

Evidence of *Protaphorura fimata* (Collembola: Poduromorpha: Onychiuridae) feeding on germinating lettuce in the Salinas Valley of California

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ABSTRACT A series of experiments were conducted to determine the impact of *Protaphorura fimata* Gisin (Family: Onychiuridae) feeding on seeds and germinating seedlings of lettuce, *Lactuca sativa* L. (Asteraceae). First, various densities of *P. fimata* were incubated with 25 lettuce seeds for 7 d and feeding injury was evaluated in three soilless arena experiments. As a second step, 100 *P. fimata* were incubated with 25 lettuce seeds in three arena experiments with soil media. Finally, in a commercial field the incidence and impact of *P. fimata* on recently planted lettuce was assessed following applications of pyrethroid–insecticides: 2 d before planting, at planting, and 20 d later. In experiments without soil, the number of ungerminated seeds, feeding injury sites, and plants with injury were significantly greater in arenas with *P. fimata* than without. Similarly, the number of germinated seedlings, shoot fresh, and dry weights, and the length and width of fully opened-leaves were greater in arenas without than with *P. fimata* in assays with soil. In the field, *P. fimata* densities were significantly lower in beds that received insecticides at 2 d before and at planting than in untreated beds. Also, the fresh and dry weights of lettuce plants were significantly greater in the beds that received insecticide than in untreated. The results clearly show that *P. fimata* is a pest of lettuce and can cause severe feeding injury to germinating seeds or seedlings, thereby reducing their growth rate. The potential implications of *P. fimata* feeding and feeding injury characteristics are discussed.

KEY WORDS springtail, feeding injury, seed predation, *Lactuca sativa*, vegetable production, central coast of California

Introduction

A subterranean springtail, *Protaphorura fimata* Gisin (Family: Onychiuridae), was found associated with poor germination of lettuce, *Lactuca sativa* L. (Asteraceae), particularly during February to May in the northern part of Salinas Valley of California. The young lettuce seedlings in fields with high densities of *P. fimata* show retarded or stunted growth and do not emerge in a synchronous pattern. The value of lettuce is estimated to be ~US\$1.3 billion in the Salinas Valley (Monterey County Crop report 2012). Scott (1964) reported that *Onychiurus armatus* Tullberg (= *Protaphorura armata* Tullberg) and *Onychiurus pseudarmatus* Folsom were pests of a wide range of vegetable crops including lettuce (*L. sativa*), celery (*Apium graveolens* var. *dulce* Miller), broccoli (*Brassica oleracea* var. *italica* Plenck), cauliflower (*Brassica oleracea* L. var. *botrytis*), sugar beet (*Beta vulgaris* L.),

spinach (*Spinacia oleracea* L.), and lima beans (*Phaseolus lunatus* L.) in the Salinas Valley; however, Scott (1953, 1964) reported onychiurids as pests of vegetables in the Salinas Valley but did not present evidence for *Protaphorura* spp. feeding damage on any of the crops. Greenslade and Ireson (1986) indicated that members of the family Onychiuridae could only be reliably identified to a group level such as *P. armata* group.

P. fimata is less than 2.5 mm in length; lacks eyes, pigmentation, and furcula; and carries 33/022/33333 pseudocelli dorsally on the head and body (Fjellberg 1998). Unlike other springtails, *P. fimata* lacks a furcula, and when disturbed does not jump but instead curls up. Many onychiurids primarily reproduce parthenogenically (Christiansen 1964); however, sexual reproduction is also widespread (Larsen et al. 2009). The species was originally described from Switzerland and seems to be widely distributed in Europe (Pomorski 1998, Fjellberg 1998), but has not been previously reported from the United States under the name *P. fimata*. Based on pseudocelli number, most records of *P. armata* reported in Christiansen and Bellinger (1998) appear to refer to *P. fimata*, suggesting that the species is widespread throughout the country. However, other members of the *P. armata* species group with the same pseudocelli number might be present in

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other localities and species determination will require examination of individuals from different populations. The taxonomy of North American members of the *P. armata* species complex has not been fully worked out. Christiansen and Bellinger (1998) follow Bødvarsson (1970) and include forms with at least four combinations of pseudocelli and chaetotaxy details under the name *P. armata*.

Springtails occur in diverse habitats worldwide (Hopkin 1997) and are generally considered as beneficial arthropods because they aid in the decomposition of decaying plant material by feeding, thereby contributing to the cycling of carbon and nitrogen, which in turn improves soil health and structure (Coleman et al. 1983, Hopkin 1997, Filser 2002). *P. fimata* is primarily known to feed on soil fungi (Crist and Friese 1993, Jørgensen et al. 2003) but also feeds on live plant roots (Endlweber et al. 2009). However, there are several reports of springtails as pests of crops reducing yields and productivity. The onychiurids, especially *P. fimata*, have been associated with feeding damage to germinating sugar beet seeds (Baker and Dunning 1975, Boetel et al. 2001, Brown 1983, Heijbroek et al. 1980, Hurej et al. 1992) and sugarcane (Spencer and Stracener 1929, 1930). *Folsomia candida* Willem, a common soil springtail, has been reported feeding on poppy seeds, *Papaver somniferum* (L.) (Greenslade 2006), and weed seeds such as *Plantago major* L. (Nietschke et al. 2011). Foliage-feeding springtails such as lucerne flea, *Sminthurus viridis* (L.), and garden springtail, *Bourletiella hortensis* (Fitch), attack several plant species including Lucerne (*Medicago sativa* L.), clover (*Trifolium* sp.), and sugar beet (*Be. vulgaris*; Cleland 1955, Ireson 1984, 1993; Honma 1988). *Thalassophorura encarpata* (Denis) (identified as *Onychiurus hortensis* Gisin, in the original report) also is reported to feed on bean foliage (Edwards 1962).

Growers in the Salinas Valley facing an irregular lettuce stand are usually uncertain about what caused the problem and often blame the factors such as poor seed quality, planting error, irregular irrigation timing or distribution, high salt levels in the soil or water, soilborne pathogens of seedlings, bulb mites, and garden symphylan (*Scutigera immaculata* Newport) feeding for the losses. Also, several springtails were collected from the soil associated with lettuce and it is not clear if they were feeding and contributing to the irregular lettuce stand. The onychiurids including *P. fimata* have been reported for their ability to cause plant injury in peas, maize, and weed plants (Scott 1964, Lawrence 1979, Endlweber et al. 2009, Nietschke et al. 2011) but they have not usually been identified as a sole causal factor for the poor lettuce stand in the Salinas Valley of California. There is a knowledge gap because springtail species specific damage or association to lettuce production has not been accurately documented. Often, *P. fimata* are misidentified as garden symphylan (*S. immaculata*) by the field personnel.

Although Scott (1964) described that several springtail species as possible economic pests of lettuce and other vegetables, the specific role of *P. fimata* in causing severe feeding damage to lettuce was not clearly

demonstrated. The major objectives of the present study were to document 1) the ability of *P. fimata* to injure germinating seeds of lettuce in laboratory and field, and 2) to characterize the feeding injury of *P. fimata* on germinating seeds and seedlings of lettuce. Our hypothesis is that the subterranean springtail, *P. fimata*, which is detected in the lettuce and brassica fields of the Salinas Valley could affect crop stands through feeding.

Materials and Methods

Species Identification. Individuals collected from the soil in the Salinas Valley in association with lettuce were identified using the keys provided in Christiansen and Bellinger (1998), Fjellberg (1998), and Pomorski (1998). A subset of individuals of the same species were reared in the laboratory and used for all the studies presented in this manuscript. The voucher specimens were deposited in the University of California Cooperative Extension, Entomology Laboratory in Salinas, CA.

Springtail Rearing. *P. fimata* were collected from a field in Salinas, CA, using beet (*Be. vulgaris*) root slices. Beet root slices were placed ~3-cm-deep subsurface of the soil for 2 d. The collected *P. fimata* were reared in sealed plastic containers and were provided with fish food (Wardley, The Hartz Mountain Corp., Secaucus, NJ) as nutrition at biweekly intervals. In the container, a layer of clay soil (2 cm) was provided and covered with moist paper towel. The springtail containers were sprayed with tap water at biweekly intervals. The containers were maintained at 20°C; ~45% relative humidity (RH), in complete darkness in the laboratory. A single colony of *P. fimata* was used in all the laboratory experiments.

Laboratory Soilless Arena. Three soilless arena experiments were conducted in the laboratory. An experiment unit or assay consisted of 4.5-cm-diameter plastic petri dish (Fischer Scientific, Pittsburgh, PA) with a Whatman No.1 filter paper (GE healthcare UK Ltd., Little Chalfont, Buckinghamshire, United Kingdom). The filter paper was soaked in 50 ml of distilled water for 5 s before being added to the petri dish. Twenty-five uncoated and untreated 'Bibb Heirloom' lettuce seeds (*L. sativa*; Livingston Seed Co., Columbus, OH) were added on to the moistened filter paper before the springtails were introduced. In the first experiment, two *P. fimata* densities (treatments), 0 and 100 individuals were added and were replicated five times (five petri dishes) per treatment. Later, two more experiments were conducted with four *P. fimata* densities (treatments): 0, 20, 50, and 100 individuals. The treatments in both the experiments were replicated five times (five petri dishes per treatment) in a completely randomized design. All petri dishes were sealed using parafilm and secured using rubber bands around the petri dishes. Numbers of *P. fimata* used as treatments were randomly selected because there is no baseline threshold information on how many *P. fimata* could cause economic injury on lettuce. Beet slice samples collected varying number of *P. fimata* but usually

ranged from 0 to 200 individuals per slice (S.V.J. unpublished data) from the soil when slices were placed in subsurface of soil for 2 d. The petri dish assays provided a value in understanding the feeding behavior of *P. fimata* when other environmental factors were controlled.

The assays were maintained with *P. fimata* at $\sim 21^{\circ}\text{C}$, a photoperiod of 16:8 (L:D) h, and $\sim 45\%$ RH for 7 d before evaluation. The parameters evaluated were ungerminated lettuce seeds due to feeding injury, total number of feeding injury sites, and number of germinated seedlings with distinct feeding injury. In the third experiment, the location (e.g., leaf, stem, plant crown, or root) of the feeding injury on the plants was also recorded. This information was not recorded from two previous soilless experiments.

Laboratory Soil Arena. Three experiments were conducted with soil media in the laboratory. For each experiment, the "Clear Lake clay" soil was collected from a field in Salinas, CA, where *P. fimata* was previously collected from the soil and later identified. The soil was oven-dried twice at $\sim 105^{\circ}\text{C}$ for 48 h. An experiment unit consisted of 4.5-cm-diameter plastic petri dish with 25 g of oven-dried soil. To maintain uniform soil moisture, 3-ml of distilled water was added to each petri dish. For each experiment, there were two *P. fimata* densities (treatments), 0 and 100 individuals and were replicated five times (five petri dishes) per treatment. The petri dish assays were covered by inverting another 4.5-cm petri dish and sealed using parafilm around the edges. These assays were maintained at $\sim 21^{\circ}\text{C}$, a photoperiod of 16:8 (L:D) h, and $\sim 45\%$ RH for 14 d. After 14 d, 25 uncoated and untreated 'Bibb' lettuce seeds (*L. sativa*) were added onto the soil surface of each petri dish assay. The petri dish assays were maintained at $\sim 21^{\circ}\text{C}$, a photoperiod of 16:8 (L:D) h, and $\sim 45\%$ RH for more 7 d and then evaluated to determine the effects of *P. fimata* feeding. The parameters evaluated were number of lettuce seeds germinated, shoot fresh, and dry weights, and the length and width of fully opened leaves of seedlings. To determine the length and width of seedling leaves, 10 leaves were randomly selected from each petri dish and measured.

Field Experiment. This experiment was conducted in a 'Sparx' Romaine lettuce (*L. sativa*) field in Salinas, CA, in March to April 2013. The soil type of the field is "Clear Lake clay." Eight (for springtails) and five (for biomass) replicates of two main treatments, insecticide-treated and untreated and subplot treatments, sample dates were evaluated in a randomized split-plot design. Before planting lettuce, the *Be. vulgaris* slice traps were deployed in the soil and were monitored for *P. fimata* activity. Based on high trap captures of *P. fimata* prior to planting, the field was selected for the study. In the field, 12 203.2-cm-wide beds received insecticide applications and 12 beds were left unsprayed. Because lettuce seeds are typically planted ~ 1 -cm-deep in the bed and *P. fimata* are captured from subsurface of the soil profile, insecticide applications were targeted onto the soil surface. Two commonly used insecticides registered for lettuce with soil

application use pattern on label were selected for the study. The assumption was that the repeated use of maximum label rate of these selected insecticides at early stages of plant development would suppress *P. fimata* densities and protect the seeds or seedlings from *P. fimata* feeding. On selected beds, maximum label rates of pyrethroid insecticides were applied three times: 2 d before planting (9 March), at planting (11 March), and 20 d after planting (30 March). Applications were made using a commercial tractor mounted sprayer at 20.7×10^4 Pa and running at 9.7 km/h. Two pyrethroid insecticides and their rates used were Mustang (zeta-cypermethrin, FMC Corporation, Philadelphia, PA) at 0.29 liter/ha and Warrior II (λ -cyhalothrin, Syngenta Crop Protection, Greensboro, NC) at 0.12 liter/ha. Both the Mustang and Warrior II were tank-mixed and applied at 2 d before planting and 20 d after planting, but only Warrior II was applied at planting to conform to the label. An adjuvant, Widespread Max (Loveland Products, Inc., Loveland, CO), at 0.15 liter/ha was added with all the applications. Following the first application (2 d before planting), beds were shaped and preirrigated. This way, insecticides would get incorporated into the soil where lettuce seeds are planted and *P. fimata* were found active. The second (at planting) and third (20 d after planting) insecticide applications were applied on the surface of the bed but concentrating to the 6-cm bandwidth of seed line, assuming that the application would suppress the *P. fimata* populations along the seed line. The volume of water used for all the applications was 467.5 liter/ha.

A slice of beet root (~ 4.5 cm in diameter, ~ 1 cm in width) was used as traps to monitor *P. fimata* densities in the subsurface of the soil. Beet root traps were placed in the soil at 3-cm depth along the seed line and were covered with disposable white plastic bowls (Hefty Consumer Products, Lake Forest, IL). The area covered by the beet root trap ~ 4.5 cm diameter of the soil where all the *P. fimata* was collected from the underside of the slice. Sixteen beet root traps with eight traps per insecticide treatment (treated and untreated) were deployed at 15.2-m spacing starting 1 wk before planting up to 5 wk after planting. Because early stages of the lettuce crop were considered most vulnerable to *P. fimata* feeding injury, beet root traps were only monitored up to 4 wk on 7, 15, 22, and 28 March 2013 and were discontinued thereafter. The beet root traps were exposed for 2 d in the soil and were replaced with fresh beet root slices every week. At the end of each 2-d exposure period, beet root slices were removed, placed into plastic bags, and transported to the laboratory in Salinas, CA. The captured *P. fimata* were quantified within 24 h by examining the slices with a dissecting microscope.

To determine treatment effects on plant growth, five plots were randomly blocked within treated and untreated beds. The plot size was 30.4 m by 203.2-cm (bed width). Thirty-five plants were randomly sampled per plot on 4 April (at prethinning stage), 22 April (postthinning stage), and 30 March 2013 (closer to harvest). All plant samples were cleaned with a soft brush to remove adhered soil particles; fresh and dry weights

were then determined. To determine dry weight, plant samples were oven-dried at 60°C for 72 h before weighing. In addition, the number of all live plants regardless of size of the plant was counted from each plot. *P. fimata* activity was not monitored in these plots using beet slice traps.

Statistical Analyses. For the laboratory assays (with and without soil), all the independent variables, which included number of ungerminated seeds, injured plants, total number of injured sites, germinated plants, fresh and dry weights, length and width of leaves, and

number of *P. fimata* were log-transformed ($\ln[x + 1]$) to establish homogeneity of variance. The number of injury sites at seedling location, e.g., leaf, stem, crown area, and root were also log-transformed ($\ln[x + 1]$). Transformed data for each experiment were analyzed using the PROC TTEST procedure in SAS (SAS Institute 2010, Cary, NC). The null hypothesis was that the variance was equal between *P. fimata* exposed or unexposed assays or between insecticide-treated or untreated treatments ($P < 0.05$). However, multilevel variable data for experiments with more than two

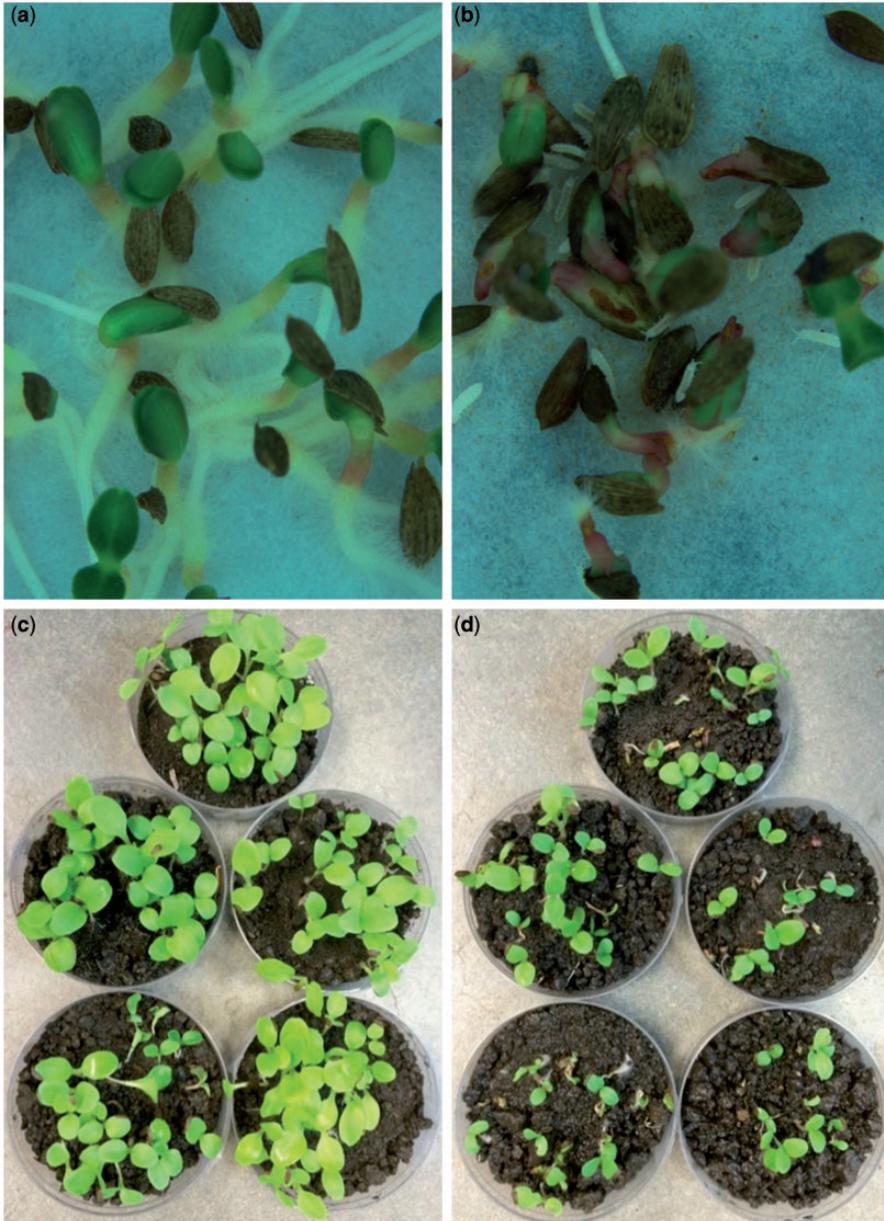


Fig. 1. Effects of *P. fimata* on germinating lettuce seeds exposed after 7 d in assays (a) without soil and *P. fimata*, (b) without soil but with *P. fimata*, (c) with soil but without *P. fimata*, and (d) with soil and *P. fimata*.

P. fimata densities and location of injury sites (e.g., leaf, stem, plant crown, or root) were subjected to PROC GLM procedure in SAS and means were separated using the Tukey's honestly significant difference (HSD) method ($P < 0.05$).

For the field experiment, analysis of variance using the generalized linear model procedure in SAS was used to evaluate the effects of mainplot and subplot treatments on *P. fimata* captures, plant density, and fresh and dry weight. The main effect, insecticide treatment was tested using insecticide treatment \times replication as error term at $\alpha = 0.05$. *P. fimata*, plant density, and fresh and dry weight data were square root-transformed to establish homogeneity of variance. To determine treatment effects for each sample date, transformed data of *P. fimata* captures, plant density, and fresh and dry weight were analyzed using the PROC TTEST procedure in SAS. Means and standard error for the variables were calculated using PROC MEANS procedure in SAS.

Results

Species Identification. The 20 specimens collected on beet roots and associated with lettuce were key out to *P. armata*. However, individuals with the combination of pseudocelli (33/022/33333) and chaetotaxy (sixth abdominal segment inner microsetae convergent) characterizing the Californian population are associated with the name *P. fimata*.

Injury Characteristics. Fig. 1 provides a visual illustration of *P. fimata* feeding injury on germinating lettuce seeds in the presence and absence of *P. fimata*. *P. fimata* could feed on various parts of seed or young seedling (Fig. 2). *P. fimata* could directly feed and injure the seed with only the seed coat remaining (Fig. 2a and b) or completely sever the radicle (Fig. 2c) of germinated seed, and partially feed on the radicle (Fig. 2d). If the seedlings survive the *P. fimata* feeding, the plants demonstrate a reduced seedling development (Fig. 1b). A section of the plant tissue was removed and the injured living tissue surrounding

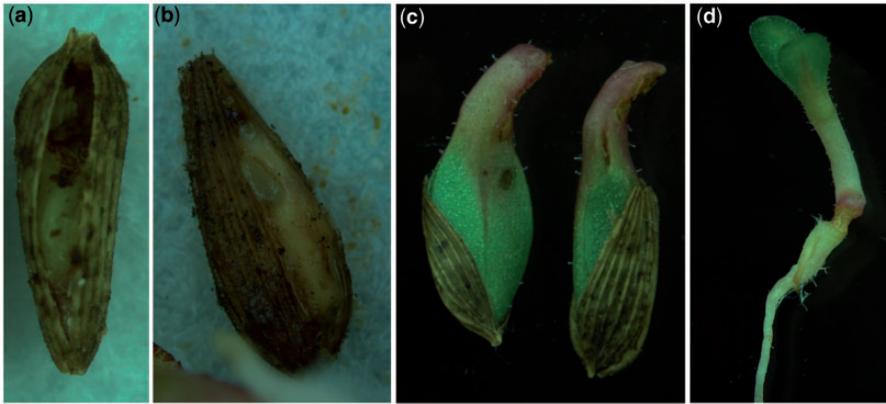


Fig. 2. Feeding injury of *P. fimata* on (a) seed—completely injured, (b) seed—incompletely injured, (c) radicle—completely severed, and (d) radicle—partially severed after 7 d of exposure.

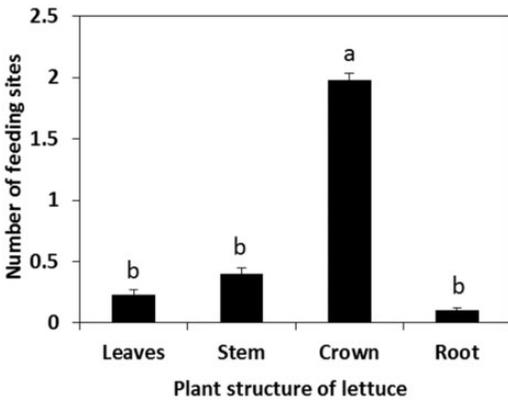


Fig. 3. Mean (\pm SE) of *P. fimata* feeding injury sites at various parts of the germinated lettuce seedlings after 7-d exposure in a soilless arena. Symbols following means with similar case letters among histograms are not significantly different (Tukey's HSD Test, $P > 0.05$). Not transformed data are presented.

Table 1. Mean (\pm SE) of ungerminated lettuce seeds, total number of *P. fimata* feeding sites, and plants with *P. fimata* feeding injury after exposing two densities of *P. fimata* for 7 d in a soilless assay.

Experiment	No. of <i>P. fimata</i>	Ungerminated seeds ^a	Injury sites ^b	Plants with injury ^c
1	0	0 \pm 0b	0 \pm 0b	0 \pm 0b
	100	4.6 \pm 1.3a	19.8 \pm 2.1a	13.8 \pm 2.9a
2	0	0 \pm 0b	0 \pm 0b	0 \pm 0b
	20	4.2 \pm 1.2a	22.4 \pm 4.7a	12.8 \pm 1.6a
	50	8.0 \pm 3.9a	24.4 \pm 3.0a	12.2 \pm 2.3a
3	100	14.2 \pm 1.8a	22.8 \pm 4.2a	9.8 \pm 1.7a
	0	0 \pm 0b	0 \pm 0b	0 \pm 0b
	20	13.0 \pm 3.1a	34.0 \pm 5.5a	11.2 \pm 2.8a
	50	7.8 \pm 1.1a	40.2 \pm 1.4a	16.6 \pm 1.2a
	100	13.2 \pm 3.3a	44.2 \pm 4.9a	11.4 \pm 3.1a

^a Seeds not germinated to *P. fimata* feeding injury.

^b Includes total number of distinct *P. fimata* feeding sites.

^c At least one *P. fimata* feeding injury site detected. Symbols following means with similar case letters within the same column and experiment are not significantly different ($P > 0.05$). Not transformed data are presented.

Table 2. Mean (\pm SE) of lettuce seedling, fresh, and dry weight, and leaf dimensions after exposing two densities of *P. fimata* for 7-d in the soil assay

Experiment	No. of <i>P. fimata</i>	No. of seedlings	Fresh weight (g)	Dry weight (g)	Leaf length (cm)	Leaf width (cm)
1	0	21.0 \pm 0.44a	0.298 \pm 0.026a	0.023 \pm 0.001a	1.63 \pm 0.05a	0.48 \pm 0.05a
	100	15.6 \pm 1.94b	0.119 \pm 0.014b	0.018 \pm 0.003a	1.08 \pm 0.07b	0.29 \pm 0.01b
2	0	20.0 \pm 0.6a	0.194 \pm 0.017a	0.021 \pm 0.002a	0.41 \pm 0.03a	0.74 \pm 0.04a
	100	16.5 \pm 0.9b	0.253 \pm 0.047a	0.013 \pm 0.000b	0.34 \pm 0.13b	0.54 \pm .03b
3	0	19.6 \pm 0.7a	0.192 \pm 0.014a	0.023 \pm 0.002a	0.37 \pm 0.04a	0.52 \pm 0.02a
	100	20.2 \pm 0.4a	0.144 \pm 0.017a	0.016 \pm 0.003a	0.26 \pm 0.01b	0.42 \pm 0.02b

Symbols following means with similar case letters within the same column and experiment are not significantly different ($P > 0.05$). Not transformed data are presented.

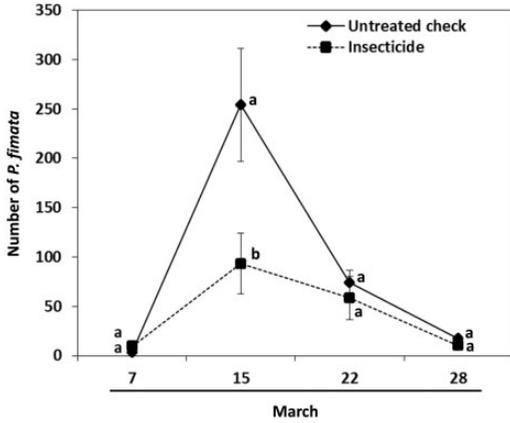


Fig. 4. Mean (\pm SE) of *P. fimata* densities to insecticide treatment on romaine lettuce field in March 2013. Symbols with similar case letters within sample date are not significantly different ($P > 0.05$). Not transformed data are presented.

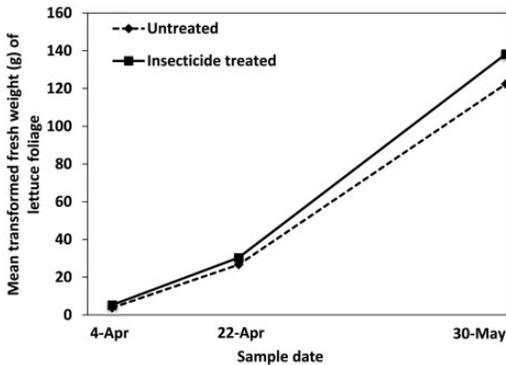


Fig. 5. Interaction effect of *P. fimata* feeding on fresh weight of romaine lettuce in the field. Square root-transformed data are presented.

the feeding site appeared stained with reddish brown coloration (Fig. 2d). On a developed seedlings, most of the feeding activity was noticed at the crown area of the seedling and not much on other plant structures such as root, leaves or stem ($F = 351.9$; $df = 3, 1002$; $P < 0.001$; Figs. 2d and 3).

Lab Soilless Arena. In experiment 1, the number of ungerminated lettuce seeds ($t = -3.6$; $df = 8$;

$P = 0.007$), total *P. fimata* feeding injury sites ($t = -9.3$; $df = 8$; $P < 0.001$), and number of plants with feeding injury ($t = -4.8$; $df = 8$; $P = 0.001$) were significantly greater when *P. fimata* were present in the assay than absent (Table 1). In experiments 2 and 3, the number of ungerminated lettuce seeds (experiment 2: $F = 76.3$; $df = 3, 12$; $P < 0.001$) (experiment 3: $F = 34.1$; $df = 3, 12$; $P < 0.001$), total *P. fimata* feeding injury sites (experiment 2: $F = 69.8$; $df = 3, 12$; $P < 0.001$; experiment 3: $F = 268.3$; $df = 3, 12$; $P < 0.001$), and number of plants with feeding injury (experiment 2: $F = 13.2$; $df = 3, 12$; $P < 0.001$; experiment 3: $F = 64.0$; $df = 3, 12$; $P < 0.001$) were significantly greater when *P. fimata* were present regardless of *P. fimata* densities than absent (Table 1).

Lab Soil Arena. In experiment 1, the number of germinated seeds ($t = 2.5$; $df = 8$; $P = 0.036$), fresh weight ($t = 6.1$; $df = 8$; $P < 0.001$), and both the length ($t = 5.5$; $df = 8$; $P < 0.001$) and width ($t = 4.3$; $df = 8$; $P < 0.001$) of the leaves of seedlings were significantly lower in arenas with *P. fimata* than without (Table 2). The only variable that was not significantly different between treatments was dry weight ($t = 1.5$; $df = 8$; $P = 0.168$). In the experiment 2, the number of germinated seeds ($t = 3.3$; $df = 7$; $P = 0.013$), dry weight ($t = 2.7$; $df = 7$; $P = 0.032$), and both the length ($t = 3.9$; $df = 7$; $P = 0.005$) and width ($t = 2.4$; $df = 7$; $P = 0.045$) of the leaves of seedlings were significantly lower in arenas with *P. fimata* than without (Table 2). The fresh weight ($t = 1.5$; $df = 8$; $P = 0.168$) was not significantly different between treatments. In experiment 3, although the number of germinated seeds ($t = -0.7$; $df = 8$; $P = 0.478$), fresh weight ($t = 2.2$; $df = 8$; $P = 0.056$), and dry weight ($t = 1.5$; $df = 8$; $P = 0.166$) was not significantly different with and without *P. fimata*, the leaf length ($t = 3.7$; $df = 8$; $P = 0.006$) and width ($t = 2.8$; $df = 8$; $P = 0.024$) was significantly smaller when *P. fimata* were present than absent.

Field Experiment. The average number of *P. fimata* collected in beet slice trap samples over all sample dates were significantly less on the insecticide treated than untreated beds ($F = 5.7$; $df = 1, 18$; $P = 0.049$), although there was no significant interaction ($F = 2.9$; $df = 3, 18$; $P = 0.060$) between mainplots (insecticide treatment) and subplots (sample date) on *P. fimata* captures. The number of *P. fimata* collected was significantly lower in the insecticide-treated than untreated beds ($t = 2.9$; $df = 14$; $P = 0.011$) on 15 March (4d after planting; Fig. 4), although number of *P. fimata* captured on 7

Table 3. Mean (\pm SE) of lettuce plants, fresh, and dry weight after insecticide treatment in the field

Sampling timing	Treatment	No. of plants germinated	Fresh weight (g)	Dry weight (g)
Prethinning (4 April)	Untreated	2,318.0 \pm 94.5a	14.3 \pm 0.8b	1.4 \pm 0.07b
	Insecticide treated	2,338.0 \pm 130.9a	27.7 \pm 0.9a	2.6 \pm 0.07a
Postthinning (22 April)	Untreated	781.4 \pm 26.8a	713.9 \pm 32.7b	101.1 \pm 3.8b
	Insecticide treated	747.4 \pm 20.0a	925.1 \pm 61.9a	118.3 \pm 4.7a
Near harvest (30 May)	Untreated	688.0 \pm 26.2a	14,986.7 \pm 372.3b	–
	Insecticide treated	673.6 \pm 16.9a	19,132.5 \pm 695.4a	–

Symbols following means with similar case letters within the same column and sample date are not significantly different ($P > 0.05$). Not transformed data are presented.

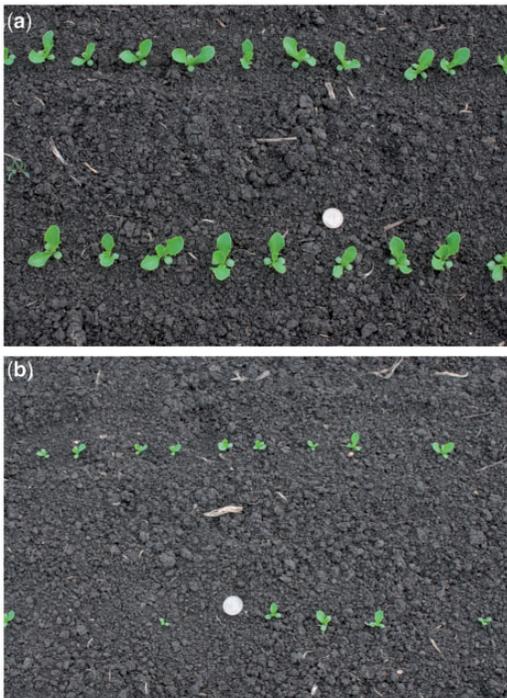


Fig. 6. Effect of *P. fimata* feeding on young seedling of lettuce in the field after (a) insecticide treated, and (b) untreated check in March 2013.

(before planting), 22 (3 wk after planting) and 28 March (4 wk after planting) were similar between insecticide-treated or untreated beds ($P < 0.05$).

The average fresh ($F = 29.1$; $df = 1, 8$; $P = 0.006$) and dry ($F = 9.7$; $df = 1, 4$; $P = 0.036$) weight over all sample dates were significantly greater on the insecticide-treated than untreated treatments. A significant interaction between mainplots (insecticide treatments) and subplots (sample date) for fresh weight was observed ($F = 17.7$; $df = 2, 8$; $P = 0.001$), where fresh weight increased with time at greater rate in insecticide-treated beds than untreated (Fig. 5), although there was no significant interaction effect ($F = 0.9$; $df = 1, 4$; $P = 0.389$) between insecticide treatment and sample date for dry weight. Before thinning (on 4 April), the fresh ($t = -11.2$; $df = 8$; $P < 0.001$), and dry ($t = -11.2$; $df = 8$; $P < 0.001$) weights of lettuce were significantly greater in the insecticide-treated than the untreated beds (Table 3 and Fig. 6).

Immediately after thinning (on 22 April), both the fresh ($t = -3.1$; $df = 8$; $P = 0.016$) and dry ($t = -2.8$; $df = 8$; $P = 0.023$) weights of plants were significantly greater in the insecticide-treated than in untreated beds. Similarly, when sampled near harvest (on 30 May), fresh weight of plants was significantly greater ($t = -5.4$; $df = 8$; $P = 0.001$) in the insecticide treated than in untreated. The dry weight was not evaluated for near harvest sample. The number of plants was similar between insecticide-treated and untreated beds on all sample dates ($P > 0.05$).

Discussion

Results demonstrate that *P. fimata* can feed on germinating lettuce seeds or young seedlings, resulting in reduction in lettuce growth. *P. fimata* has been reported to cause injury to germinating poppy seeds and maize roots (Greenslade 2006, Endlweber et al. 2009). Other onychiurids (*Onychiurus* spp.) were reported as a pest of sugar beet as they feed on developing roots (Baker and Dunning 1975, Heijbroek et al. 1980; Hurej et al. 1992). In the Salinas Valley, sugar beet (*Be. vulgaris* L.) was extensively grown until 1982 (Seavey 2010), and it is likely that *P. fimata* was a pest of sugar beet in the Salinas Valley (Scott 1964).

In the Salinas Valley, before the lettuce seeds are planted, fields are watered deeply and irrigations continue for at least 3 wk after planting. It has been observed that the *P. fimata* density increased from the subsurface of soil when the field was recently irrigated or after a rain event (S.V.J. unpublished data). This cultural practice which maintains high moisture levels for seed germination on the subsurface profiles of the soil might be favoring faster build up of *P. fimata* populations. In the field trial, the *P. fimata* captures were greater immediately after irrigation in the untreated beds than insecticide-treated beds, which was reflected in reduced lettuce biomass in the untreated beds (Fig. 4 and Table 3). However, in the soilless assays, total number of feeding injury sites on the growing seedlings was not influenced by various densities *P. fimata*. According to Edwards and Lofty (1969), *Onychiurus* spp. could cause substantial crop damage even at low densities. In our assays, we confined *P. fimata* in petri dishes without soil media; perhaps with limited food choices, they survived feeding on germinating seeds even at lower densities.

P. fimata attacked seeds and young seedlings alike. In the assays, *P. fimata* directly fed through the seed

coat (pericarp) of a few seeds. This is possibly due to the moistening of the pericarp, enabling *P. fimata* to feed through the softened coating (Fig. 2a and b). In some instances, *P. fimata* fed on the growing radicle of the germinating seeds near micropylar region and completely severed it (Fig. 2c). Baker and Dunning (1975) reported that onychiurids injured the seed radicle of sugar beet seed. However, most of the feeding at the seed radicle or elsewhere did not entirely sever it (Fig. 2d), which allowed the seedling to survive but affected the normal development of the plant. Moreover, most of the feeding injury was evident at the crown area rather than on leaf, stem, or root. Possibly, this feeding behavior reduced plant development and affected the plant biomass in the untreated beds in the field where greater number of *P. fimata* was collected than insecticide treated beds.

In conclusion, our study clearly demonstrates that *P. fimata* is an important pest of lettuce and is capable of reducing the crop stand. Incidence of high populations of *P. fimata* could be detrimental to germination of seeds in the field (Fig. 4). *P. fimata* could be effectively suppressed to a large extent with early applications of synthetic insecticides directed to the seed line. Monitoring is the key to determine the presence and population size of *P. fimata*. Potato slices are typically deployed to detect presence of garden symphylans in the field (Umble and Fisher 2003). Also, this technique is effective for monitoring *P. fimata* in the field (S.V.J. unpublished data). Future research will evaluate insecticide application timing and action threshold for *P. fimata* management in lettuce in the Salinas Valley of California.

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