Effects of Insecticides on *Protaphorura fimata* (Collembola: Poduromorpha: Onychiuridae) Feeding on Germinating Lettuce[1]

Shimat V. Joseph[2]

University of California Cooperative Extension, 1432 Abbott Street, Salinas, California 93901, USA

J. Entomol. Sci. 52(1): 68–81 (January 2017)

Abstract The springtail, *Protaphorura fimata* Gisin (Onychiuridae), was recently identified as a serious subterranean pest of lettuce (*Lactuca sativa* L. [Asteraceae]) in the Salinas Valley of California and little is known about efficacy of insecticides to control it. The efficacy of 15 insecticides was determined against *P. fimata* individuals by evaluating their feeding injury on germinating lettuce seeds in three laboratory experiments. In two experiments, a low density of *P. fimata* (50 individuals) was exposed to insecticide-treated substrates (filter paper and soil); a high density of *P. fimata* (100 individuals) was exposed to insecticide-treated soil in the third experiment. In all three experiments, 25 uncoated, untreated lettuce seeds were placed on the surface of treated substrate and exposed to *P. fimata* for 7 d. Significantly more *P. fimata* individuals and their feeding injury were found in the distilled water (control) treatment than any insecticide treatments. Overall, percentage of injured seedlings and number of feeding sites per seedling were significantly reduced in all the insecticide treatments particularly with pyrethroid (zeta-cypermethrin, bifenthrin, and lambda-cyhalothrin) and neonicotinoid (dinotefuran, thiamethoxam, and clothianidin) insecticides, as well as tolfenpyrad, chlorpyrifos, and spinetoram (0 to ∼3% injured seedlings) compared with distilled water (up to ∼85% injured seedlings). Although cyantraniliprole, novaluron, flonicamid, and flupyradifurone insecticides reduced *P. fimata* feeding on germinating lettuce seeds relative to distilled water, their efficacy against *P. fimata* was inferior to other insecticides, especially in the high *P. fimata* density experiment.

Key Words springtail, pyrethroid, neonicotinoid, vegetable production, Salinas Valley

The subterranean springtail, *Protaphorura fimata* Gisin (Onychiuridae), is a serious pest of the direct-seeded crops, lettuce (*Lactuca sativa* L. [Asteraceae]) and broccoli (*Brassica oleracea* var. *italica* Plenck [Brassicaceae]), in the Salinas Valley of California (Joseph et al. 2015). *Protaphorura fimata* feeds on developing seeds of these crops results in severe stunting and even seedling mortality (Joseph et al. 2015, S.V.J. unpubl. data). In the field, *P. fimata* feeding symptoms develop into nonuniform to complete stand loss. In the Salinas Valley, lettuce alone is valued ∼US$1.4 billion and broccoli ∼US$412 million (Monterey County Agricultural Commissioner 2014). Although lettuce and broccoli are grown year round in the Salinas Valley, *P. fimata*–related stand losses have been mostly reported during spring and early summer months (from January through May). Studies showed that

[1]Received 7 June 2016; accepted for publication 26 September 2016.
[2]Corresponding author (email: shimatbug@gmail.com).

P. fimata individuals are active in cooler temperatures (~15°C) and cause feeding injury to slowly germinating lettuce seeds (S.V.J. unpubl. data).

Until recently, soil pests such as garden symphylan (*Scutigerella immaculata* Newport [Symphyla: Scutigerellidae]), springtails, and root-feeding maggots (*Delia* spp. [Diptera: Anthomyiidae]) were managed using organophosphate insecticides such as chlorpyrifos and diazinon (Natwick 2009a, 2009b; S.V.J. unpubl. data). The persistent use of organophosphate insecticides has resulted in higher levels of the insecticide residues in water bodies (Hunt et al. 2003) posing risks to nontarget organisms and public health through contaminated water. Currently, use of organophosphate insecticides is strictly regulated (California Environmental Protection Agency 2013) forcing growers to use other soil insecticides to combat soil pests including *P. fimata* with limited knowledge on their efficacy. Therefore, there is an urgent need to determine effective insecticides for *P. fimata* control.

Previously, efficacy of insecticides was tested against similar soil-dwelling Collembola through both laboratory bioassays (Getzin 1985, Thompson and Gore 1972, Tomlin 1975) and field experiments (Boetel et al. 2008). The results from these studies showed that efficacy of insecticides varied among Collembola species (Tomlin 1975), which warrants a species-specific evaluation. The organophosphate insecticide terbofos was most effective in suppressing onychiurid springtails, *Folsomia candida* (Willem), *Onychiurus justi porteri* (Denis), and *Hypogastrura armata* (Nicolet) when compared with phorate, carbofuran, heltachlor, methomyl, and chlorfenvinphos (Tomlin 1975), whereas, in another study, the carbamate insecticides carbofuran, thiofanox, aldicarb, and methiocarb outperformed organophosphate insecticides in suppressing the onychiurid *Onychiurus pseudarmatus* Folsom (Getzin 1985). Thompson and Gore (1972) showed that methomyl, dieldrin, and heptachlor caused significant *F. candida* mortality when 29 insecticides were tested. Similarly, in another study, residues of zinophos (O, O-diethyl O-pyrazinyl phosphoro-thioate), carbofuran, diazinon, and dieldrin effectively suppressed *F. candida* up to 16 weeks at 13°C (Thompson 1973). Unfortunately, most of these effective insecticides are currently phased out or restricted from use because of their nontarget effects, off-site movement, and prolonged persistence in the environment. These older insecticides are not available for *P. fimata* control in California. Moreover, newer insecticides, which are often referred as reduced-risk insecticides, such as spinetoram and tolfenpyrad have not been evaluated for their efficacy against *P. fimata*. Insecticide efficacy studies in the field for *P. fimata* are often challenged by poor *P. fimata* population size and inadequate feeding damage. Thus, the major objective of the present study was to determine efficacy of common insecticides against *P. fimata* based on parameters of their feeding injury on germinating lettuce seeds in the laboratory.

Materials and Methods

Arthropods. The experiments were conducted at the University of California Cooperative Extension, Entomology laboratory in Salinas, CA. *Protaphorura fimata* individuals were field-collected in 2014 and identified as *P. fimata* using the keys provided in Christiansen and Bellinger (1998), Fjellberg (1998), and Pomorski (1998); these individuals were used to establish laboratory colonies. The colonies were maintained in sealed 473.1-ml clear plastic containers (Frontier Agricultural Sciences, Newark, DE; product 9061) and were fed with fish food flakes (Wardley, The Hartz Mountain Corp., Secaucus, NJ) at biweekly intervals. A layer of Clear Lake clay (50% clay; ~20% sand; pH 8; ~1.7% organic matter [USDA SCS 1978]) soil (2 cm) was placed on the bottom of the containers and covered with moist paper towel. The *P. fimata* containers were sprayed with tap water at biweekly intervals to keep the soil moist. The containers were retained at 20°C; ~ 45% relative humidity (RH), in complete darkness in the laboratory cabinet. The voucher specimens were deposited with the University of California Cooperative Extension in Salinas, CA.

Soilless bioassay. This experiment was conducted in a soilless interface because the likelihood of direct exposure of introduced *P. fimata* individuals to insecticides would be greater in this situation than in the natural soil interface. An experiment unit consisted of a 4.5-cm-diameter plastic petri dish (Fisher Scientific, Pittsburgh, PA) with a Whatman No.1 filter paper (GE Healthcare UK Ltd., Little Chalsont, Buckinghamshire, UK) soaked in 50 ml of insecticidal solution or distilled water for 5 s placed inside it. The insecticides used for the bioassay are listed in Table 1. Because water volume used by the growers in Salinas Valley varies between 280.6 and 560.7 L/ha when applied using a tractor-mounted sprayer, an intermediate water volume of 373.9 L/ha was selected for the bioassay. Twenty-five uncoated and untreated 'Little Gem' lettuce seeds (Snow Seeds Co., Salinas, CA) were added on to the moistened filter paper before the *P. fimata* individuals were introduced. *Protaphorura fimata* feeding injury was noticed on germinating lettuce seeds at 20, 50, and 100 *P. fimata* densities (Joseph et al. 2015). Therefore, an intermediate density of 50 individuals was chosen for soilless bioassay. A day before the experiment, a moist paper towel was placed over the soil in the containers with the colonies of *P. fimata* and was sprinkled with fish food. On the day of the experiment, a substantial number of *P. fimata* moved from the soil to the paper towel feeding on the fish food. The paper towel was carefully removed from the soil surface, and the required numbers of *P. fimata* were added to the petri dishes using a paintbrush. *Protaphorura fimata* have rudimentary furcula and did not spring while transferring or after introduction to the petri dish. Also, *P. fimata* individuals were not too mobile and did not make erratic movements and, therefore, were not subjected to CO_2 or freeze exposure. After adding 50 *P. fimata* individuals into a petri dish, the dish was covered using clear plastic wrap (Glad Cling Plastic Wrap, Glad Products Co., Oakland, CA) and secured using Parafilm® (Bemis Company, Inc. Oshkosh, WI) around the edge of the petri dish. This experiment was conducted in multiple trials where each trial was comprised of three or four insecticide treatments plus distilled water (control). The insecticide treatments included in a trial were replicated five times, and each such trial was repeated three times. Thus, each insecticide treatment was replicated 15 times (petri dishes) with a total of 750 *P. fimata* individuals per insecticide treatment (product). The distilled water treatment (control) was included with every trial and, therefore, was replicated 60 times (3,000 *P. fimata* individuals). The petri dish bioassays were maintained at ~21°C, light:dark 16:8 photoperiod, and ~45% RH for 7 d in a controlled environmental chamber.

Soil bioassay. The Clear Lake clay soil was collected from a field in Salinas, CA, where *P. fimata* were naturally found. The soil was then oven-dried at ~105°C for 48 h and used in the bioassay. Ten grams of oven-dried soil was added to a

Table 1. Insecticides evaluated against *P. fimata* in the laboratory bioassay.

Class	Insecticide	Formulation	Tested rate (g A.I. per ha)
Neonicotinoids	Clothianidin	Belay EC	224.05
	Dinotefuran	Venom	294.64
	Thiamethoxam	Platinum SC	55.5
Pyrethroids	Bifenthrin	Capture LFR	89.61
	Lambda-cyhalothrin	Warrior II EC	27.98
	Zeta-cypermethrin	Mustang EC	55.99
Neonicotinoids + Pyrethroids	Imidacloprid + Beta-cyfluthrin	Leverage EC	52.56 + 25.85
Neonicotinoids + Ryanodine receptor activator	Thiamethoxam + Chlorantraniliprole	Durivo EC	189.60 + 94.05
Organophosphates	Chlorpyrifos	Lorsban Advanced	1367.12
Spinosyn	Spinetoram	Radiant SC	87.52
Ryanodine receptor activator	Cyantraniliprole	Verimark SC	197.18
Pyridazinone	Tolfenpyrad	Torac EC	237.11
Pyridinecarboxamide	Flonicamid	Beleaf 50 SG	99.71
Benzoylurea	Novaluron	Rimon 0.83 EC	87.17
Butenolides	Flupyradifurone	Sivanto SL 200	409.2

29.6-ml clear plastic container (Frontier Agricultural Sciences; product 9051). Twenty-five uncoated, untreated ‘Little Gem’ lettuce seeds (Snow Seeds Co.) were placed on the soil surface within the container, thus constituting an experimental unit. The soil in the container was moistened with 4.5 ml insecticide solution or distilled water. The insecticides used for the bioassay are listed in Table 1. After inoculating with *P. fimata*, the containers were covered using clear plastic wrap and secured using Parafilm around the edge of the containers.

The soil bioassay was conducted with two *P. fimata* densities (50 and 100 individuals). The density selection was based on injury detected in Joseph et al. (2015). This experiment was conducted in multiple trials where each trial comprised three or four insecticide treatments plus a distilled water control. Each treatment was repeated five times within a trial and each trial was repeated three times. The distilled water treatment (control) was added to every trial of the experiment. The bioassay with 50 individuals was replicated 15 times per treatment, and the bioassay with 100 individuals was replicated 10 times per treatment. The same

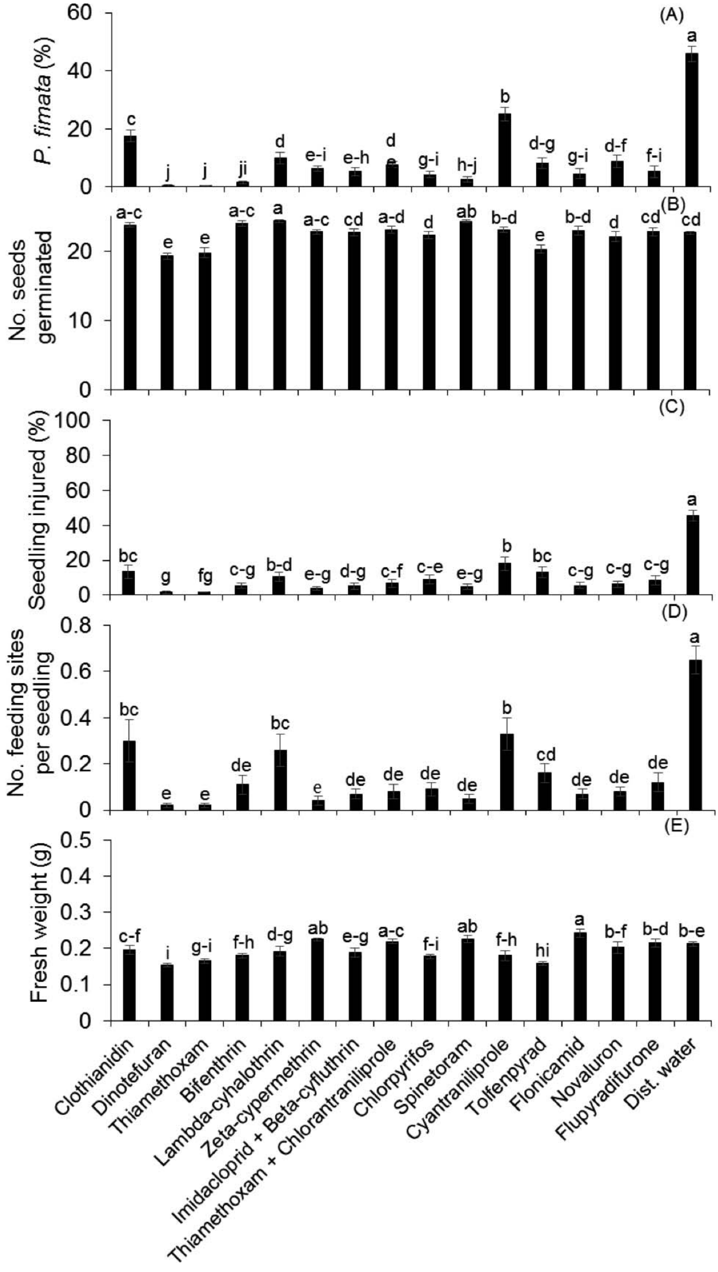

Fig. 1. Mean (± SE) (A) *P. fimata* (%) observed on the insecticide-treated substrate surface within 10 s, (B) number of seed germinated, (C) percentage of seedlings with feeding injury, (D) number of feeding injury sites per seedling, and (E) fresh weight (g) of total seedlings after exposing 50 *P. fimata* to germinating lettuce seeds in insecticide-

method described in the soilless bioassay was used to transfer *P. fimata* to the bioassay containers. All the bioassays were maintained in a controlled environmental chamber at ~21°C, light:dark 16:8 photoperiod, and ~45% RH; and evaluated after 7 d.

Evaluation. After 7 d of exposure, the number of actively moving *P. fimata* individuals on the surface of the substrate (filter paper or soil) was quantified within 10 s. The *P. fimata* feeding injury to germinating lettuce is described in Joseph et al. (2015). *Protaphorura fimata* feeding on lettuce appeared as discolored discrete areas with sections of tissue removed when observed under 10× magnification with a dissecting scope. These discolored discrete feeding areas are referred to as "feeding injury sites." The seeds were determined to be germinated if the radicle had emerged from the seed coat. The same set of parameters was used to evaluate the effect of insecticides in all the trials. The parameters documented were number of seeds germinated (out of 25 seeds), number of seedlings with at least one feeding injury site, and total number of feeding injury sites in all the emerged seedlings. In addition, fresh weight of all the lettuce seedlings per replicate (container) was recorded. The seedlings were cut at the crown area and plant material above soil level was used for evaluation.

Statistical analyses. All data were analyzed by bioassay type (substrate or *P. fimata* density). The number of injured seedlings was expressed as proportion of *P. fimata*–injured seedlings of the total seedlings. The total number of feeding injury sites on the seedlings was expressed as number of feeding injury sites per seedling. The number of live *P. fimata* individuals found on the surface of the substrate was converted into proportions. The number of germinated seeds out of 25 seeds, number of feeding sites per germinated seed, and fresh weight of the seedlings were log-transformed ($\ln[x+1]$) to establish homogeneity of variance. The proportion data, live *P. fimata* on surface, and injured seedlings data were arcsine square root transformed. Transformed data were subjected to analysis of variance using the generalized linear model (PROC GLM) procedure in SAS (Version 9.4, SAS Institute Inc., Cary, NC) by bioassay type. The means were separated using the Tukey's HSD method ($\alpha = 0.05$). The relationship between the mean number of *P. fimata* feeding injury sites and fresh weight was analyzed with linear regression (JMP 12.01, SAS Institute).

Results

Soilless bioassay. Significantly more *P. fimata* were detected on distilled water than on most of the insecticide treatments ($F = 38.5$; df = 15, 229; $P < 0.001$; Fig. 1A). Similarly, cyantraniliprole and clothianidin treatments had more *P. fimata* than other insecticide treatments, although significantly more *P. fimata* were detected in cyantraniliprole than in the clothianidin treatment. The number of germinated seeds was significantly lower in dinotefuran and thiamethoxam than in distilled water ($F = 11.6$; df = 15, 229; $P < 0.001$; Fig. 1B). The percentage of injured seedlings ($F =$

←

treated soilless media (filter paper). Means with the same letters on bars are not significantly different ($P > 0.05$).

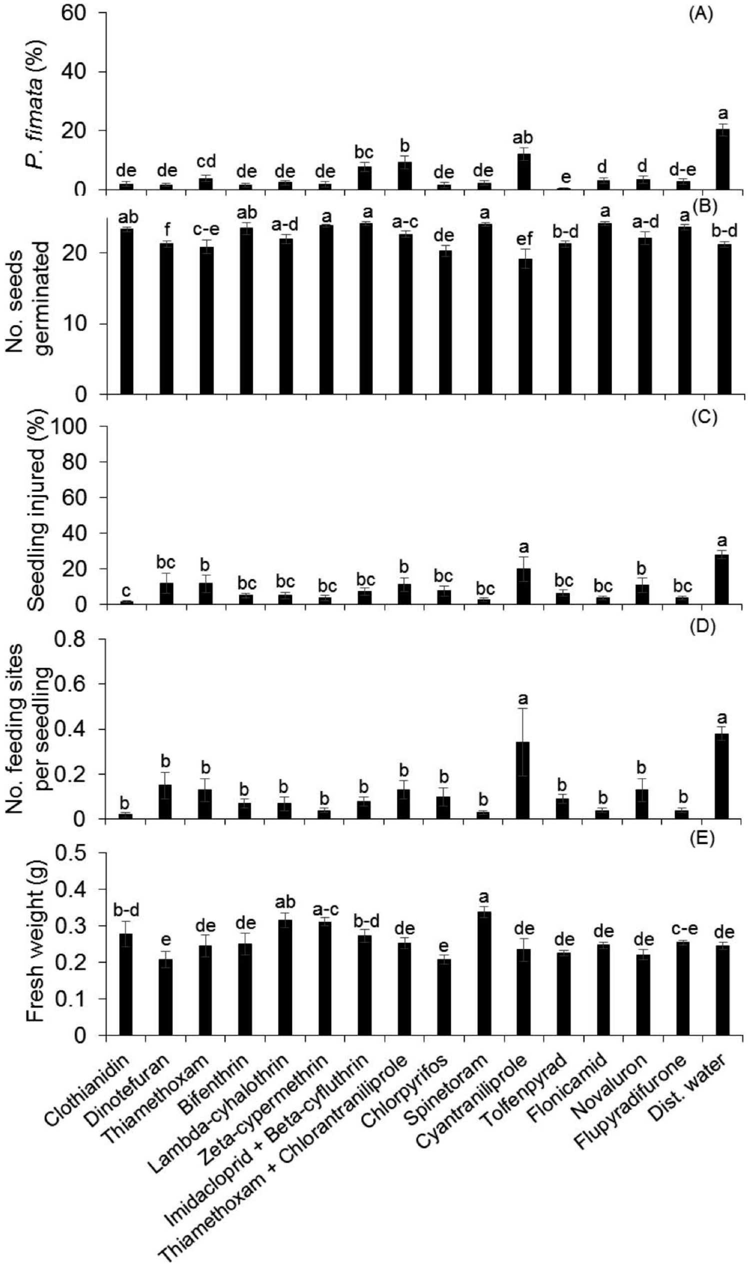

Fig. 2. Mean (± SE) (A) *P. fimata* (%) observed on the insecticide-treated substrate surface within 10 s, (B) number of seed germinated, (C) percentage of seedlings with feeding injury, (D) number of feeding injury sites per seedling, and (E) fresh weight (g) of total seedlings after exposing 50 *P. fimata* to germinating lettuce seeds in insecticide-

15.2; df = 15, 229; $P < 0.001$; Fig. 1C) was significantly greater in distilled water than in the insecticide treatments. The percentage of injured seedlings was lower in dinotefuran, thiamethoxam, bifenthrin, zeta-cypermethrin, imidacloprid + beta-cyfluthrin, spinetoram, flonicamid, novaluron, and flupyradifurone than in clothianidin and cyantraniliprole treatments. Feeding sites per seedling were significantly lower in dinotefuran, thiamethoxam, bifenthrin, zeta-cypermethrin, imidacloprid + beta-cyfluthrin, thiamethoxam + chlorantraniliprole, chlorpyrifos, spinetoram, flonicamid, novaluron, and flupyradifurone than in clothianidin, lambda-cyhalothrin, cyantraniliprole, and distilled water treatments ($F = 19.2$; df = 15, 229; $P < 0.001$; Fig. 1D). Fresh weight of lettuce seedlings was significantly greater in flonicamid, zeta-cypermethrin, spinetoram, and thiamethoxam + chlorantraniliprole than in chlorpyrifos, thiamethoxam, tolfenpyrad, and dinotefuran treatments ($F = 7.6$; df = 15, 229; $P < 0.001$; Fig. 1E). The relationship between mean feeding sites per seedling and fresh weight of seedlings was not significant among the insecticide treatments ($R^2 = 0.004$, $P = 0.803$; $y = 0.194 + 0.011x$).

Soil bioassay. In the low-density bioassay (50 *P. fimata*), the distilled water treatment had a significantly greater percentage of *P. fimata* on the soil surface than all the insecticide treatments ($F = 18.6$; df = 15, 244; $P < 0.001$; Fig. 2A) except cyantraniliprole. There was no significant difference in *P. fimata* detection in soil surface among cyantraniliprole, thiamethoxam + chlorantraniliprole, and imidacloprid + beta-cyfluthrin treatments. The number of seeds that germinated was significantly greater in zeta-cypermethrin, imidacloprid + beta-cyfluthrin, spinetoram, flonicamid, and flupyradifurone treatments than in distilled water ($F = 6.6$; df = 15, 244; $P < 0.001$; Fig. 2B). The percentage of injured seedlings was significantly greater in the distilled water than in insecticide treatments ($F = 8.9$; df = 15, 244; $P < 0.001$; Fig. 2C) except cyantraniliprole. A significantly lower percentage of seedlings were injured when treated with clothianidin than thiamethoxam and thiamethoxam + chlorantraniliprole treatments. Similarly, the number of feeding sites was significantly greater in distilled water and cyantraniliprole than in the remainder of the insecticide treatments ($F = 10.4$; df = 15, 244; $P < 0.001$; Fig. 2D). The fresh weight of seedlings was not significantly different among spinetoram, lambda-cyhalothrin and zeta-cypermethrin, but they were significantly greater than dinotefuran, bifenthrin, thiamethoxam + chlorantraniliprole, chlorpyrifos, cyantraniliprole, tolfenpyrad, flonicamid, novaluron, and distilled water ($F = 3.3$; df = 15, 244; $P < 0.001$; Fig. 2E). Based on regression analysis, the mean feeding sites per seedling and fresh weight of seedlings were not significantly related among the insecticide treatments ($R^2 = 0.165$, $P = 0.117$; $y = 0.274 + 0.147x$).

In the high-density bioassay (100 *P. fimata*), the percentage of *P. fimata* on the soil surface was significantly lower in most of the insecticide treatments compared with cyantraniliprole and distilled water treatments ($F = 26.4$; df = 15, 135; $P < 0.001$; Fig. 3A). There was no significant difference in number of germinated seeds among insecticide treatments as well as compared with distilled water ($F = 1.0$; df =

←

treated soil substrate. Means with the same letters on bars are not significantly different ($P > 0.05$).

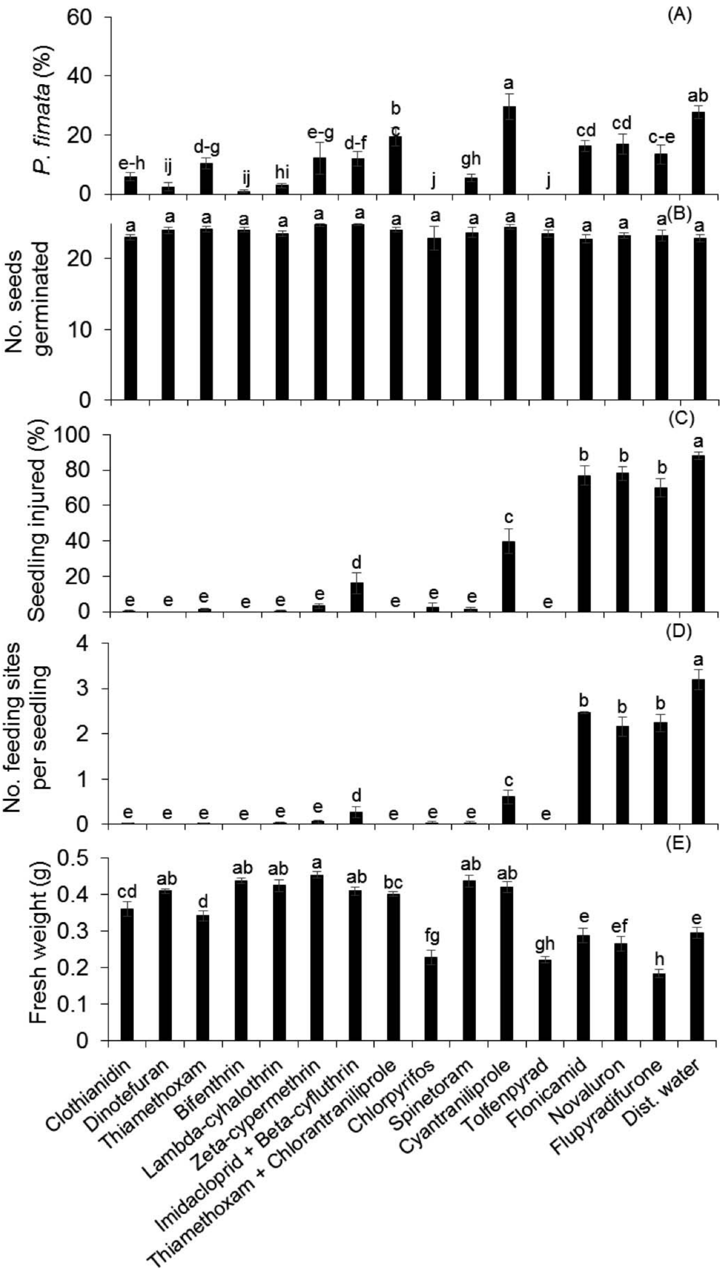

Fig. 3. Mean (± SE) (A) *P. fimata* (%) observed on the insecticide-treated substrate surface within 10 s, (B) number of seed germinated, (C) percentage of seedlings with feeding injury, (D) number of feeding injury sites per seedling, and (E) fresh weight (g) of total seedlings after exposing 100 *P. fimata* to germinating lettuce seeds in insecticide-

15, 135; $P < 0.001$; Fig. 3B). The percentage of injured seedlings ($F = 87.3$; df = 15, 135; $P < 0.001$; Fig. 3C) and feeding sites per seedling ($F = 92.3$; df = 15, 135; $P < 0.001$; Fig. 3D) were significantly lower with all the insecticide treatments than with distilled water. However, clothianidin, dinotefuran, thiamethoxam, bifenthrin, lambda-cyhalothrin, zeta-cypermethrin, thiamethoxam + chlorantraniliprole, chlorpyrifos, spinetoram, and tolfenpyrad caused significantly lower percentages of injured seedlings and feeding sites per seedling than imidacloprid + beta-cyfluthrin, cyantraniliprole, flonicamid, novaluron, flupyradifurone, and distilled water. Imidacloprid + beta-cyfluthrin had significantly lower percentages of injured seedlings and feeding sites per seedling than cyantraniliprole treatment. The percentages of injured seedlings and feeding sites per seedling were significantly lower in cyantraniliprole than in flonicamid, novaluron, and flupyradifurone treatments. The fresh weight of seedlings was significantly greater in the zeta-cypermethrin, bifenthrin, spinetoram, lambda-cyhalothrin, cyantraniliprole, imidacloprid + beta-cyfluthrin, dinotefuran, thiamethoxam + chlorantraniliprole, clothianidin, and thiamethoxam than in the distilled water treatment ($F = 30.5$; df = 15, 135; $P < 0.001$; Fig. 3E). The mean feeding sites per seedling and fresh weight of seedlings were significantly related among the insecticide treatments (Fig. 4), where lower fresh weight and higher feeding injury was observed when treated with flonicamid, novaluron, and flupyradifurone and distilled water.

Discussion

Efficacy of insecticides on *P. fimata* was indirectly evaluated based on the ability of *P. fimata* to feed on germinating lettuce seeds placed in the soil after insecticide exposure. In all the bioassays, the number of *P. fimata* individuals and their feeding injury was greater in the distilled water treatment than in any of the insecticide treatments, which suggests that *P. fimata* activity was less affected by distilled water. Previously, efficacy of insecticides against pestiferous Collembola (Getzin 1985, Thompson and Gore 1972, Tomlin 1975) was determined by quantifying pest mortality when they were exposed to lethal doses. In this study, the efficacy of insecticides was determined by *P. fimata* motor activity and feeding. The initial bioassay was conducted in a simple system with soilless interface, but later bioassays were set up with a complex soil interface because soil-borne *P. fimata* are possibly exposed to insecticide residues applied on the soil surface in the field.

The data suggest that all the insecticides reduced *P. fimata* feeding at various intensities on germinating lettuce seeds relative to untreated check. Overall, the feeding activity of *P. fimata* was lesser at lower *P. fimata* densities (50 individuals) than the higher density (100 individuals). In experiments with lower density (both with soilless and soil substrate), cyantraniliprole was the only insecticide that resulted in more feeding injury on germinating seeds compared with other insecticides. However, at the higher *P. fimata* density, more feeding injury was noticed on germinating lettuce with cyantraniliprole, flonicamid, novaluron, and

---

←

treated soil substrate. Means with the same letters on bars are not significantly different ($P > 0.05$).

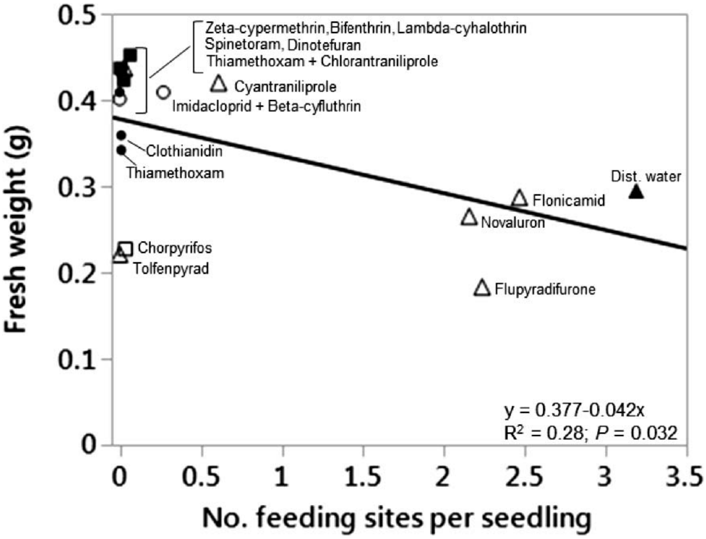

Fig. 4. The relationship between mean number of *P. fimata* feeding sites per seedling and mean fresh weight of seedlings. The symbols: • = neonicotinoid; ○ = combination product with neonicotinoid; ■ = pyrethroid; □ = organophosphate; Δ= reduced-risk insecticide; and ▲= untreated in the high-density experiment.

flupyradifurone than pyrethroid and neonicotinoid insecticides as well as chlorpyrifos, spinetoram, and tolfenpyrad. *Protaphorura fimata* can cause economic impacts from feeding injury when the population size increases in the upper soil layer surrounding germinating seeds (S.V.J. unpubl. data). Similarly, Joseph et al. (2015) showed that *P. fimata* density dramatically increases at the germinating phase of lettuce causing irregular stand.

The pyrethroid insecticides zeta-cypermethrin, bifenthrin, and lambda-cyhalothrin were effective in reducing feeding injury on germinating lettuce. This is consistent with a previous study (Joseph et al. 2015) where a combination of zeta-cypermethrin and lambda-cyhalothrin suppressed *P. fimata* populations on lettuce beds, and provided a consistent germination and uniform crop stand. However, use of pyrethroid insecticides in California's Salinas Valley is under stringent scrutiny by the Central Coast Regional Water Quality Control Board because these insecticides transport into surface waters in suspended sediments, and their levels were found toxic to nontarget organisms (Anderson et al. 2003a, 2003b, 2006; Ng and Weston 2009; Schmidt et al. 2010; Starner et al. 2006). This emerging environmental issue warrants more research to develop integrated pest management (IPM) strategies that reduce pyrethroid insecticide use for *P. fimata* control.

Neonicotinoid insecticides, particularly dinotefuran, thiamethoxam, and clothianidin, were also effective in reducing feeding injury on lettuce. Previous research on a subterranean springtail pest of sugarbeet in North Dakota showed that clothianidin, imidacloprid, and thiamethoxam provided adequate crop protection from springtail injury, and improved crop stand (Boetel et al. 2008). Until recently, the organophosphate insecticides chlorpyrifos and diazinon were the standard insecticides for controlling soil-borne pests in the Salinas Valley. Because of high concentrations of organophosphate insecticide residues detected in the water bodies (Hunt et al. 2003), use of chlorpyrifos is strictly regulated by Central Coast Regional Water Quality Control Board (California Environmental Protection Agency 2013). This suggests that chlorpyrifos is less likely to be a future option for *P. fimata* control. Thus, growers in the Central Coast of California have switched to neonicotinoid and pyrethroid insecticides such as clothianidin and zeta-cypermethrin as alternatives to chlorpyrifos for control of soil-borne pests such as garden symphylan (*S. immaculata*) and cabbage maggot (*Delia radicum* L.). In the present study, spinetoram and tolfenpyrad were the only two reduced-risk insecticides effective against *P. fimata*. Spinetoram is currently registered for soil-applied use against cabbage maggot control, and it can be a potential candidate for controlling *P. fimata*. Tolfenpyrad is not registered for use on any vegetable crop in California. Other reduced-risk insecticides, particularly cyantraniliprole, novaluron, flonicamid, and flupyradifurone, did not demonstrate adequate efficacy against *P. fimata*.

The modes of insecticide exposure that possibly affected *P. fimata* feeding on lettuce were by contact and ingestion. The primary mode of exposure for the pyrethroid insecticides chlorpyrifos, and tolfenpyrad is by contact. It is likely that the *P. fimata* individuals were exposed to these insecticides when they crawled on the treated surface. Pyrethroids are also one of the most effective insecticides against several other soil-dwelling arthropods such as garden symphylan and cabbage maggot in the Salinas Valley (Joseph 2015, Joseph and Zarate 2015). Although neonicotinoid insecticides typically reach arthropod pests through their systemic activity within the plant (Elbert et al. 2008), *P. fimata* individuals are likely exposed by their contact activity. In addition to direct contact, arthropod pests are also exposed to spinetoram by ingesting treated plant material (Dripps et al. 2008). Perhaps *P. fimata* individuals are exposed to spinetoram by both contact and ingestion.

There are some factors that might influence a better control of *P. fimata* in the Salinas Valley. First, because seed germination slows down in response to cooler temperatures during the winter months (January to April), germinating seedlings are at greater risk from prolonged *P. fimata* feeding and poor seed germination in winter or early spring months in the Salinas Valley (S.V.J. unpubl. data). This suggests that seeds planted in winter months might require extended protection with multiple insecticide applications. Second, the interaction among *P. fimata* population, insecticide, and planted seeds can be complex in the field conditions. Immediately after sowing the seeds and followed by insecticide application, the field is heavily sprinkler-irrigated for about 3 weeks to ensure proper establishment of seedlings. This intense irrigation regime possibly washes off the insecticide residues attached to soil sediments or dissolved in the runoff water from the seeded beds. Moreover, heavy rain from December through April along California's Central Coast can enhance insecticide movement from the soil.

In conclusion, results clearly show that pyrethroid (zeta-cypermethrin, bifenthrin, and lambda-cyhalothrin) and neonicotinoid insecticides (dinotefuran, thiamethoxam, and clothianidin), as well as chlorpyrifos, tolfenpyrad, and spinetoram were effective in reducing *P. fimata* feeding on lettuce. As an IPM approach, these insecticides should be used along with a proper monitoring program. Joseph and Bettiga (2016) demonstrated that beet or potato slice baits can be used to monitor *P. fimata* in lettuce fields and insecticide use should be based on *P. fimata* detection on the bait at or before planting the seeds until an action threshold for insecticide use has been developed. The effectiveness of insecticide use can be enhanced by properly timing the application when *P. fimata* activity is most injurious to lettuce seedlings. Studies show that *P. fimata* feeding injury is most destructive to lettuce during the germinating phase of seeds (Joseph et al. 2015, S.V.J. unpubl. data). This suggests that the effective insecticides should be used during the germinating phase if the *P. fimata* are detected in the baits. Future research will investigate IPM options including insecticide seed treatment and nonchemical options for *P. fimata* control.

Acknowledgments

I thank J. Martinez and C. Bettiga for technical assistance provided, S. Nair for review of the previous version of the manuscript, and the California Leafy Green Research Program for providing funding (LGR-2015-19) for this project.

References Cited

Anderson, B.S., J.W. Hunt, B.M. Phillips, P.A. Nicely, V. de Vlaming, V. Connor, N. Richard and R.S. Tjeerdema. 2003a. Integrated assessment of the impacts of agricultural drainwater in the Salinas River (California, USA). Environ. Pollut. 124: 523–532.

Anderson, B.S., J.W. Hunt, B.M. Phillips, P.A. Nicely, K.D. Gilbert, V. de Vlaming, V. Connor, N. Richard and R.S. Tjeerdema. 2003b. Ecotoxicologic impacts of agricultural drain water in the Salinas River, California, USA. Environ. Toxicol. Chem. 22: 2375–2384.

Anderson, B.S., B.M. Phillips, J.W. Hunt, N. Richard, V. Connor and R.S. Tjeerdema. 2006. Identifying primary stressors impacting macroinvertebrates in the Salinas River (California, USA): Relative effects of pesticides and suspended particles. Environ. Pollut. 141: 402–408.

Boetel, M.A., R.J. Dregseth and A.J. Schroeder. 2008. Control of subterranean springtails in sugarbeet using granular, liquid, and seed treatment insecticides. Entomology Research. Sugarbeet Research and Education Board of Minnesota and North Dakota. 28 January 2016. (http://www.sbreb.org/research/ento/ento08/subterranean.pdf).

California Environmental Protection Agency, Central Coast Water Board. **2013.** Agricultural order adopted. (http://www.waterboards.ca.gov/centralcoast/water_issues/programs/ag_waivers/index.shtml) 12 January 2017.

Christiansen, K. and P. Bellinger. 1998. The Collembola of North America North of the Rio Grande: A Taxonomic Analysis. 2nd ed. Grinnell College, Grinnell, IA.

Dripps, J., B. Olson, T. Sparks and G. Crouse. 2008. Spinetoram: How artificial intelligence combined natural fermentation with synthetic chemistry to produce a new spinosyn insecticide.Plant Health Prog. doi:10.1094/PHP-2008-0822-01-PS.

Elbert, A., M. Haas, B. Springer, W. Thielert and R. Nauen. 2008. Applied aspects of neonicotinoid uses in crop protection. Pest Manag. Sci. 64: 1099–1105.

Fjellberg, A. 1998. The Collembola of Fennoscandia and Denmark. Part I: Poduromorpha. Fauna Entomologica Scandinavia 35: 184.

Getzin, L. W. 1985. Chemical control of the springtail *Onychiurus pseudarmatus* (Collembola: Onychiuridae). J. Econ. Entomol. 78: 1337–1340.

Hunt, J.W., B.S. Anderson, B.M. Phillips, P.N. Nicely, R.S. Tjeerdema, H.M. Puckett, M. Stephenson, K. Worcester and V. de Vlaming. 2003. Ambient toxicity due to chlorpyrifos and diazinon in a central California coastal watershed. Environ. Monit. Assess. 82: 83–112.

Joseph, S.V. 2015. Effects of direct and indirect exposure of insecticides to garden symphylan (Symphyla: Scutigerellidae) in laboratory bioassays. J. Econ. Entomol. 108: 2729–2736.

Joseph, S.V. and C. Bettiga. **2016.** Captures of *Protaphorura fimata* (Collembola: Poduromorpha: Onychiuridae) on beet and potato baits in the Salinas Valley of California. J. Entomol. Sci. 51: 79–86.

Joseph, S.V., C. Bettiga, C. Ramirez and F.N. Soto-Adames. **2015.** Evidence of *Protaphorura fimata* (Collembola: Poduromorpha: Onychiuridae) feeding on germinating lettuce in the Salinas Valley of California. J. Econ. Entomol. 108: 228–236.

Joseph, S.V. and J. Zarate. **2015.** Comparing efficacy of insecticides against cabbage maggot (Diptera: Anthomyiidae) in the laboratory. Crop Prot. 77: 148–156.

Monterey County Agricultural Commissioner. **2014.** 2014 Crop report. 5 January 2016. (http://www.co.monterey.ca.us/Home/ShowDocument?id=1581).

Ng, C.M. and D.P. Weston. 2009. Pyrethroid pesticide transport into Monterey Bay though riverine suspended solids. UC Water Resources Center Technical Completion Report, Project No.WR1018.

Natwick, E. T. 2009a. Garden symphylan. UC IPM pest management guidelines: Cole crops UC ANR Publication 3442. 10 February 2016. (http://www.ipm.ucdavis.edu/PMG/r108300111.html).

Natwick, E.T. 2009b. Cabbage maggot. UC IPM pest management guidelines: Cole crops UC ANR Publication 3442. 10 February 2016. (http://www.ipm.ucdavis.edu/PMG/r108300111.html).

Pomorski, R.J. 1998. Onychiurinae of Poland (Collembola: Onychiuridae). Genus – Supplement. 9:1–201.

Schmidt, K., S.G. Lopez and P. Krone-Davis. 2010. Pesticides and toxicity to *Hyalella azteca* in sediments. Central Coast Region Conditional Waiver Cooperative Monitoring Program. Follow-up Monitoring Report. Central Coast Water Quality Preservation, Inc.

Starner, K., J. White, F. Spurlock and K. Kelley. 2006. Pyrethroid insecticides in California surface waters and bed sediments: Concentrations and estimated toxicities. 23 January 2016. (http://www.cdpr.ca.gov/docs/emon/surfwtr/swposters/starner_pyreth06.pdf).

Thompson, A. R. 1973. Persistence of biological activity of seven insecticides in soil assayed with *Folsomia candida*. J. Econ. Entomol. 66: 855–857.

Thompson, A.R. and F.L. Gore. 1972. Toxicity of twenty-nine insecticides to *Folsomia candida*: Laboratory studies. J. Econ. Entomol. 65: 1255–1260.

Tomlin, A.D. 1975. Toxicity of soil applications of insecticides to three species of springtails (Collembola) under laboratory conditions. Can. Entomol. 107: 769–774.

[USDA SCS] U.S. Department of Agriculture, Soil Conservation Service. **1978**. Soil Survey of Monterey County, California. USDA, Washington DC.