

The Artificial Sweetener, Erythritol, Has Insecticidal Properties Against Pear Psylla (Hemiptera: Psyllidae)

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Abstract

Erythritol is a dietary sweetener that is used for low-calorie or diabetic diets. Although safe for human consumption, erythritol is lethal to certain Dipteran pests, but insecticidal effects of erythritol on phloem-feeding insects have yet to be examined. Our goal was to determine whether erythritol has insecticidal activity against pear psylla, *Cacopsylla pyricola* (Foerster) (Hemiptera: Psyllidae). We first demonstrated that ingestion of erythritol solutions compared with water by pear psylla caused reduced feeding, impaired motor functions, and reduced survival time of adults. We then tested whether foliar treatment of pear leaves with erythritol was also lethal to pear psylla. Foliar treatment of erythritol led to reduced 3-d survival of pear psylla nymphs and adults, and reduced rates of oviposition by pear psylla adults. Psylla adults also preferred to settle on untreated leaves than on erythritol-treated leaves in preference assays. Finally, we conducted field experiments to test whether applications of erythritol provided pear trees with protection against pear psylla under natural field conditions. Those experiments showed a reduction in pear psylla nymphs on erythritol-treated trees compared with untreated trees, but only if the erythritol was completely dissolved into solution by heating. Laboratory trials confirmed the importance of heating. Results of our experiments demonstrate that erythritol is insecticidal to pear psylla nymphs and adults and provide the first report that erythritol is lethal to a phloem-feeding insect. These findings suggest that erythritol may provide a new safe and effective tool for the management of pear psylla.

Key words: pear psylla, erythritol, psyllid, *Cacopsylla*

Pear psylla, *Cacopsylla pyricola* (Foerster) (Hemiptera: Psyllidae), is a key pest of commercial pear, accounting for ~46% of all pear pest management costs (Gallardo et al. 2016). The nymphs produce copious amounts of sticky honeydew that cause fruit russetting, serves as a medium for the growth of sooty mold, and increase costs of harvest (Westgard and Zwick 1972). Pear psylla occurs as two distinct seasonal morphotypes—summerform and winterform—that differ with respect to diapause, feeding behavior, and plant attraction (Ullman and McLean 1988; Krysan and Higbee 1990; Horton et al. 1998, 2007; Civolani et al. 2011). Management of pear psylla typically involves applications of horticultural oil or kaolin during early spring to target winterform psylla as they colonize pear orchards, and repeated applications of chemical insecticides from spring until harvest to manage the summerform populations. The use of insecticides can eliminate natural enemies that suppress other pests of pear, thus necessitating additional insecticide applications (Murray and DeFrancesco 2014). Pear psylla can rapidly develop resistance to conventional insecticides. Indeed, certain chemistries are no longer

effective for managing psylla in certain pear growing regions of the western United States (Burts et al. 1989, Van De Baan and Croft 1991, Courtney 2017). New tools to manage pear psylla are needed to mitigate the development of insecticide resistance in pear psylla populations and to limit insecticide exposure to consumers, workers, and natural enemies.

The sugar alcohol sweetener, erythritol, has insecticidal properties against certain insects and may provide a new management tool for pear psylla, but the effects of erythritol on pear psylla have not yet been assessed. Erythritol is safe for human consumption and is widely used as an alternative to dietary sucrose (Storey et al. 2007). It is a byproduct produced by fermentation of glucose by the yeast strain *Moniliella pollinis* (van Beyma) (incertae sedis: Moniliellaceae). Although safe for human consumption, fruit flies (Diptera: Drosophilidae, Tephritidae) that ingest erythritol have increased mortality and reduced fecundity (Braudier et al. 2014; Marenda and O'Donnell 2015; Choi et al. 2017, 2019; Sampson et al. 2017). Erythritol appears to affect the motor function of fruit

flies, which display a decreased ability to climb after consuming diets containing this compound (Braudier et al. 2014). Erythritol is also lethal to termites (Blattodea: Rhinotermitidae) and ants (Hymenoptera: Formicidae) in a dose-dependent manner when ingested (Zhang et al. 2017, Caponera et al. 2020). The mode-of-action of erythritol is not yet fully understood, but accumulation of erythritol in the insects' hemolymph is thought to elevate osmotic pressure and disrupt cellular processes (Tang et al. 2017).

No previous studies have examined the insecticidal properties of erythritol on phloem-feeding insects. The goal of this study was to examine the insecticidal activity of erythritol on pear psylla, a phloem-feeding pest in pear orchards. We first examined whether ingestion of an erythritol solution by pear psylla increases mortality of psylla adults. We then tested the effects of erythritol on pear psylla when applied to pear leaves under laboratory and field conditions. Results of these experiments demonstrate that erythritol is lethal to pear psylla and could be developed into an effective new tool for management of this pest in commercial pear.

Materials and Methods

Sources of Insects and Plants

The sources of pear psylla were dependent upon availability at the start of each assay and included a mixture of field-collected and colony-reared insects. Where indicated, field-collected adult pear psylla were obtained from a commercial pear orchard that is adjacent to the USDA laboratory in Wapato, WA. The adults were either of the summerform or winterform morphotype, depending on the time of year in which the laboratory assays were conducted. Laboratory-reared pear psylla were obtained by confining field collected adults on pear 'Bartlett' seedlings and monitoring the development of the resulting offspring. The colonies were kept in an environmentally controlled room at 25°C with a 16:8 (L:D) h photoperiod. Colony insects were of the F₁ or F₂ generation. For laboratory assays requiring pear leaves, the leaves were excised using a clean razor blade from Bartlett seedlings grown in a greenhouse maintained at 20–25°C with supplemental lighting to provide a 16:8 (L:D) h photoperiod.

Survival and Feeding Rates After Ingesting Erythritol Solutions

Feeding was monitored with 3-ml of either pure water, 30% sucrose, or 30% erythritol dispensed in the bottom half of 100-ml Petri dishes covered with parafilm according to Jimenez et al. (2017). Our initial experiments used 30% sucrose or food-grade erythritol (Pyure Brands, LLC, Naples, FL) because pear psylla feed more extensively from 30% sucrose than from other sucrose concentrations (Jimenez et al. 2017). The erythritol required gentle heating at 31°C to help speed the rate at which it dissolved it into a high concentration solution. Five field-collected pear psylla adults were confined to each feeding dish which were then placed in a growth chamber maintained at 25°C with a 16:8 (L:D) h photoperiod. The number of psylla that were feeding on the diet through the parafilm was counted after 24 h under 25× magnification. The dishes were then returned to the growth chamber and pear psylla survival was monitored daily until all the insects had died. The experiment was conducted three times (trials) and each trial included five replications (dishes) per treatment. Two trials included summerform adults collected in August of 2018 whereas the third trial included winterform adults collected in October of 2018. Unless otherwise stated, all statistical analyses were performed using the GLIMMIX procedure of

SAS 9.4 using simulation-based adjustment for multiple comparisons. The proportion of living pear psylla that were actively feeding after 24 h was compared among treatments by logistic regression using the events/observations syntax with trial included as a random effect. Survival of pear psylla was compared among treatments using PROC LIFETEST of SAS 9.4 while controlling for trial.

To determine whether mortality was caused by antibiotic effects or by lack of feeding, feeding dishes were prepared as described above with water, no water, or 30% erythritol. Ten pear psylla adults obtained from a colony were placed on each dish. Mortality rates were examined after 3 d. This experiment included only one trial with five replications (dishes) per treatment. Data were analyzed by logistic regression.

Liquid diets consisting of 0, 1, 10, 20, or 30% erythritol were used to examine whether the effects of erythritol were dose-dependent. Five field-collected pear psylla adults were confined to each dish and placed in a growth chamber maintained at a 25°C with a 16:8 (L:D) h photoperiod. Mortality was evaluated after 3 d. This assay was conducted three times (trials), and each trial included five replications per treatment. Two trials included winterform pear psylla, and one trial included the summerform. Mortality rates after 3 d were compared among treatments by logistic regression while including trial as a random variable.

Survival on Treated Leaves

Excised pear leaves were dipped into solutions of 30% sucrose, 30% erythritol, or water. Silwet L77 (Helena Agri-Enterprises, Collierville, TN) was added to each solution as a surfactant/spreader at a concentration of 0.1% (w/v). It was not known at the start of the assay whether a surfactant was required. The cut petiole of each leaf was placed in a 15-ml conical-bottom centrifuge tube filled with water and a 30-ml deli cup (Solo Cup Company, Lake Forest, IL) was glued to the top of the lid of each centrifuge tube (Cooper et al. 2015). A small hole through the bottom of the deli cup and lid of the centrifuge tube provided entry for the leaf petiole and a mesh window in the deli cup lid provided ventilation. Thus, the cut petiole of each leaf was submersed in water and individual psyllids were confined to the leaf by the deli cup. The assays were kept in a growth chamber maintained at 25°C with a 16:8 (L:D) h photoperiod, and mortality was examined after three days. Experiments were conducted three times (trials) with different cohorts of insects, and each trial included five replications. Experiments examining effects of erythritol on adults and nymphs were conducted independently and were therefore analyzed separately. Data were analyzed by logistic regression while including trial as a random variable.

A separate trial was conducted to examine the direct topical effects of erythritol on pear psylla nymphs. For this trial, fourth instar nymphs were gently removed from colony plants, briefly submersed in water, 30% sucrose, or 30% erythritol, and confined to untreated excised pear leaves as described above. This experiment included 10 replications per treatment in a single trial. The number of living nymphs was examined after 3 d using logistic regression.

A no-choice assay was conducted using adult summerform females obtained from the laboratory colony to compare the number of eggs oviposited on leaves treated with erythritol versus water. The experimental setup was as described for trials examining adult survival on treated versus untreated leaves. The experiment measuring egg counts was conducted twice (trials) with five replications per trial. The number of eggs per leaf was compared among treatments by analysis of variance with trial as random

variable while modeling for a negative binomial distribution for count data.

Choice-preference assays were conducted by releasing five pear psylla adults into the center of each of five 20-liter buckets containing a leaf treated with 30% erythritol and a leaf treated with water (control). The cut petiole of each leaf was placed in water as described for the no-choice assays. The buckets were placed in a greenhouse, and the number of pear psylla present on each leaf was recorded after 24 h. The experiment was conducted three times (trials) and each trial included five replications. Adult setting and oviposition was analyzed by logistic regression using the events/observations syntax where events = the number of adults or eggs on each plant and observations = the number adults or eggs counted on both plants within each cage. Pear psylla that were not found on a leaf were not included in the analysis.

Field Trials

Two independent field trials were conducted in the spring of 2019 in Moxee, WA and Wenatchee, WA. In Moxee, the experiment was conducted in a Bartlett pear orchard located at the USDA-ARS experimental farm near Moxee, WA. The orchard was planted in 2001 with 5 × 5-m spacing. Plots were organized in a randomized complete block design. Each of the four blocks occurred with a row, and each experimental row was separated by an untreated row. Plots in the same row were separated by at least three untreated trees. Within a block, plots were randomly assigned a foliar treatment: untreated control consisting of water + Regulaid (nonionic surfactant; KALO, Overland Park, KS), 20% erythritol, or 20% erythritol + Regulaid. Each plot consisted of three consecutive Bartlett trees, but insect sampling occurred on the center tree only. The erythritol treatments were dissolved in water by heating the solution to 31°C prior to applying the treatments. Foliar treatments were applied weekly at a rate of 1-liter per tree using a gas-powered backpack sprayer (Stihl Inc., Virginia Beach, VA; model SR420). Spray volumes were estimated using spray times with a sprayer rate of 32 ml/second. Pear psylla populations were sampled each week from 9 April until 14 May 2019. Adults were sampled by tapping a branch three times from each of the four cardinal directions with a 0.5-m-long host to dislodge the insects onto a 0.2 m² white beat tray. Beginning on 30 April, nymphs were sampled in situ by counting the number of nymphs on the 10 most terminal leaves on one shoot from each of the four cardinal directions around each tree (four shoots per tree).

In Wenatchee, the experiment was conducted in a mixed planting Anjou and Bartlett pear orchard located at the Washington State University Tree Fruit Research and Education Center in Wenatchee, WA. The orchard was planted in 1972 with 5 × 5.8-m spacing. Plots were organized in a randomized complete block design. Each block occurred in one of three experimental rows, and each experimental row was separated by at least one untreated barrier row. Plots in the same row were separated by at least three untreated barrier trees. Within a block, plots were randomly assigned a foliar treatment: untreated control (water + Regulaid), 20% erythritol, or 20% erythritol + Regulaid. Each plot consisted of three consecutive Bartlett trees, but insect sampling occurred on the center tree only. Foliar treatments were applied weekly at a rate of 1.5-liters per tree to account for the larger trees and spacing in this plot, using a handgun sprayer connection from an airblast sprayer (Pak-Blast, OVS McMinnville, OR). Erythritol solutions were not heated prior to application at this location but were instead vigorously mixed by an in-tank agitator. Spray volumes were estimated by calibration prior to applications at 250 ml/second (3 s per tree side). Pear psylla populations were

sampled on 6 May and 13 May 2019 as described for the trial conducted in Moxee, WA.

Data for both experiments were analyzed by repeated measures. In separate analyses, the numbers of nymphs or adults were included as the dependent variable, and treatment, week, and treatment by week interaction were included as fixed effects. The repeated variable was indicated by including the random statement 'RANDOM WEEK SUBJECT = BLOCK TYPE = VC RESIDUAL'. The simulation-based adjustment for multiple comparisons was used to determine differences among means when the overall ANOVA indicated significance. All four analyses were modeled assuming a negative binomial distribution of count data.

Effects of Heating Erythritol Solution

Because the methods for preparing erythritol differed in experiments conducted in Moxee and Wenatchee, we performed a laboratory assay to compare the psyllicidal effects of erythritol that was heat dissolved into solution versus agitated. Excised pear leaves were treated with water, heat dissolved erythritol, and agitated erythritol solutions without heating. Treatments were applied to excised pear leaves as described in the 'Survival and feeding rates of pear psylla on treated leaves' subsection, and five colony-reared adults were confined to each leaf for three days. This experiment included five replications per treatment included in a single trial. Mortality rates were compared among treatments using logistic regression.

Results and Discussion

Survival and Feeding Rates After Ingesting Erythritol Solutions

Significantly fewer pear psylla were observed feeding on erythritol diets compared with those consisting of sucrose or water only (Fig. 1; $F = 9.1$; d.f. = 2, 39; $P = 0.006$). Survival time was also significantly reduced for pear psylla that were fed erythritol compared with those that were fed pure water or 30% sucrose (Fig. 2; $\chi^2 = 49.6$; d.f. = 2; $P < 0.001$). After demonstrating that 30% erythritol was lethal to pear psylla adults when ingested from liquid diets, we examined the lethality of various erythritol concentrations ranging from 0 to 30%. Three-day mortality rates increased as concentration of erythritol increased from 0 to 30% (Fig. 3; $F = 16.0$; d.f. = 4, 38; $P < 0.001$). Mortality rates approached 100% at the highest two concentrations (Fig. 3).

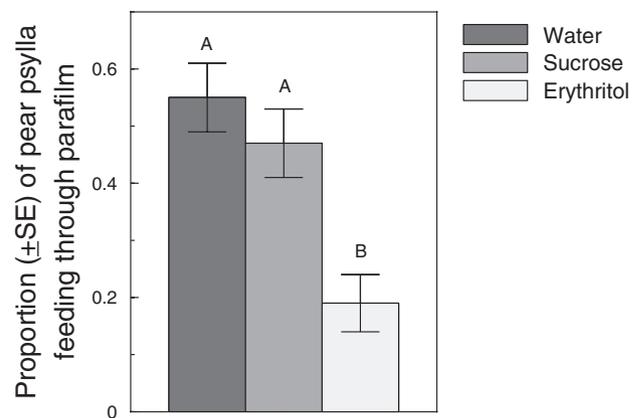


Fig. 1. Proportion (\pm S.E.) of living psylla adults that were actively feeding after a 24-h settling time on liquid diets consisting of water only, 30% erythritol, or 30% sucrose. Different letters denote significant differences among treatment means.

Results of these assays demonstrate that erythritol has dose-dependent insecticidal properties when ingested from liquid solutions by pear psylla adults. We did not specifically compare the effects of erythritol on winterform and summerform psylla, but our assays included either morphotype depending upon availability and demonstrated that erythritol is lethal to both seasonal morphotypes. Results of these assays are consistent with published reports that erythritol is insecticidal (Braudier et al. 2014; O'Donnell et al. 2016; Choi et al. 2017, 2019; Burgess and King 2018; Gilkey et al. 2018; Sampson et al. 2019; Caponera et al. 2020), but our study is the first to demonstrate that erythritol is lethal to a phloem-feeding insect.

Observations after the 24-h settling time revealed altered behavior or impaired motor skills by pear psylla that ingested erythritol. Pear psylla that were fed erythritol appeared to spend more time grooming their stylets compared with psylla that were fed sucrose or water. In addition, many of the erythritol-fed psylla appeared to have an impaired ability to climb on the lid of the petri dish. While these observations should be interpreted cautiously because our experiment was not specifically designed to examine the effects of erythritol on the behavior of pear psylla, these observations are consistent with a report of impaired motor functions by fruit flies after ingesting erythritol. In that experiment, *Drosophila melanogaster* (Meigen) (Diptera: Drosophilidae) adults that were fed erythritol exhibited a decreased ability to climb compared with adults that were fed water or other artificial sweeteners (Braudier et al. 2014).

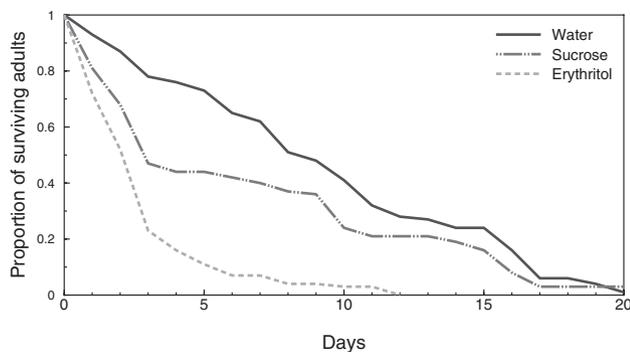


Fig. 2. Survival rates of pear psylla adults on liquid diets consisting of water, 30% sucrose, or 30% erythritol. Although the x-axis is limited to 20 d to allow visual comparisons, survival on water and sucrose exceeded 30 d.

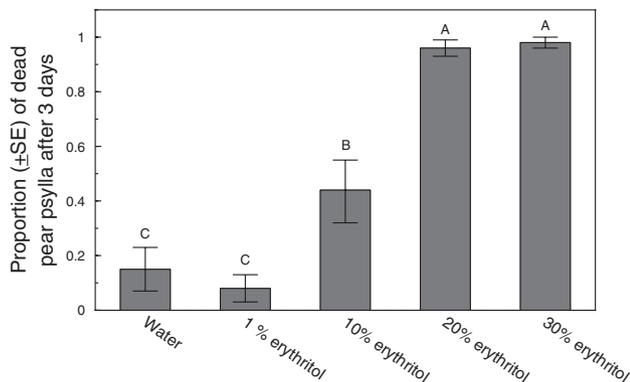


Fig. 3. Three-day mortality rates (\pm S.E.) of pear psylla fed increasing doses of erythritol in liquid diets. Different letters denote significant differences among treatment means.

Survival on Treated Leaves

Laboratory assays with excised leaves were used to examine the effects of foliar treatment of erythritol on mortality of pear psylla adults and nymphs (Fig. 4). Mortality rates of both nymphs ($F = 6.7$; d.f. = 2, 11; $P = 0.013$) and adults ($F = 6.0$; d.f. = 2, 23; $P = 0.008$) were significantly different among treatments (water, 30% sucrose, and 30% erythritol). Mortality rates of nymphs confined to leaves treated with water or sucrose were similar, but mortality was significantly higher for nymphs that were confined to leaves treated with erythritol (Fig. 4A). All pear psylla adults that were confined to leaves treated with water survived, so this treatment was removed from the analysis. As observed for nymphs, significantly more adults died after three days when confined to erythritol-treated leaves compared with those confined to sucrose-treated leaves (Fig. 4B). Nearly all nymphs, regardless of treatment were still alive three days after being briefly submersed in erythritol, sucrose, or water and then confined to untreated leaves, suggesting that the psyllicidal properties are due to exposure to erythritol on leaf surfaces, not direct topical activity.

Mean egg deposition by psyllids was higher on water-treated leaves (18.96 ± 12.22) than on erythritol-treated leaves (0.14 ± 0.14) under no-choice conditions ($F = 23.4$; d.f. = 1, 10; $P < 0.001$). Studies of fruit flies demonstrated that adults readily lay eggs in erythritol-treated substrates even when provided a choice, but adults exposed to erythritol produced substantially fewer eggs (O'Donnell et al. 2017). It seems unlikely that 3 d exposure to erythritol-treated leaves would cause a physiological reduction in egg production by pear psylla adults, so our results likely indicated that erythritol is repellent to ovipositing females or suppresses oviposition activities. This is consistent with the results of our choice-preference assays which showed a clear preference by adults for untreated versus erythritol-treated leaves (Fig. 5; $F = 16.9$; d.f. = 1, 12; $P = 0.002$).

There are several possible mechanisms by which foliar treatment of erythritol could cause mortality of pear psylla. First, the antixenotic effects of erythritol may prevent pear psylla from feeding, thus causing them to die from desiccation. To test this possibility, we compared mortality of pear psylla that were kept for three days on dry feeding plates, or on feeding plates with 30% erythritol or with water only. Nearly all pear psylla that were provided water were still living after 3 d. However, mortality rates were 100% and 77% for pear psylla that were maintained on dry plates or plates filled with erythritol solution, respectively, demonstrating that psylla cannot survive even short durations without water. It is also possible that pear psylla ingest erythritol from leaves. Erythritol may be absorbed by plant cells (Collander

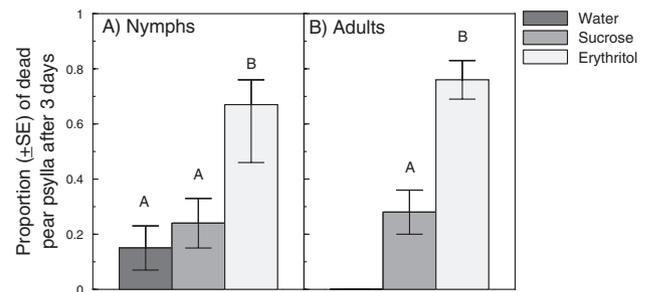


Fig. 4. Three-day mortality (\pm S.E.) of pear psylla adults (A) and nymphs (B) confined to pear leaves treated with water, 30% sucrose, or 30% erythritol. Different letters denote significant differences among treatment means.

1937) and therefore could be ingested by psylla during stylet-probing activities. Psyllids and other phloem-feeding Hemiptera initiate feeding with short-duration exploratory probes (Civolani et al. 2011), so it is also possible that psylla ingest erythritol from the surface of leaves during these initial feeding activities before probing plant tissues.

Field Trials

Repeated measures analysis of the numbers of pear psylla nymphs collected in an orchard near Moxee, WA did not indicate a significant treatment by week interaction indicating that the effects of treatment were similar among weeks ($F = 2.3$; d.f. = 4, 12; $P = 0.118$).

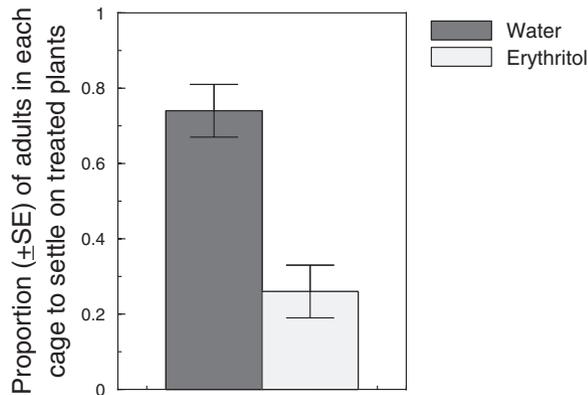


Fig. 5. Mean proportion (\pm S.E.) of the total number of pear psylla adults in each cage to settle on pear leaves treated with water (control) or 30% erythritol in preference assays.

Numbers of nymphs on all treatments declined from week 1 to week 3 (Fig. 6A; $F = 16.6$; d.f. = 2, 6; $P = 0.004$). Examination of treatment main effects showed that nymphal counts were lower on trees treated with erythritol or erythritol plus Regulaid compared with controls (Fig. 6B; $F = 6.2$; d.f. = 2, 6; $P = 0.035$). This is consistent with other reports that demonstrated insecticidal properties of erythritol under field conditions (Sampson et al. 2017, 2019). Numbers of adults did not differ among treatments ($F = 0.22$; d.f.=2, 36; $P = 0.805$) and there was no treatment by week interaction ($F = 0.9$; d.f.=10,36; $P = 0.547$), but numbers of adults generally declined each week regardless of treatment ($F = 22.0$; d.f.=5, 18; $P < 0.001$). A previous report indicated that higher concentrations of erythritol is harmful to both (*Zea mays*) and tomato (*Solanum lycopersicum*) seedlings (Scanga et al. 2018), but erythritol did not appear to damage the foliage of pear.

Repeated measures analysis of the numbers of pear psylla collected in an orchard near Wenatchee, WA did not indicate a significant treatment by week interaction for nymphs ($F = 1.4$; d.f. = 2, 8; $P = 0.312$), but populations of nymphs declined from the initial sampling date (Fig. 6C; $F = 11.1$; d.f. = 1, 4; $P = 0.029$). Although there were numerically fewer nymphs on erythritol-treated trees than on control trees on week 1 (Fig. 6D), the analysis did not indicate significant differences among treatments for nymphs ($F = 2.0$; d.f. = 2, 8; $P = 0.195$). As observed in the Moxee trial, there was no significant week by treatment interaction ($F = 0.7$; d.f. = 12, 48; $P = 0.760$) and no significant differences in psylla adults among treatments ($F = 0.5$ d.f. = 2, 8; $P = 0.608$), but pear psylla adult counts generally declined from the initial sampling date ($F = 50.2$; d.f. = 6, 24; $P < 0.001$).

The experiment conducted at the Moxee location was consistent with the results obtained from laboratory assays but results of field

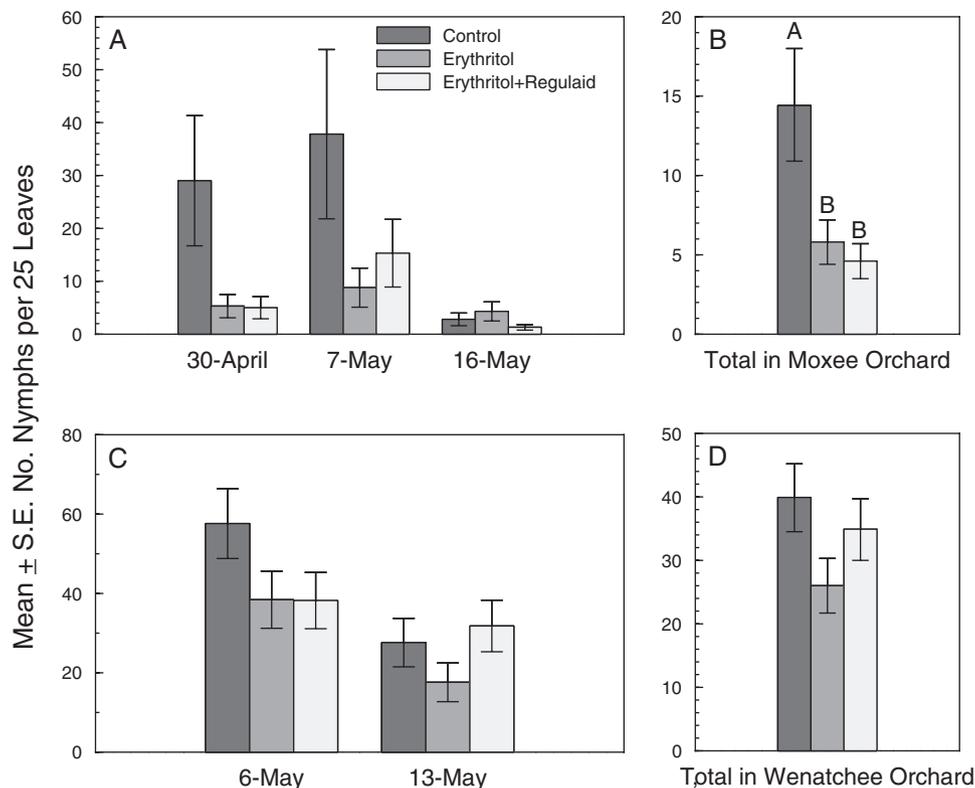


Fig. 6. Mean number (\pm S.E.) of pear psylla nymphs per 25 leaves on trees treated with control (water mixed with surfactant), erythritol, or erythritol mixed with a surfactant in orchards near Moxee, WA (A and B) or Wenatchee, WA (C and D). Different letters within dates denote significant differences among treatment means.

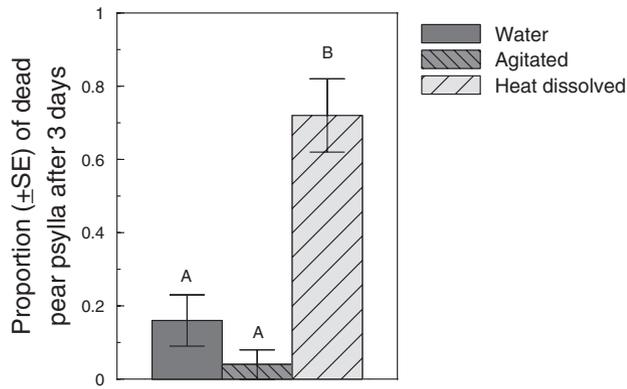


Fig. 7. Three-day mortality (\pm S.E.) of pear psylla adults confined to pear leaves treated with water, 30% erythritol that was agitated into solution, or 30% erythritol that was dissolved into solution by heating to 31°C. Different letters denote significant differences among treatment means.

experiments from the two locations differed. The major difference in methods used at the two locations is the method in which the erythritol treatments were prepared. Solutions were heated to 31°C to help dissolve the erythritol before treatment of trees at the Moxee location, but not before treatment at the Wenatchee location. We conducted a follow-up laboratory experiment using excised leaves to compare pear psylla survival on leaves treated with erythritol that was dissolved into solution by heating versus erythritol that was mixed by agitation in water without heat. That experiment indicated that heat-dissolving is required for erythritol to be effective as an insecticide against pear psylla when applied to pear leaves (Fig. 7; $F = 9.4$; d.f. = 2, 11; $P = 0.004$). Erythritol is reportedly heat stable above 180°C (Perko and DeCock 2008), so it is unlikely that heating to 31°C altered the chemical structure of erythritol applied to trees. Instead, heating likely helps to completely dissolve erythritol into solutions at high concentrations providing better efficacy against a phloem-feeding insect.

Conclusions

Results of our study demonstrate that erythritol is lethal to pear psylla nymphs and adults and that the psyllicidal effects of erythritol are dose-dependent up to 20% w/v. We also showed in both laboratory and field trials that erythritol is lethal to pear psylla when applied topically to leaves, but erythritol is more effective against pear psylla when gentle heating is used to help dissolve the erythritol into solution. The mechanisms by which erythritol is lethal to pear psylla are not yet known, but our results suggest that they may include a combination of antixenotic and antibiotic effects. Tang et al. (2017) showed that erythritol accumulates in the hemolymph of insects, elevates osmotic pressure, and interferes with cellular processes. If erythritol accumulates in the hemolymph of pear psylla as shown for fruit flies, then natural enemies that feed on pear psylla may be impacted if the psylla had previously ingested erythritol. Further work is therefore needed to examine the nontarget effects of erythritol on key natural enemies.

This report adds to the growing body of literature that indicates that erythritol is insecticidal to insects (Braudier et al. 2014, O'Donnell et al. 2016, Choi et al. 2017, Zhang et al. 2017, Sampson et al. 2019). Our study is the first to show that erythritol is lethal to a phloem-feeding insect. Erythritol is safe for human consumption (Storey et al. 2007) and is a popular

alternative to sucrose in low calorie or diabetic diets. Results of our study indicate that erythritol could be used as a safe and effective tool for management of pear psylla that may be applied close to pear harvest when the number of products for use against this pest are limited by preharvest intervals. Studies are needed to determine whether erythritol is insecticidal to other psyllid pests, including the vectors of 'Candidatus Liberibacter' potato psyllid (*Bactericera cockerelli* (Šulc); Trioziidae) and citrus psyllid (*Diaphorina citri* Kuwayama; Lividae).

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References Cited

- Braudier, K. M., S. D. Kaschock-Marenda, N. Patel, K. L. Diangelus, S. O'Donnell, and D. R. Marenda. 2014. Erythritol, a non-nutritive sugar alcohol sweetener and the main component of Truvia, is a palatable insecticide. *PLoS One* 9: e9849.
- Burgess, E. R., and B. H. King. 2018. Insecticidal potential of two sugar alcohols to *Musca domestica* (Diptera: Muscidae). *J. Econ. Entomol.* 110: 2252–2258.
- Burts, E. C., H. E. van de Baan, and B. A. Croft. 1989. Pyrethroid resistance in pear psylla, *Psylla pyricola* Forester (Homoptera: Psyllidae), and synergism of pyrethroids with piperonyl butoxide. *Can. Entomol.* 121: 219–223.
- Caponera, V., M. Barrett, D. R. Marenda, and S. O'donnell. 2020. Erythritol ingestion causes concentration-dependent mortality in Eastern Subterranean termites (Blattodea: Rhinotermitidae). *J. Econ. Entomol.* 113: 348–352.
- Choi, M. Y., S. B. Tang, S. J. Ahn, K. G. Amarasekare, P. Shearer, and J. C. Lee. 2017. Effect of non-nutritive sugars to decrease the survivorship of spotted wing drosophila, *Drosophila suzukii*. *J. Insect Physiol.* 99: 86–94.
- Choi, M. Y., H. Lucas, R. Sagili, D. H. Cha, and J. C. Lee. 2019. Effect of Erythritol on *Drosophila suzukii* (Diptera: Drosophilidae) in the presence of naturally-occurring sugar sources, and on the survival of *Apis mellifera* (Hymenoptera: Apidae). *J. Econ. Entomol.* 112: 981–985.
- Civolani, S., M. Leis, G. Grandi, E. Garzo, E. Pasqualini, S. Musacchi, M. Chicca, G. Castaldelli, R. Rossi, and W. F. Tjallingii. 2011. Stylet penetration of *Cacopsylla pyri*; an electrical penetration graph (EPG) study. *J. Insect Physiol.* 57: 1407–1419.
- Collander, R. 1937. The permeability of plant protoplasts to non-electrolytes. *Trans. Faraday Soc.* 33: 985–990.
- Cooper, W. R., and D. R. Horton. 2017. Elicitors of host plant defenses partially suppress *Cacopsylla pyricola* (Hemiptera: Psyllidae) populations under field conditions. *J. Insect Sci.* 17: 1–5.
- Cooper, W. R., J. W. Dillwith, and G. J. Puterka. 2010. Salivary proteins of Russian wheat aphid (Hemiptera: Aphididae). *Environ. Entomol.* 39: 223–231.
- Cooper, W. R., K. D. Swisher, S. F. Garczynski, T. Mustafa, J. E. Munyaneza, and D. R. Horton. 2015. Wolbachia infection differs among divergent mitochondrial haplotypes of *Bactericera cockerelli* (Hemiptera: Trioziidae). *Ann. Entomol. Soc. Am.* 108: 137–145.
- Courtney, R. 2017. Pear psylla, just like spider mites, showing resistance to pesticides. *Good Fruit Grower*, April 1st 2017. <https://www.goodfruit.com/pear-psylla-just-like-spider-mites-showing-resistance-to-pesticides/>. Accessed 28 May 2020.

- Gallardo, R. K., J. F. Brunner, and S. Castagnoli. 2016. Capturing the economic value of biological control in western tree fruit. *Biol. Control*. 102: 93–100.
- Gilkey, P. L., D. T. Bolshakov, J. G. Kowala, L. A. Taylor, S. O'Donnell, D. R. Marena, and L. K. Sirot. 2018. Lethal effects of erythritol on the mosquito *Aedes aegypti* Linnaeus (Diptera: Culicidae). *J. Appl. Entomol.* 142: 873–881.
- Horton, D. R., D. A. Broers, T. Hinojosa, and T. M. Lewis. 1998. Ovarian development in overwintering pear psylla, *Cacopsylla pyricola* (Homoptera: Psyllidae): seasonality and effects of photoperiod. *Can. Entomol.* 130: 859–867.
- Horton, D. R., C. Guedot, and P. J. Landolt. 2007. Diapause status of females affects attraction of male pear psylla, *Cacopsylla pyricola*, to volatiles from female-infested pear shoots. *Entomol. Exp. Appl.* 123: 185–192.
- Jimenez, F., W. R. Cooper, S. F. Garczynski, G. J. Puterka, and N. M. Barcenas. 2017. Collection of salivary proteins of psyllids (Hemiptera: Psylloidea). *J. Entomol. Sci.* 52: 201–206.
- Krysan, J. L. and B. S. Higbee. 1990. Seasonality of mating and ovarian development in overwintering *Cacopsylla pyricola* (Homoptera: Psyllidae). *Environ. Entomol.* 19: 544–550.
- Marena, D. R. and S. O'Donnell. 2015. Use of erythritol or compositions comprising same as mammal-safe insecticides. Patent # W2015/153957.
- Murray, K. and J. DeFrancesco. 2014. Pest management strategic plan for pears in Oregon and Washington. https://agsci.oregonstate.edu/sites/agscid7/files/nwrec/attachments/pear_pmsp_-_final_-_pdf_version.pdf. Accessed 28 May 2020.
- O'Donnell, S., K. Baudier, and D. R. Marena. 2016. Non-nutritive polyol sweeteners differ in insecticidal activity when ingested by adult *Drosophila melanogaster* (Diptera: Drosophilidae). *J. Insect Sci.* 16: 47.
- O'Donnell, S., K. Baudier, K. Fiocca, and D. R. Marena. 2017. Erythritol ingestion impairs adult reproduction and causes larval mortality in *Drosophila melanogaster* fruit flies (Diptera: Drosophilidae). *J. Appl. Entomol.* 142: 37–42.
- Perko, R., and P. DeCock. 2008. Erythritol. In, *Sweeteners and sugar alternatives in food technology*, pp 155. H. Mitchell (ed.). Blackwell Publishing Ltd, Ames, IA.
- Sampson, B. J., C. T. Werle, S. J. Stringer, and J. J. Adamczyk. 2017. Ingestible insecticides for spotted wing drosophila control: a polyol, erythritol, and an insect growth regulator, Lufenuron. *J. Appl. Entomol.* 141: 8–18.
- Sampson, B. J., M. W. Easson, S. J. Stringer, C. T. Werle, D. Magee, and J. J. Adamczyk. 2019. Laboratory and field assessments of erythritol derivatives on the survival, reproductive rate, and control of *Drosophila suzukii* (Diptera: Drosophilidae). *J. Econ. Entomol.* 112: 173–180.
- Scanga, S. E., B. Hasanspahić, E. Zvorničanin, J. Samardžić Koženjić, A. K. Rahme, and J. H. Shinn-Thomas. 2018. Erythritol, at insecticidal doses, has harmful effects on two common agricultural crop plants. *PLoS One*. 13: e0192749.
- Storey, D., A. Lee, F. Bornet, and F. Brouns. 2007. Gastrointestinal tolerance of erythritol and xylitol ingested in a liquid. *Eur. J. Clin. Nutr.* 61: 349–354.
- Tang, S. B., J. C. Lee, J. K. Jung, and M. Y. Choi. 2017. Effect of erythritol formulation on the mortality, fecundity and physiological excretion in *Drosophila suzukii*. *J. Insect Physiol.* 101: 178–184.
- Ullman, D. R., and D. L. McLean. 1988. Feeding behavior of the winter-form pear psylla, *Psylla pyricola* (Homoptera: Psyllidae), on reproductive and transitory host plants. *Environ. Entomol.* 17: 675–678.
- Van De Baan, H., and A. Croft. 1991. Resistance to insecticides in winter- and summer-forms of pear psylla, *Psylla pyricola*. *Pest. Manage. Sci.* 32: 225–233.
- Westigard, P. H. and R. W. Zwick. 1972. The pear psylla in Oregon. Oregon State University Agricultural Experiment Station Technical Bulletin 122, USDA Bulletins, Washington DC.
- Zhang, X., S. Chen, Z. Li, and Y. Xu. 2017. Effect of sweeteners on the survival of *Solenopsis invicta* (Hymenoptera: Formicidae). *J. Econ. Entomol.* 110: 593–597.