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The European earwig *Forficula auricularia* (Dermaptera: Forficulidae) in California citrus: a sampling method, population surveys, and description of earwig movement into the tree canopy

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The European earwig *F. auricularia* L. is an omnivore that has only recently been identified as a direct, fruit-feeding pest of citrus. Here, we start to build the basic tools needed for integrated pest management for this species. We introduce a time-efficient sampling method based on small wooden boards placed on the ground, and we use them in a 2-yr survey of 93 commercial citrus blocks in California's San Joaquin Valley. Insecticides were not applied targeting *F. auricularia* in any of these citrus blocks. We find that *F. auricularia* populations are very low or undetectable in most blocks, with higher densities occurring only sporadically. To know when control measures should be implemented, we used video-monitoring of citrus tree trunks to characterize the timing of *F. auricularia* movement from their soil nests into the tree canopy. Movement of earwigs along the tree trunks was observed throughout our sampling period (22 March to 18 June), suggesting that control measures (sticky bands placed on trunks, or insecticides applied to trunks and surrounding soil surface) should be applied early, well before petal fall when fruit are susceptible to *F. auricularia* herbivory. Sticky barriers effectively reduced the vertical movement of 2 crawling arthropods, *F. auricularia* and the Fuller rose beetle *Napactus godmanni*, along citrus trunks. We failed to find any relationship between estimated *F. auricularia* densities and damage to maturing or harvested fruit. This highlights a set of important and still unresolved questions about the biology of this species, underscoring the need for additional research.

Keywords: sampling method, population survey, video monitoring, sticky barrier, economic injury level

Like many omnivorous arthropods, the European earwig *Forficula auricularia* can be either a beneficial or a pest species in commercial agriculture, depending on the particular crop setting (Crumb et al. 1941, Romeu-Dalmau et al. 2012b, Unruh et al. 2016, Orpet et al. 2019a, Alins et al. 2023, Hanel et al. 2023, Bischoff et al. 2024). Work conducted in Spanish citrus groves, where aphid population densities are frequently high, has demonstrated that *F. auricularia* can be an important predator of aphids (Romeu-Dalmau et al. 2012a, b); furthermore, no adverse effect on total yield was observed (Romeu-Dalmau et al. 2012b). In California, however, *F. auricularia* has recently been demonstrated experimentally to feed on very young, developing citrus fruits, resulting in deep, scabby scars on the mature fruit that cause downgrading at the packinghouse (Kahl et al. 2021, 2022). Thus, there may be effects on fruit quality that would not be registered as changes in total yield. Aphid populations are present only very sporadically in California citrus, and contributions by earwigs to aphid population suppression have not been detected (Kahl 2021).

The damage potential of *F. auricularia* on citrus fruit has long escaped notice by economic entomologists for several reasons. First, *F. auricularia* is nocturnal, and thus fruit feeding by these earwigs is rarely observed as it occurs. Second, fruit damage generated by *F. auricularia* is largely indistinguishable from damage generated by other early-season chewing herbivores that attack developing citrus fruit, including a complex of lepidopteran pests and the fork-tailed bush katydid, *Scudderia furcata* (Cass et al. 2023). *Scudderia furcata* is also nocturnal, is damaging even when present at low densities, and is quite cryptic, making sampling very difficult; thus, it has been easy to assign any otherwise unexplained fruit scarring damage to *S. furcata*, without considering a possible role for *F. auricularia*. Further exacerbating these difficulties, recent work has shown that the appearance of scarring damage generated by *S. furcata* and *F. auricularia* varies considerably across different commercial citrus species, including sweet navels (*Citrus sinensis*), true mandarins (*Citrus reticulata*), and clementines (*Citrus clementina*) (Cass et al. 2021, 2023, Kahl et al. 2022). Finally, Kallsen (2013) has suggested that *F. auricularia* has recently emerged as a more important pest in citrus at least in part because citrus growers have shifted away from the use of broad-spectrum insecticides for armored scale insect control that formerly also suppressed earwig populations (see also Saladini et al. 2016).

Recent research has therefore elevated *F. auricularia* to the status of a pest that should be managed alongside other citrus herbivores. However, we currently lack the basic tools for implementing an integrated pest management program for *F. auricularia* in California citrus. First, we need a farmer-friendly method for sampling *F. auricularia* densities. Although sampling methods suitable for researchers have been developed, including the use of cardboard traps placed into tree canopies, these are likely to be too labor-intensive for use by commercial field scouts, especially in citrus trees whose canopies are so dense that locating and accessing traps can be quite difficult. Second, although chemical controls and sticky barriers placed on tree trunks have been shown to be potentially effective (Kahl 2021), we need to understand the timing of *F. auricularia* movement from their protected subterranean nests up into the citrus tree canopies to time the application of these control measures effectively. Third, we currently lack any knowledge of the relationship between *F. auricularia* densities and the prevalence of fruit scarring that would allow us to calculate an economic injury level for this pest.

Thus, the goals of this project were as follows. First, we aimed to demonstrate under commercial field conditions the utility of a simple and time-efficient sampling device, a wooden board trap, for *F. auricularia*. Second, using board traps, we conducted the first surveys of *F. auricularia* across a set of ca. 90 blocks of commercial citrus to characterize the range of densities observed for this earwig in citrus under California conditions. Third, we used automated sampling via video cameras to document the daily and seasonal patterns of movement of earwigs into citrus tree canopies along the central tree trunk. Adult *F. auricularia* are winged, but are very reluctant fliers; mark–release–recapture experiments suggest very low mobility (Moerkens et al. 2010). Past work has shown that sticky barriers can substantially reduce *F. auricularia* densities in tree canopies (Saladini et al. 2016, Kahl 2021). We also present data for another citrus pest, the Fuller rose beetle *Naupactus godmanni* (Crotch), which is strictly wingless and also uses the tree trunk to colonize the citrus canopy. Finally, we looked for relationships between observed densities of *F. auricularia* and the incidence of scarring in fruit sampled either as they are maturing in the fall on the citrus trees or at harvest in bins before fruit are taken to the packing house ('bin samples'). Like many other researchers working with *F. auricularia*, we failed to observe the expected density-damage relationships, and we discuss possible reasons for this.

Materials and Methods

Surveys of *F. auricularia* Densities

The University of California currently makes no recommendations for quantitative sampling of *F. auricularia* in mature citrus plantings. During 24 March 2021 to 8 July 2021 we examined, somewhat informally, a series of potential *F. auricularia* sampling methods in a single block of sweet navel oranges growing at the University of California Lindcove Research and Extension Center. We examined 4 different methods. First, on 24 March 2021, we performed a single timed search (ca. 2 person-hours) of the ground, turning over large dirt clods and looking under soil surface debris (prunings, dried fruit rinds, etc.) to determine if an *F. auricularia* population was present in the block. We found 2 adult females guarding egg masses in their nests, 18 larger nymphs (third to fourth instar), 2 adult males, and 4 adult females. This search confirmed that a population was present, but the method would be difficult to use as a general protocol, because many groves are managed to have a clean floor, eliminating the favored refuges that we exploited to locate earwigs. Second, on 3 dates (22 April, 5 May, and 20 May) we used trowels to turn over all leaf litter and the upper ca. 5 cm of soil within 30 small, 0.25 m^2 plots. This method was laborious, and failed to uncover a single earwig; we therefore abandoned this approach. Third, we used earwig traps, made of a rolled strip of cardboard placed within a plastic cup and wired to a branch within the citrus canopy. This is a standard method (Unruh et al. 2016, Orpet et al. 2019a, b, Hanel et al. 2023) and was the method we had used in our previous research (Kahl et al. 2021, 2022); here we placed 2 traps in each of 30 trees, and checked them on 8 dates (Supplementary Table S1). Fourth, we used wooden boards ($N = 27$, sizes variable), placed flat on the ground at the edge of the tree canopy to create a refuge for earwigs, and lifted on 6 dates (Supplementary Table S1) to check occupancy. This work suggested that board traps revealed many more *F. auricularia* per trap checked than did the cardboard roll traps (Supplementary Table S1). We subsequently learned that some pest control consultants used variants of this method in their scouting of commercial citrus for *F. auricularia*. Board traps could be checked to count *F. auricularia* quite rapidly (< 1 min).

We manufactured wooden board traps to survey 93 commercial citrus blocks, including navel oranges, *Citrus sinensis* ($n = 73$ blocks), clementines, *Citrus clementina* ($n = 16$ blocks), tangelos, *Citrus × tangelo* ($n = 2$), and mixed varieties ($n = 2$) growing in eastern Tulare and Fresno Counties, CA. None of the blocks received pesticide applications targeting *F. auricularia*, and no insecticides were applied to the soil surface against any arthropod pest; foliar pesticide applications were made targeting other pests, however (see Discussion). Board traps were 25.4 × 25.4 cm squares of OSB (oriented strand board) sheathing, 1.82 cm thick; OSB is an inexpensive, engineered wood panel, made of small wood strands glued together with waterproof adhesives. Boards were distributed across each block in 6 locations, at each of which 3 adjacent trees received one board trap each for a total of 18 boards/citrus block, except for a few very small blocks that received 9 boards/block. Boards were deployed in the citrus blocks during February, 2022, placed under the edge of the citrus canopy, and subsequently visited during 5 time periods in the spring and late fall of 2022 and 2023 to count *F. auricularia* (4 to 8 April 2022; 9 to 18 November 2022; 9 February to 2 March 2023; 5 to 12 April 2023; and 23 November to 1 December 2023). During each survey we counted the total number of *F. auricularia* adults, egg masses (no attempt was made to count the number of eggs per egg mass), and aggregations of newly hatched nymphs (first and second instars; again, no attempt was made to count the number of nymphs per aggregation). Another common earwig, the ring-legged earwig *Euborellia annulipes* (Dermaptera: Anisolabididae) (Lucas), was distinguished from *F. auricularia* and was not counted, as this species has never been observed to climb into the citrus canopy to damage fruit. Sampling dates were chosen to focus on times of the year when earwigs are present below ground, where they build nests, oviposit, and care for their young, or are actively foraging on the ground soon after nymphs emerge from their nests (Orpet et al. 2019a). Citrus fruits are known to be vulnerable to *F. auricularia* herbivory immediately after fruit set ('petal fall'), which typically occurs in late April to late May in this region. A few sites were omitted from some surveys, because the sites were actively receiving pesticide applications and could not be visited safely.

We used linear mixed effect models implemented with R package *lme4* (Bates et al. 2015) to test for effects of citrus species and time (survey round) on densities of adult *F. auricularia*; blockID was included as a random effect to account for the repeated measures nature of the survey data.

The repeated earwig surveys also provided a crude, but still useful, opportunity to evaluate whether our sampling method was working in the sense that successive density estimates are positively correlated. Positive correlations would suggest that our sampling method is successfully measuring differences in population densities across citrus groves.

Movement into Citrus Canopies

Treatment Set-up

Observations were conducted in a navel orange (*C. sinensis*) cv. "Washington" block at the University of California Lindcove Research and Extension Center (36.360895, -119.062348). The block was managed using standard commercial practices, except that no insecticides or miticides were applied during the 2021 growing season. To eliminate pathways for crawling arthropods to reach the tree canopy other than the tree trunk, on 17 March 2021 we pruned the skirts of all experimental trees to ca. 0.6 m above the ground and removed any weeds that might create bridges to the tree canopy. Skirt pruning is recommended as a standard cultural practice for Fuller rose beetle control in citrus (UCIPM 2017). Focal trees were also pruned to create gaps of ca. 1.5 m between adjacent trees within rows. Pruning and weeding was maintained as needed throughout the season. Petal fall was declared by Tulare County Agricultural Commissioner on 30 April, 2021.

On 18 March 2021, 2 treatments were established, each replicated 9 times on individual trees: (i) a sticky barrier applied to the tree trunk and (ii) a no barrier control. Trees receiving the 2 treatments were interspersed and spread across a sub-block of 143 trees (11 rows of trees, each with 13 trees). Sticky barriers were created by wrapping a 20 cm wide band of polyester batting around the tree trunk ca. 10 cm above the ground. The batting was secured with a 15 cm band of a stretchable paper tape ("Tangle Guard Tree Wrap") wrapped over it and around the trunk, leaving some batting exposed on either side. A viscous, sticky material ("Tree Tanglefoot") was applied over the paper tape band, creating a 15 cm sticky barrier. All focal trees received a paper tag with a 2.54-cm scale bar, placed on the sticky barrier.

Videography

We conducted videography during daylight hours using natural light and during nighttime hours using infrared lamps (Tendelux A14 IR Illuminators, mounted on a plywood base and powered with a portable gas generator). Compact video cameras (GoPro Hero 6, modified for IR photography, with 12 megapixel full spectrum lenses and mounted on flexible tripods). Cameras were powered with supplementary battery packs (9 Hr ActionPack Extended Battery Modules, manufactured by Re-Fuel). To reduce the focal distance each camera was fitted with a + 1 and a + 2 Vivitar Close Up 52mm macro lens attached using a 3D-printed lens adapter. Cameras were positioned with the lens 13 cm away from the tree trunk. For the trees with sticky barriers, we captured as much of the barrier as possible, with the bottom edge of the barrier always included in the camera frame. For all trees, images captured an area of the trunk starting 5 to 10 cm off the ground.

Filming took place over 3 consecutive days every 2 wk from 22 March to 18 June 2021. Cameras were used in timelapse mode, taking one picture frame every 10 s. On each filming day we attempted to film 3 sticky barrier and 3 control trees; occasional camera failures resulted in 15 to 18 trees successfully recorded during each filming period. For the first 4 filming periods (22 March to 7 May), cameras were run for a 24-h period to establish a full daily pattern of activity. During this period, the battery packs were changed 2 to 3 times a day. For the final 3 filming periods (17 May to 18 June), trees were filmed for 12 h, starting at sunset, and with no battery changes.

Extracting Data from the Videotape

Images were converted into time lapse videos with a frame rate of 4 images per second. Time lapse videos were reviewed, and all observed arthropods other than mites, which were too small to resolve reliably, were recorded and identified to the lowest taxonomic level possible (Order, Family, or Species, depending on how distinctive the arthropod was). We recorded the starting and final locations of all arthropods (above or below a horizontal line bisecting the frame of the video). Insects that entered and left the field of view on opposite halves of the visual field were recorded as having moved vertically. So, an animal that first appeared on the bottom half of the field of view ("B"), and that last appeared on the upper half ("A") was recorded as having moved up (B-A), and an insect that first appeared in the top half of the field of view ("A"), and that last appeared on the bottom half ("B") was recorded as having moved down (A-B). Animals that entered and left from the same halves of the visual field (B-B, or A-A) were recorded as having failed to move vertically. We scored a new observation if the animal left the field of view for >3 s of the timelapse video (2 min of real time).

We used a generalized linear model with binomially distributed errors to test the efficacy of sticky barriers in blocking vertical movement of *F. auricularia* and *N. godmanni* on citrus tree trunks. The model included main effects for insect species (*F. auricularia* vs. *N. godmanni*) and banding treatment (banded vs. control); Julian Date was also included as a main effect to see if dust, dirt, insect bodies or other debris that accumulate on the sticky surface would gradually erode the efficacy of the barrier.

Density–Damage Relationship

In 2022 and 2023, we assessed the relationship between *F. auricularia* densities and fruit scarring. Earwig density estimates were obtained from the survey of commercial citrus blocks conducted in April, just prior to the period of fruit vulnerability to earwig feeding damage. We used 2 estimates of fruit scarring. Our first estimate was derived from 'bin samples'. When fruit are picked, they are placed in large bins, which are eventually loaded onto trucks for transport to the packinghouse. We inspected the visible portions (roughly the top half) of all fruit in the top layer of the bins, which typically involved ca. 200-300 fruit, and recorded the total number of fruit per bin bearing deep scabby scars. In 2022, we had fruit scarring and earwig density estimates for 33 blocks, based on an average of 96.8 ± 108.0 bins checked per block; in 2023, we had fruit scarring and earwig density estimates for 30 blocks.

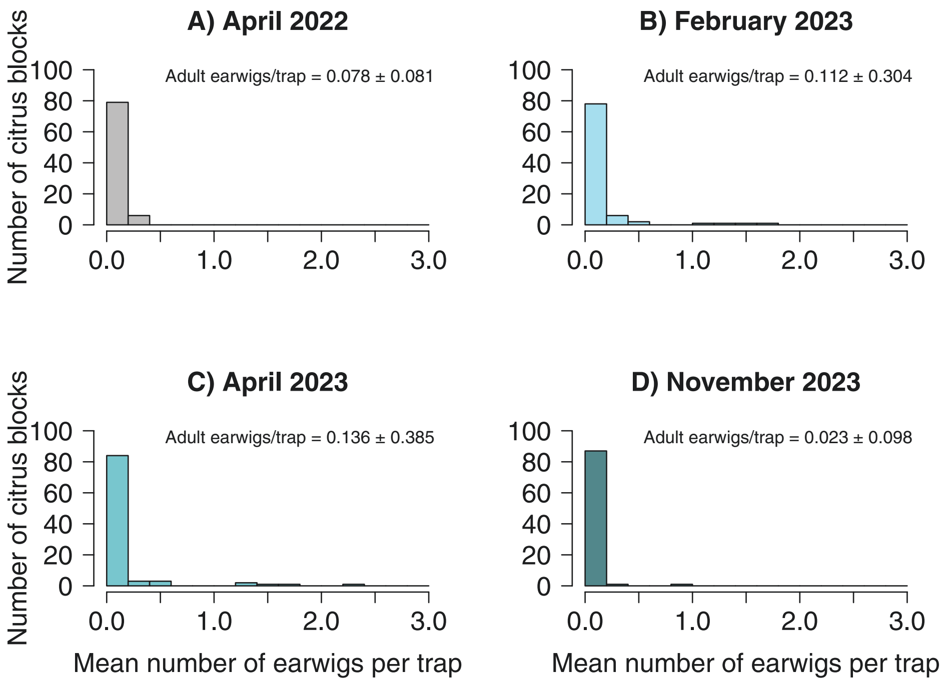

Fig. 1. Mean densities of adult *F. auricularia* in commercial citrus blocks surveyed using wooden board traps placed on the ground under the periphery of the tree canopy.

As described below, the bin samples failed to reveal any relationship between *F. auricularia* densities and the incidence of scarring on harvested fruit. Because all citrus trees set many more fruit than they can mature, natural abscission rates are generally very high. Previous research has shown that fork-tailed bush katydids, which generate damage that is very similar to that generated by *F. auricularia*, can elicit late abscission of nearly mature fruit, which split along the scarred rind and then rot and abscise (Cass et al. 2021). To be sure that a parallel process of selective abscission of damaged fruit was not hiding an underlying relationship between *F. auricularia* densities and fruit scarring, we sampled fruit maturing on trees during September 2023, prior to the period when splitting of katydid-damaged fruit had been observed. We chose a subset of $N = 30$ commercial citrus blocks that had been surveyed for *F. auricularia* densities, including all blocks that had high earwig densities and a subset of the many blocks that had few or no detected earwigs. In each of these blocks we sampled 20 fruit from each of 25 trees located across the block ($N = 500$ fruit total per block) and recorded the presence/absence of deep, scabby scars as well as the approximate area of the scarred surface. Scarring generated by insects with chewing mouthparts is distinctive and is readily distinguished from other sources of scars, including the citrus thrips *Scirtothrips citri*, the common garden snail *Cornu aspersum*, or mechanical processes (eg limb rub).

Results

Sampling Method

Board traps proved to be easy to use; traps were easily checked in less than a minute. A system facilitating location of traps within blocks (we used wire flags, flagging ribbon, and spray paint marks applied to tree trunks) was critical for efficient sampling, as the traps themselves are inconspicuous.

Surveys of *F. auricularia* Densities

Surveys of commercial citrus blocks revealed that *F. auricularia* were distributed very patchily (Fig. 1). Most blocks had zero detected *F. auricularia* or very low densities (< 0.25 adult earwigs per trap, on average), despite *F. auricularia* never being the target of pesticide applications. Some blocks did, however, harbor *F. auricularia* populations, with densities > 1 adult per trap on some sampling dates (Fig. 1). All life stages (eggs, nymphs, and adults) were observed at each of our survey dates (Fig. 2). Earwig densities fluctuated strongly across the sampling period (April 2022 to November 2023; maximum likelihood test for effect of survey date: $X^2 = 15.1$, df = 3, $P = 0.0018$), but did not differ significantly across different *Citrus* species ($X^2 = 2.0$, df = 2, $P = 0.38$).

Although our surveys documented strong fluctuations in overall *F. auricularia* densities over time, we still observed consistently positive correlations between successive samples (Supplementary Fig. S1). This was true for both successive samples taken within a single earwig generation (February 2023 vs. April 2023; Supplementary Fig. S1A) and successive samples taken across earwig generations (April 2022 vs. April 2023, Supplementary Fig. S1B; and April 2023 vs. November 2023, Supplementary Fig. S1C).

Movement into Citrus Canopies

Videographic monitoring revealed a diverse community of animals moving on citrus tree trunks (Table 1). Two important pests of citrus, *F. auricularia* and *N. godmanni* were among the most common arthropods observed. Other commonly observed arthropods included unidentified beetles and spiders, pill bugs (Isopoda), cockroaches (Blattodea), caterpillars (Lepidoptera), and millipedes (Myriapoda).

As has previously been reported, *F. auricularia* appears to be strictly nocturnal: activity was only observed during the period between sunset

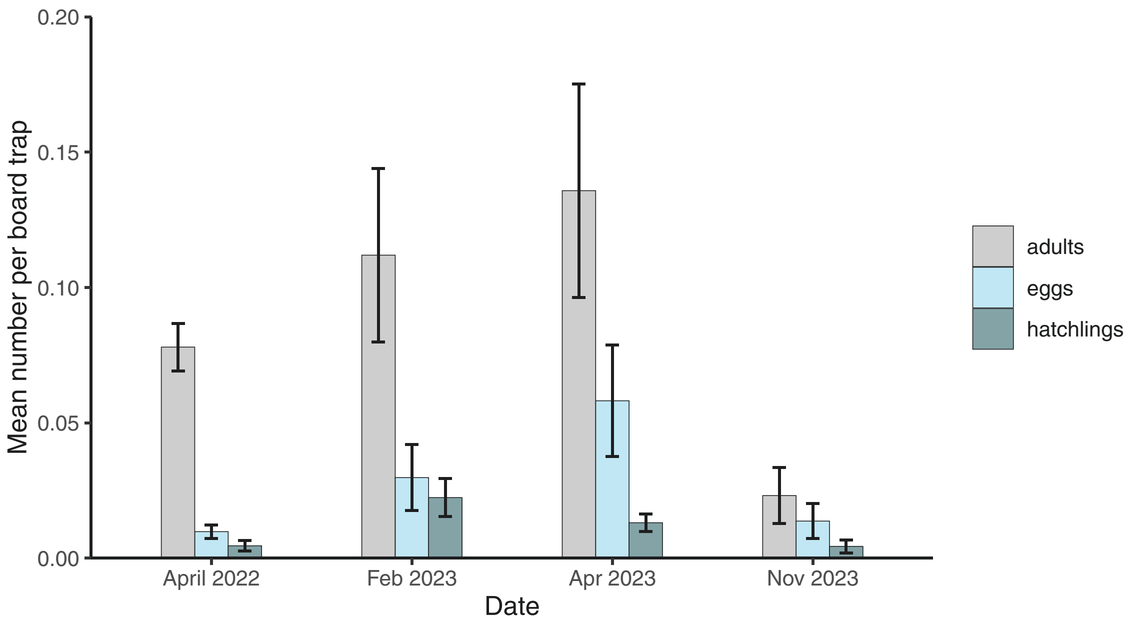

Fig. 2. Life stages of *F. auricularia* observed in commercial citrus blocks. We counted the number of egg masses (rather than attempting to count each egg) and similarly counted the number of clusters of young hatchling nymphs (first or second instars).

Table 1. Survey of animals seen in videographic monitoring of unmanipulated (no sticky band) citrus tree trunks conducted every 2 wk from 22 March to 18 June 2021. Videographic monitoring was conducted over 24-h periods for 22 March to 7 May and over 12-h periods starting at sunset for 17 May to 18 June.

Animal	Total number of sightings
Forficula auricularia	81
Beetles (Coleoptera)	
Unidentified	166
Naupactus godmanni	36
Spiders (Aranaea)	
Unidentified	71
Family Salticidae	3
Family Lycosidae	1
Latrodectus sp.	2
Heteropoda venatoria	1
Pill bugs (Isopoda)	25
Cockroaches (Blattodea)	14
Lepidoptera	
Caterpillars (larval stage)	11
Moth (adult stage)	1
Millipedes (Myriapoda)	8
Garden snail, *Cornu aspersum*	3
Mouse (Rodentia)	3
Harvestman, unidentified (Opiliones)	1
Wind scorpion (Solifugae)	1
Lacewing adult (Family Chrysopidae)	1
Fork-tailed bush katydid, *Scudderia furcata*	1
Unidentified arthropod	1

and sunrise (Fig. 3B). *Naupactus godmanni* was also primarily nocturnal but showed more activity during the crepuscular hours, including some activity in the early morning after sunrise (Fig. 3A).

Both *F. auricularia* and *N. godmanni* were already moving on citrus tree trunks when we began our 24-h surveillance on 22 to 24 March, and movement of both pests continued throughout our monitoring period, which ended in mid-June (Fig. 3). There was a major increase in the number of *F. auricularia* observed during the last 2 observation periods (2 to 4 June and 14 to 16 June; Fig. 3B); however, this was 5 to 7 wk after petal fall in 2021, and fruit were likely already too large to be susceptible to earwig damage (Kahl et al. 2021).

Forficula auricularia appeared to be moving in similar frequencies upwards and downwards on unbanded tree trunks, in contrast to *N. godmanni* which, in all but one case, was moving upwards (Fig. 3). Our data do not reveal, however, the frequency with which individual *F. auricularia* move between the ground and the citrus tree canopy habitats.

Sticky barriers, while not creating an impassible obstacle for crawling *F. auricularia* and *N. godmanni*, did appear to be highly effective in reducing vertical movement of both species along citrus tree trunks (Fig. 4; GLM, effect of banding treatment, $z = 7.0$, $P < 0.0001$). Whereas 34.1% of 88 *F. auricularia* observed moving on control tree trunks moved vertically, only 2.6% of 157 *F.* auricularia observed moving on banded tree trunks moved vertically, walking on the sticky barrier surface. Sticky barriers appeared to be similarly effective against both species (GLM, effect of species, $z = 1.6$, $P = 0.10$), and we saw no evidence of declining effectiveness over the 3 mo of monitoring (GLM, effect of Julian date, $z = -1.0$, $P = 0.30$).

Density–Damage Relationship

We found no evidence for a positive relationship between *F. auricularia* densities, as estimated with board traps, and the incidence of deep scabby scars on fruit harvested following the 2022 growing season (Fig. 5A; linear regression, effect of earwig density = −0.25 ± 1.11 (SE), $N = 33$, $r = -0.04$, $P = 0.83$) or on still-maturing fruit sampled in September 2023 (Fig. 5B; linear regression, effect of earwig density = 0.0066 ± 0.0088 (SE), $N = 32$, $r = 0.14$, $P = 0.46$). Earwig densities were higher in 2023, with some blocks harboring mean adult densities > 1 per board trap, but no signal of elevated damage in these blocks was seen.

Discussion

Recent observations and experimentation have suggested that the European earwig *F. auricularia* is a pest species in California citrus

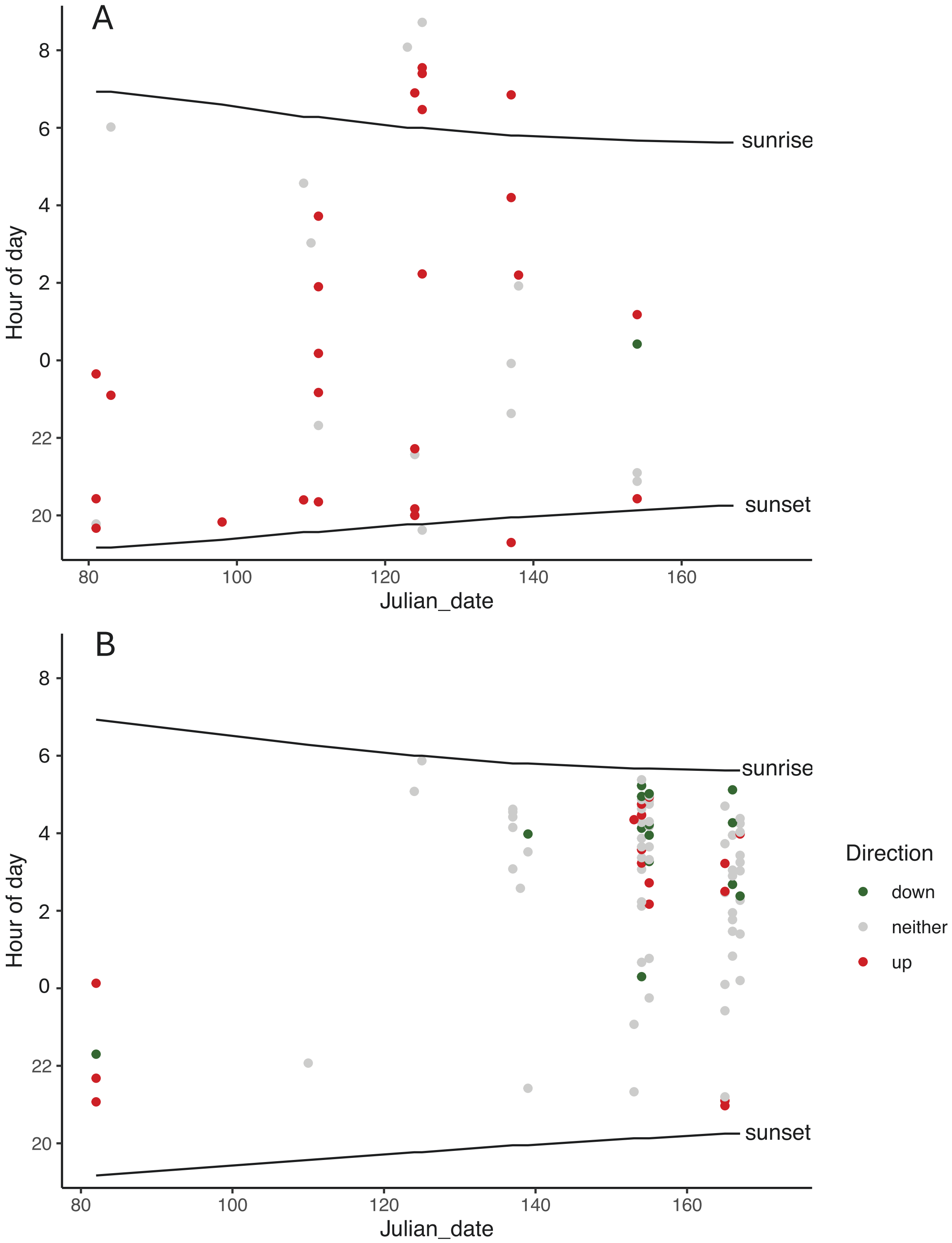

Fig. 3. Daily and seasonal movement of (A) the Fuller rose beetle *N. godmanni* and (B) the European earwig *F. auricularia* travelling up, down, or horizontally ("neither") through the videographic field of view on control citrus tree trunks (ie no sticky barriers present). Hour of day 0 corresponds to midnight. Curving lines show the seasonal change in the times of sunrise and sunset. Videography was performed over 24-h periods for the first 4 sampling periods (Julian dates 81 to 127) and over 12-h periods starting at sunset for the last three sampling periods (Julian dates 137 to 168). No insect activity was seen between 10:00 – 18:00 h, so those times are not plotted.

(Kahl 2021, Kahl et al. 2021, 2022). After spending the late fall and winter in shallow soil nests, *F. auricularia* nymphs and adults emerge in the spring, climb into citrus tree canopies, and feed on tiny developing fruit, creating damage that eventually becomes deep, scabby scars on mature fruit rind that cause downgrading at the packinghouse. The new recognition of the pest potential of *F. auricularia* means that farmers now need the basic set of integrated pest management tools for this species. These include (i) a time- and cost-efficient sampling method; (ii) a knowledge of *F. auricularia* biology that can help farmers to time control measures appropriately; and (iii) a quantitative description of the relationship between pest density and crop damage that can guide management decisions by estimating an economic injury level. In this report, we present progress on sampling and knowledge of optimal timing, but we were stymied in our attempt to calculate an economic injury level.

Wooden board traps appear to offer a farmer-friendly means of sampling *F. auricularia*. A local fabricator firm charged us $1.90 per board for their production. To use any sampling method that involves sampling earwigs on the ground, one must distinguish between *F. auricularia* and the ring-legged earwig *E. annulipes*, which is a non-pest. This required some training to recognize distinguishing characteristics (eg wing pads or wings are present on *F. auricularia* but absent in *E. annulipes*) but is easy once learned. Boards placed on the ground are a favorite device used by herpetologists to sample the herpetofauna, and we were concerned that we might inadvertently create refuge habitat for rattlesnakes; although we did see salamanders and a toad under the boards, we saw no snakes. But, we avoided citrus blocks that had a known history of rattlesnake populations. We chose smaller dimensions for the traps in part to reduce the likelihood that we would create refuges for rattlesnakes.

Our surveys showed that *F. auricularia* is distributed patchily, being rare or absent in most of the sampled citrus blocks and relatively common in only a handful of sites (Fig. 1). Across all the surveyed sites mean population densities varied considerably across our 4 sampling periods. This high level of spatial and temporal variation in population densities in California citrus mirrors what has been recorded for populations of *F. auricularia* within its native range in Europe (Moerkens et al. 2009, Romeu-Dalmau et al. 2012a, Saladini et al. 2016). Densities of *F. auricularia* were positively correlated across successive surveys (Supplementary Fig. S1), suggesting that our sampling method successfully resolved underlying differences in population densities across our surveyed citrus blocks.

Our videographic monitoring of citrus tree trunks revealed 2-way traffic of *F. auricularia* on citrus tree trunks throughout the spring. Earwigs were already moving up into tree canopies when we initiated our monitoring in mid-March. This suggests that sticky barriers or insecticides directed at the soil surface and tree trunks may need to be applied quite early, and well before petal fall when citrus fruit become vulnerable to *F. auricularia*. Field trials are needed to test this hypothesis. In properly skirt-pruned citrus groves, the tree trunk appears to be the primary path along which 2 important pests, *F. auricularia* and *N. godmanni*, gain access to the tree canopies. This may provide an opportunity to manage these pests with minimal disruption to beneficial insect communities residing in the canopies.

The Elusive Economic Injury Level

The published literature reveals that the task of developing an economic injury level for *F. auricularia* has proven to be surprisingly difficult. Multiple researchers have sought, unsuccessfully, to characterize what is expected to be a straightforward positive relationship between *F. auricularia* density and fruit damage for different tree crops (eg apricots: Saladini et al. 2016, cherries: Quarrell et al. 2021, see review by Orpet et al. 2019a). This is true despite successful experimental demonstrations of the damage potential of *F. auricularia* in some of the same studies (eg Quarrell et al. 2021). Romeu-Dalmau et al. (2012a) did document a positive relationship between estimated *F. auricularia* density and flower survival on citrus, but flower survival is not expected to be linked to harvest quantity or quality for citrus crops. Why has the density–damage relationship proved to be so elusive for *F. auricularia*?

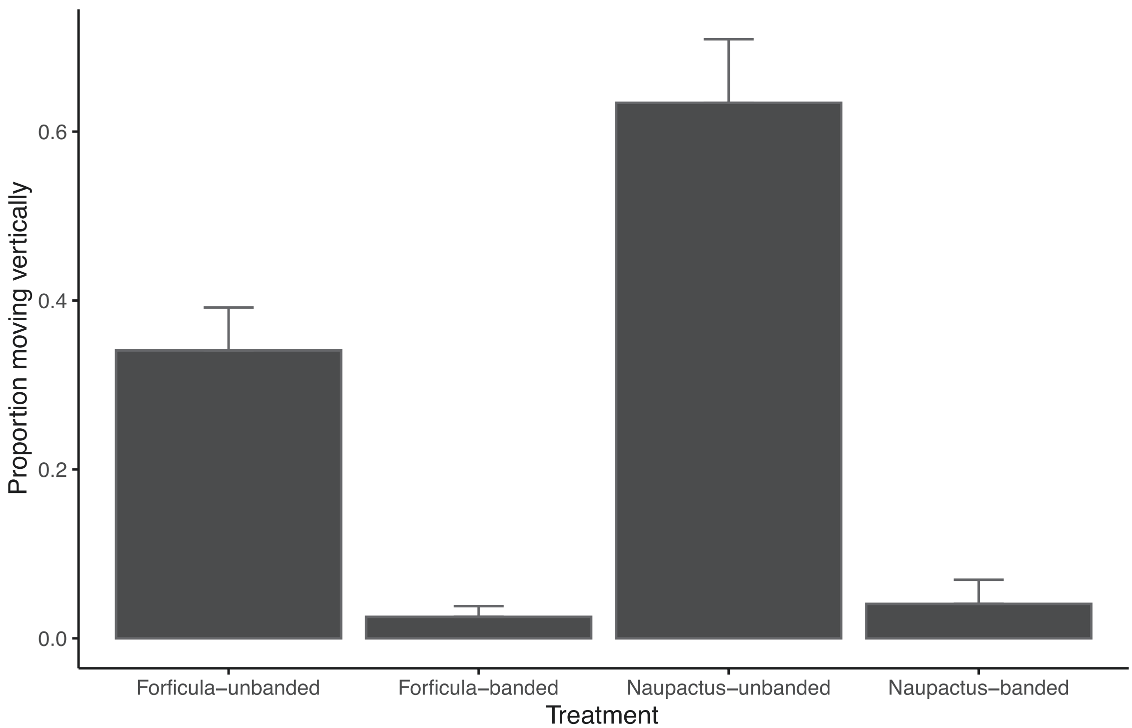

Fig. 4. Efficacy of a sticky barrier placed on citrus trunks in blocking vertical movement of the European earwig *F. auricularia* ("Forficula") and the Fuller rose beetle *N. godmanni* ("Naupactus"). Shown are the mean ± SE proportion of insects observed in video monitoring that were moving vertically (across the midpoint of the video field of view, which for banded trees was located in the sticky barrier).

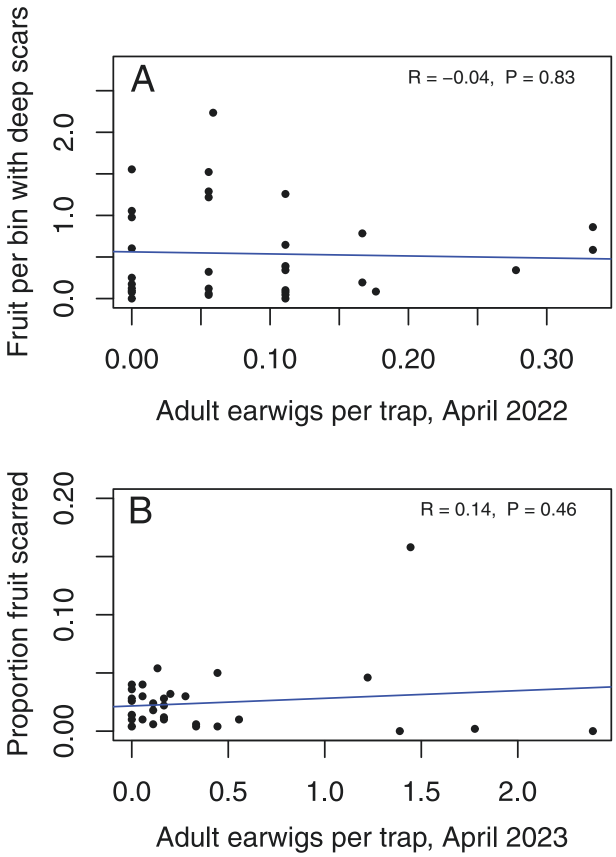

Fig. 5. Linear regression analysis shows no significant relationship between the mean number of adult *F. auricularia* per board trap during April sampling and (A) the mean number of fruit bearing deep, scabby scars at harvest per bin (bin samples; 200 to 300 fruit checked/bin) in 2022; or (B) the mean proportion of fruit bearing deep, scabby scars during September 2023 sampling (fruits still maturing on trees).

We might have failed to observe a relationship between *F. auricularia* and citrus fruit damage in the present study for several reasons. First, for a study like ours that is conducted in a commercial setting, it is possible that pesticides, even if applied to target other pests, might be suppressing *F. auricularia* populations. Foliar residues of many common insecticides are highly toxic to *F. auricularia* (eg Shaw and Wallis 2010, Laure et al. 2015, Niedobová et al. 2024). California citrus is often treated following petalfall to protect the crop from a complex of pests, including the citrus thrips *Scirtothrips citri*, the fork-tailed bush katydid *S. furcata*, the California red scale *Aonidiella aurantii*, and sometimes the citrus red mite *Panonychus citri*. For example, a subset of the commercial citrus blocks that we sampled received an average of 4.1 such pesticide applications (range: 1 to 5, $N = 50$) between 1 April and 31 May 2023. In most cases, we do not know if pesticide applications targeting other pests are also suppressing *F. auricularia* densities. This is, however, an obvious candidate explanation for the otherwise enigmatic observations of citrus blocks with high *F. auricularia* densities but negligible fruit scarring (Fig. 5B).

Second, our inability to distinguish damage generated by *F. auricularia* from that generated by *S. furcata* may also be a key stumbling block. Both of these pests are nocturnal, cryptic, potentially damaging even when present at low absolute densities, and quite difficult to sample (Crumb et al. 1941, Cass et al. 2019, Orpet et al. 2019a). Thus, the citrus blocks with high levels of fruit scarring despite very low *F. auricularia* density estimates (Fig. 5A) may reflect a hidden role for the katydid *S. furcata*. Damage by *F. auricularia* is somewhat nonspecific and is often difficult to separate from other sources (Orpet et al. 2019a, b, Hanel et al. 2023).

Third, our density estimates for *F. auricularia* may not be as accurate as we are imagining. Sampling *F. auricularia* is particularly difficult for at least 2 reasons. First, *F. auricularia* produces an aggregation pheromone, producing what is often a highly clustered distribution and traps with increasing attractiveness over time (Crumb et al. 1941, Lordan et al. 2014). Second, the sampling efficacy of refuge-based traps like the board traps we used here may change across different locations in response to variation in the availability of competing refuges (Moerkens et al. 2009, Orpet et al. 2019a, Quarrell et al. 2021, Alins et al. 2023). Thus, densities may appear especially elevated in orchards with clean floors, simply because there are no alternate protected resting locations for *F. auricularia*.

Other factors may also contribute to the difficulty of characterizing the density-damage relationship for *F. auricularia*. This species is an omnivore, and it may switch between acting as a predator versus acting as an herbivore in response to changing availability of prey, thereby changing its impact on the host plant (eg Rosenheim et al. 2006). Experiments have demonstrated varying susceptibility to *F. auricularia* feeding across different *Citrus* species (true mandarins, *Citrus reticulata*, have a high natural resistance to both *F. auricularia* (Kahl et al. 2022) and *S. furcata* (Cass et al. 2019), and it may be that important but unrecognized variation also exists among cultivars within navel oranges and clementines studied here.

Finally, it may be that *F. auricularia* population densities are simply too low in California citrus groves to produce measurable scarring damage to fruit. Although it is difficult to compare absolute *F. auricularia* density estimates across studies that employ somewhat different sampling methods, it does appear that California citrus groves harbor quite low densities of *F. auricularia* compared to what has been recorded elsewhere (e.g., Crumb et al. 1941, Moerkens et al. 2009, Romeu-Dalmau et al. 2012a, b, Lordan et al. 2014, Laure et al. 2015, Marshall and Beers 2022, Alins et al. 2023, Hanel et al. 2023). Nevertheless, Kahl (2021) demonstrated that placing sticky barriers on citrus tree trunks in California to exclude *F. auricularia* from citrus canopies resulted in a statistically significant and meaningful (ca. 50%) decrease in fruit scarring recorded at harvest. Mean *F. auricularia* densities never exceeded 0.6 earwigs per cardboard roll trap during this experiment. Thus, it does appear that under California growing conditions even low densities of *F. auricularia* are capable of generating measurable damage to citrus fruit.

Additional research is needed to evaluate each of these possible explanations for the absence of the expected density–damage relationship and to develop clear management recommendations for *F. auricularia*.

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Author contributions

Jay Rosenheim (Conceptualization [lead], Data curation [lead], Formal analysis [lead], Funding acquisition [lead], Investigation [equal], Methodology [equal], Supervision [equal], Visualization [lead], Writing—original draft [lead], Writing—review & editing [lead]), Emma Cluff (Conceptualization [supporting], Data curation [supporting], Formal analysis [supporting], Investigation [equal], Methodology [equal], Writing—review & editing [supporting]), and Kelley Morrow (Conceptualization [supporting], Data curation [supporting], Funding acquisition [supporting], Investigation [equal], Methodology [equal], Supervision [equal], Writing—review & editing [supporting])

Conflicts of interest. None declared.

Supplementary material

Supplementary material is available at *Journal of Economic Entomology* online.

Data Availability

Data from this study are available from DRYAD: https://doi.org/10.5061/dryad.k6djh9whd. Rosenheim, Cluff and Morrow, 2024.

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