industry for pear psylla management.

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