

## Arthropod Infestation Levels on Mandarins in California

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### Abstract

Integrated pest management (IPM) guidelines for horticulture are typically established from years of experimental research and experience for a crop species. Ecoinformatics methods can help to quickly adapt these guidelines following major changes in growing practices. Citrus production in California is facing several major challenges, one of which is a shift away from sweet oranges [*Citrus sinensis* (L.) Osbeck Sapindales: Rutaceae] toward mandarins (including mostly cultivars of *C. reticulata* Blanco and *C. clementina* hort. ex Tanaka). In the absence of IPM guidelines for mandarins, growers are relying on pest information developed from oranges. We mined a database of management records from commercial growers and consultants to determine densities for four arthropod pests: cottony cushion scale (*Icerya purchasi* Maskell Hemiptera: Monophlebidae), citricola scale (*Coccus pseudomagnoliarum* Kuwana Hemiptera: Coccidae), European earwig (*Forficula auricularia* Linnaeus Dermaptera: Forficulidae), citrus red mite (*Panonychus citri* McGregor Acari: Tetranychidae), and a natural enemy, predatory mites in the genus *Euseius* (Congdon Acarina: Phytoseiidae). Densities of cottony cushion scale were approximately 10–40 times higher in the two most commonly grown mandarin species than in sweet oranges, suggesting this pest is reaching outbreak levels more often on mandarins. Densities of the other pests and predatory mites did not differ significantly across citrus species. This is a first step toward establishing IPM guidelines for mandarins for these pests; more research is needed to determine how arthropod densities relate to crop performance in mandarins.

**Key words:** ecoinformatics, data mining, *Citrus*, cultivar, integrated pest management (IPM)

Integrated pest management (IPM), in which pest densities are monitored and maintained below acceptable economic injury levels through preventative cultural methods and application of mechanical, biological, and chemical controls, aims to maximize economic, ecological, and social interests concurrently (Stern et al. 1959, van den Bosch and Stern 1962, Flint and van den Bosch 1981). This practice relies on an understanding of the biology in the agroecosystem, with guidelines usually established from many years of field experiments and experience. The extensive resources needed to conduct these fundamental agroecological studies can pose a barrier to IPM implementation (van den Bosch and Stern 1962). Ecoinformatics or data mining approaches can help to determine crop–pest interactions following sweeping changes in agroecosystems, to see where and how practices need to be updated (Bekker et al. 2007; Rosenheim et al. 2011, 2017; Rosenheim and Meisner 2013; Rosenheim and Gratton 2017).

Citrus is a top commodity in California, with a long production history that for many years was dominated by sweet oranges. Over the past ca. 20 yr, there has been a major shift toward mandarins, which now account for the majority of new citrus acreage and market

value (California Department of Food and Agriculture and California Agricultural Statistics Service 2018, California Department of Food and Agriculture 2019). The umbrella term ‘mandarin’ hides substantial genetic diversity, with cultivars of *C. reticulata* (e.g., ‘Tango’ and ‘W. Murcott Afourer’) and *C. clementina* (e.g., ‘Clemenules’), the most commonly grown (California Department of Food and Agriculture and California Agricultural Statistics Service 2018). The IPM program was established from decades of research and experience in sweet oranges and has not been updated for mandarins (Dreistadt 2012, Grafton-Cardwell 2014, Grafton-Cardwell et al. 2020). Extensive monitoring efforts by professional pest control advisors (PCAs) contribute to the success of the IPM program. This field scouting generates a wealth of observational data covering a broad range of commercial growing conditions, presenting an opportunity to help understand mandarin–arthropod interactions.

A number of pests are commonly monitored in commercial citrus groves in the Central Valley using qualitative and quantitative density estimates. Some of these including California red scale (*Aonidiella aurantii* Maskell Hemiptera: Diaspididae), citrus thrips (*Scirtothrips citri* Moulton Thysanoptera: Thripidae), fork-tailed

bush katydid (*Scudderia furcata* Brunner von Tattenyll Orthoptera: Tettigoniidae), and lepidopteran caterpillars (mostly citrus cutworm, *Egira curialis* Grote Lepidoptera: Noctuidae) are known to cause characteristic damage directly to the orange fruit, which is commonly monitored in harvest bin sampling. The relationships between field densities and damage levels of these ‘direct’ pests were assessed in mandarins in a previous study (Cass et al. 2019b). Other common pests that are the subject of the present study are cottony cushion scale, citricola scale, European earwig, and citrus red mite. Cottony cushion scale and citricola scale settle on citrus leaves and branches to feed on sap, which reduces tree vigor and can cause twig dieback. These scales also excrete honeydew, which is a substrate for sooty mold growth, interferes with photosynthesis, and damages fruit (Flanders 1942, Bartlett 1953, Quezada and DeBach 1973, Bernal et al. 2001). European earwigs are omnivores that feed on buds, leaves, and fruit in the spring (Kallsen 2006, Dreistadt 2012, Romeu-Dalmau et al. 2012). Citrus red mites feed on leaves, where they can cause stippling and dried leaf patches (mesophyll collapse). They also sometimes feed on fruit where they can cause stippling, silvering, or sunburn, and in very high densities, they can lower yield (Quayle 1912; Kennett and Flaherty 1974; Hare et al. 1990, 1992). Predatory mites in the genus *Euseius* (herein ‘predatory mites’) are also monitored for their contributions to pest control. They are generalist predators that feed on citrus thrips (Tanigoshi et al. 1983, 1984), citrus red mite (Congdon and McMurtry 1988, McMurtry et al. 1992), other small insects such as scale crawlers, and leaf sap and pollen (Kennett et al. 1979, Ouyang et al. 1992, Dreistadt 2012). We mined quantitative sampling data collected on these arthropods by PCAs in commercial citrus groves to test whether the mandarin species now commonly being grown harbor different densities compared with oranges.

## Materials and Methods

### Citrusformatics Database and Data Subset

We analyzed a subset of a SQL server database (*Citrusformatics*, Ten2Eleven Business Solutions, LLC) of commercial citrus production records from Fresno and Tulare counties, CA, in crop years 2007–2014. The database was compiled from multiple sources and included grove agronomic data, field scouting reports, and agrichemical use records provided by cooperating commercial citrus growers and PCAs and accessed from the Pesticide Use Reporting database (California Department of Pesticide Regulation 2018), as described

previously (Livingston et al. 2018, Cass et al. 2019b). Subsetting of the data exported from the SQL server, and all subsequent analyses and graphing were performed in R version 3.6.1 (R Core Team 2018) using R packages in *tidyverse* (Wickham et al. 2019), based on the code provided in Cass et al. (2019b). Records for 155 commercial citrus groves from 55 ranches, each observed for 2–8 yr were used in the analyses, for a total of 1,014 grove-years. Not all arthropod species were sampled in each grove-year, and density estimates were not available for some citrus species–arthropod combinations where they were not surveyed.

The median area of the sampled groves was 10.2 hectares (range 1.0–142.2) with a median tree age of 9 yr (range 1–105; groves that had mixed tree ages due to partial replanting were excluded from analyses). The citrus genus has a complex phylogeny (Wu et al. 2018), with many commercially grown cultivars being interspecific hybrids that are clonally propagated through nuclear embryony (Wang et al. 2017) or grafting (Mudge et al. 2009). The cultivars represented in the data were grouped by citrus species determined from the University of California Riverside Citrus Variety Collection (University of California Riverside 2018), as per Table 1.

### Arthropod Density Estimates

Pest and natural enemy sampling conducted by PCAs was based on methodologies recommended in the University of California Pest Management Guidelines (Grafton-Cardwell et al. 2020). Pest densities were estimated for each grove from the proportion of sample units infested with the organism (presence/absence sampling). Percent sample units infested were used as an estimate of pest density or pressure within a grove, instead of a count estimate of absolute pest density (number/leaf), as under commercial conditions, most data fall in the approximately linear portion of the curve linking percent sampling units present versus pest density, allowing us to calculate averages with only modest error (Jones and Parrella 1984), and because percent samples infested is the measure used by farmers, and thus is the ‘real’ currency of pest management decision making. One sample unit was monitored per tree. Sampled trees were selected by walking in a circle from approximately the fifth to tenth tree of the fourth row from the corner of the grove. In larger groves, the sampled trees were spread out over equal-sized quadrants. The number of sample units checked per scouting depended on the grove area, grove shape, and time available for sampling. In general, 25 sample units for groves less than 8 hectares, 50 sample units for groves 8–16 hectares, and at least 100 sample units for groves larger than 16

**Table 1.** Citrus cultivars represented per species assignment in the analysis

Citrus type	Citrus species	Citrus cultivar	No. grove-years
Sweet orange	<i>C. sinensis</i>	‘Atwood’ navel	61
		‘Barnfield’ navel	6
		‘Cara Cara’ navel	49
		‘Chislett’ navel	8
		‘Fisher’ navel	45
		‘Fukumoto’ navel	38
		‘Lane Late’ navel	64
		‘Powell’ navel	184
		‘Spring’ navel	8
		‘Washington’ navel	186
		Valencia	2
		Other/unspecified navel	30
Mandarin	<i>C. reticulata</i>	‘Tango’	118
		‘W. Murcott Afourer’	97
		‘Clemenules’	118
	<i>C. clementina</i>		

hectares. In the dataset analyzed, most observations were approximately 25, 50, or 100 sample units (median: 50, range: 10–480). For citricola scale, predatory mites, and citrus red mite, the sample units were individual leaves examined on both the upper and lower sides, or occasionally for citricola scale, approximately 15-cm portions of branches. For cottony cushion scale, the sample units were approximately 60-cm portions of tree trunks or inner branches. These arthropods were monitored in trees of all ages, whereas earwigs were only commonly monitored in newly planted groves in the protective wraps placed around young tree trunks. For earwigs, the sample units were these tree trunk isolation wrappings that were shaken. When two separate estimates were made for the same organism, in the same grove, on the same day (e.g., by two different PCAs on two different data sheets), they were combined by taking an unweighted average. The arthropods were sampled frequently throughout the year as described in the University of California Pest Management Guidelines (Grafton-Cardwell et al. 2020).

Grove-year was the replicate unit used for our analyses. Mean pest densities for each grove-year were calculated from cumulative pest-days, equivalent to the area under the curve that plots pest density versus day of year by linear interpolation between consecutive observations, as per Cass et al. (2019b). For mites, interpolations were taken between points within each calendar year. For scales and earwigs, interpolations extended into the subsequent year if there was at least one density observation in that calendar year. Density estimates were adjusted using pesticide application records assuming complete pesticide effectiveness for the targeted pest, as groves are not usually sampled immediately following pesticide applications for safety considerations. This was done by setting the pest densities to zero on the day after a spray targeting the pest, unless there was a scouting observation on that day and only when a spray occurred between two scouting observations. As a check of the assumption of complete pesticide effectiveness, we also ran the models without this pesticide correction, i.e., assuming pesticide failure such that arthropod densities remained unaffected by the sprays in the interpolation, and not including any correction in the statistical model for pesticide pressure. As reported below, there was no change in the overall results, so we did not test scenarios for intermediate changes in populations following sprays. Mean pest densities for each grove-year were then calculated from the daily estimates for the calendar year for the number of days in the range of sampled dates in that year.

### Statistical Analyses

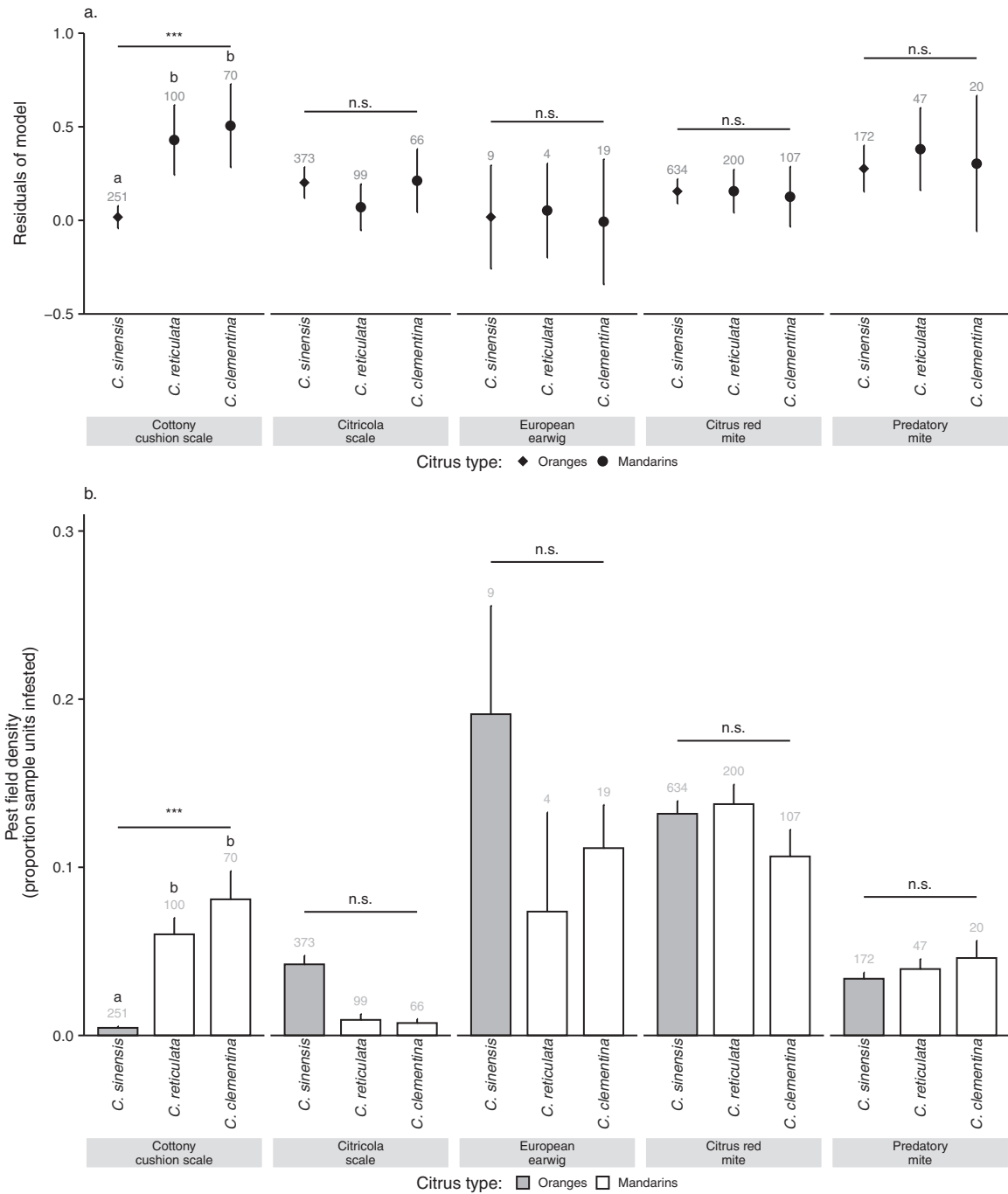
Analyses were performed in R version 3.6.1 (R Core Team 2018). Differences in mean estimated daily arthropod density per grove-year among citrus species were tested for each pest using generalized additive mixed models in the *mgcv* package version 1.8.28 (Wood 2006, 2011), run with the *gam* function. This function allows for nonlinear relationships via flexible thin plate regression spline ‘tp’ smooths on the continuous predictors, and random effects added as ‘re’ smooths. For each arthropod, the response variable was the organism *density* (mean daily proportion of sample units infested), and the predictor variable was *citrus species* with a beta family (logit link). Other covariates included in the model were as follows: *year*, *tree age* (years since planting), *grove area*, *grove latitude and longitude by year*, and *number of targeted pesticide sprays* for each grove-year. *Ranch* and *grove identifiers* were also included as random effects. The inclusion of these covariates reduced the amount of unexplained variance and opportunities for spurious associations between the *citrus species* predictor of interest and the *density* response variable.

The *year* covariate was included to capture much of the weather-generated year-to-year variation that could affect pest densities. The *tree age*, *grove area*, and *number of targeted pesticide sprays* are variables that could influence arthropod densities separately from citrus species. The grove location (*grove latitude and longitude by year*) provided statistical control for spatial autocorrelation of the observations, incorporating the possibility that pest densities were patchy and that the locations of the patches varied across years. The *grove identifier* was the basic management unit for commercial farming operations and its inclusion accounted for the repeated-measures (time-series) nature of the data set. A ranch identified a set of contiguous groves managed by the same grower following a common set of agronomic practices; including *ranch identifier* controlled for between-farmer differences in farming practices.

Sprays were counted as targeting the pest when listed by the PCA or based on discussions with the PCAs about which active ingredients were used for each pest. Applications covering partial groves (based on the acreage covered compared to the total grove acreage) were counted as partial sprays. For predatory mites, sprays targeting any mite were counted. We tested running the models with broader pesticide target groups: *number of pesticide sprays targeting pest group* (sprays targeting any scale insect for cottony cushion scale or citricola scale, or any mite for citrus red mite) and *total number of insecticide and acaricide sprays*. We also ran each model on a subset of the data using only groves within the range of tree age overlap for each organism and citrus species (i.e., excluding the orange groves older than the maximum age of the youngest mandarin species surveyed for the pest: 15 yr for cottony cushion scale, 13 yr for citricola scale, 15 yr for citrus red mite, and 12 yr for predatory mites), to account for the longer history of orange production potentially confounding the *tree age* and *citrus species* terms. Earwigs were only compared in newly established groves (trees up to 3 yr since planting), as this is where they were routinely sampled. For *C. sinensis*, which has multiple cultivars represented, the models were run on a subset of the data with *citrus cultivar* as a predictor instead of *citrus species* to test for within-species cultivar effects, for cultivars that had a sufficient number of grove-years represented. Note that for the two *C. reticulata* cultivars, ‘Tango’ was derived from ‘W. Murcott Afourer’ through irradiation of budwood to obtain a low seeded variety (University of California Riverside 2018), so we would not expect there to be differences between these two cultivars. Where there was a significant effect of *citrus species* or *citrus cultivar*, pairwise contrasts were made between species or cultivars by assessing the overlap of confidence intervals at an alpha level of 0.05 of the mean residual values from the statistical models with the *citrus species* or *citrus cultivar* variable withheld.

### Results

There was a significant effect of citrus species on the densities of cottony cushion scale, but not on the densities of citricola scale, European earwig, citrus red mite, or predatory mites. The results were mirrored in models run without any pesticide correction (Supp Fig. S1 [online only], Supp Table 1 [online only]) and in models run on subsets of the data of only groves within the range of overlapping tree ages among the citrus species (Supp Table 2 [online only]) or using broader categories to count the number of pesticide sprays targeting any insect or mite (Supp Table 3 [online only]). To control statistically for the effects of other variables on pest densities, in Fig. 1a we plotted the mean residual values from the statistical models with the *citrus species* variable withheld, to isolate the effect



**Fig. 1.** Arthropod densities in commercial groves of sweet oranges and mandarins in Fresno and Tulare counties, CA, between 2007 and 2014. (a) Residuals of the model run with the citrus species term withheld. (b) Mean densities. Error bars show 95% confidence intervals. Numbers in gray above bars indicate number of grove-years sampled. Significance of the explanatory variable *citrus species* on the response variable *density* is indicated above bars for each pest group (\*\*\*)  $P < 0.001$ , \*\*  $P < 0.01$ , \*  $P < 0.05$ , n.s. 'not significant'  $P > 0.05$ ). Letters above bars indicate groups with overlapping confidence intervals at 95% where there was a significant effect of the explanatory variable *citrus species*.

of citrus species. The raw means are presented in Fig. 1b and the full statistical model outputs are provided in Table 2. Cottony cushion scale densities were higher in *C. clementina* and *C. reticulata* than in *C. sinensis*, a pattern that held before and after accounting for effects of the other covariates (Fig. 1, Table 2).

Comparing Fig. 1a with Fig. 1b shows the importance of including multiple covariates in the statistical model, to isolate effects of *citrus species* from the influences of other factors that can shape citrus arthropod densities in pooled, observational data: in

several cases, univariate mean insect density estimates appeared to be quite different across citrus species, but the apparent differences disappeared when the explanatory roles of other covariates were incorporated. For example, citricola scale densities appeared to be much lower in both mandarin species than in oranges looking at the raw densities (Fig. 1b), but this difference was entirely explained by variation in other covariates, such as significant effects of tree age, year, and pesticide pressure (Fig. 1a, Table 2). Similarly, for citrus red mites, the raw densities appeared lower in mandarins, especially

**Table 2.** Generalized additive mixed model<sup>a</sup> output for influence of citrus species on arthropod densities

Pest	No. grove-years	Parameter	Degrees of freedom	$\chi^2$	P-value		
Cottony cushion scale	421	<i>citrus species</i>	2	38.9	<0.0001***		
		<i>s(tree age)</i>	1.0	0.3	0.873		
		<i>s(grove area)</i>	1.0	<0.1	0.929		
		<i>s(number targeted sprays)</i>	1.0	0.9	0.344		
		<i>year</i>	4	8.7	0.070		
		<i>s(longitude, latitude) 2010</i>	2.6	4.1	0.143		
		<i>s(longitude, latitude) 2011</i>	2.6	9.5	0.011*		
		<i>s(longitude, latitude) 2012</i>	2.0	0.9	0.641		
		<i>s(longitude, latitude) 2013</i>	2.6	4.1	0.337		
		<i>s(longitude, latitude) 2014</i>	2.3	1.8	0.554		
		<i>s(ranch identifier)</i>	35.3	155.3	<0.0001***		
		<i>s(grove identifier)</i>	0.1	0.1	0.719		
		Citricola scale	538	<i>citrus species</i>	2	0.4	0.818
				<i>s(tree age)</i>	2.0	29.7	<0.0001***
<i>s(grove area)</i>	1.0			0.1	0.721		
<i>s(number targeted sprays)</i>	1.2			39.5	<0.0001***		
<i>year</i>	7			73.0	<0.0001***		
<i>s(longitude, latitude) 2007</i>	2.8			4.8	0.148		
<i>s(longitude, latitude) 2008</i>	2.4			2.0	0.362		
<i>s(longitude, latitude) 2009</i>	1.0			<0.1	0.982		
<i>s(longitude, latitude) 2010</i>	2.0			11.8	0.003**		
<i>s(longitude, latitude) 2011</i>	2.0			15.0	<0.001***		
<i>s(longitude, latitude) 2012</i>	2.2			5.1	0.113		
<i>s(longitude, latitude) 2013</i>	2.0			1.2	0.547		
<i>s(longitude, latitude) 2014</i>	2.6			7.7	0.058		
<i>s(ranch identifier)</i>	<0.1			<0.1	0.592		
<i>s(grove identifier)</i>	<0.1			<0.1	0.986		
Earwig <sup>b</sup>	32			<i>citrus species</i>	2	0.8	0.685
		<i>s(tree age)</i>	1.2	0.4	0.586		
		<i>s(grove area)</i>	1.4	0.4	0.542		
		<i>number targeted sprays</i>	1	19.1	<0.0001***		
		<i>year</i>	2	14.4	<0.001***		
		<i>s(grove identifier)</i>	10.3	57.5	<0.0001***		
		Citrus red mite	941	<i>citrus species</i>	2	5.4	0.328
				<i>s(tree age)</i>	1.0	<0.1	0.102
				<i>s(grove area)</i>	1.0	8.8	0.003***
				<i>s(number targeted sprays)</i>	1.7	32.4	<0.0001***
<i>year</i>	7			484.2	<0.0001***		
<i>s(longitude, latitude) 2007</i>	2.3			32.4	0.030*		
<i>s(longitude, latitude) 2008</i>	2.9			7.4	<0.001***		
<i>s(longitude, latitude) 2009</i>	2.0			20.3	0.249		
<i>s(longitude, latitude) 2010</i>	2.0			2.8	0.004**		
<i>s(longitude, latitude) 2011</i>	2.0			10.8	0.001**		
<i>s(longitude, latitude) 2012</i>	2.0	13.1	0.737				
<i>s(longitude, latitude) 2013</i>	2.9	0.6	<0.0001***				
<i>s(longitude, latitude) 2014</i>	2.0	26.4	<0.0001***				
<i>s(ranch identifier)</i>	32.6	24.7	<0.0001***				
<i>s(grove identifier)</i>	65.8	402.0	<0.0001***				
Predatory mites <sup>c</sup>	239	<i>citrus species</i>	2	2.3	0.312		
		<i>s(tree age)</i>	1.0	2.1	0.149		
		<i>s(grove area)</i>	1.0	11.8	<0.001***		
		<i>s(number targeted sprays)</i>	1.0	0.4	0.513		
		<i>year</i>	3	15.2	0.002**		
		<i>s(longitude, latitude) 2008</i>	2.7	13.6	0.017*		
		<i>s(longitude, latitude) 2009</i>	1.0	0.5	0.463		
		<i>s(longitude, latitude) 2011</i>	2.5	14.4	0.001**		
		<i>s(longitude, latitude) 2012</i>	2.8	5.6	0.084		
		<i>s(longitude, latitude) 2013</i>	2.0	2.7	0.253		
		<i>s(ranch identifier)</i>	<0.1	<0.1	0.614		
		<i>s(grove identifier)</i>	64.8	156.5	<0.0001***		

<sup>a</sup>Beta family (logit link) GAMM:  $density \sim citrus\ species + year + s(tree\ age, bs = 'tp') + s(grove\ area, bs = 'tp') + s(number\ of\ targeted\ pesticide\ sprays, bs = 'tp') + s(longitude, latitude, bs = 'tp', by = year) + s(ranch\ identifier, bs = 're') + s(grove\ identifier, bs = 're')$ .

<sup>b</sup>Ranch identifier term removed and smooth for number of targeted pesticide sprays removed due to insufficient statistical power.

<sup>c</sup>Number of targeted pesticide sprays included sprays targeting any mites.

\*\*\*  $P < 0.001$ , \*\*  $P < 0.01$ , \*  $P < 0.05$ .



*C. clementina* (Fig. 1b), but this trend disappeared after removing variation explained by the other covariates, including significant effects of grove area, year, pesticide pressure, and grove location (Fig. 1a, Table 2). Predatory mite raw densities were slightly higher in mandarins, especially *C. clementina* (Fig. 1b), but again, these differences were accounted for by the other covariates, including grove area and year (Fig. 1a, Table 2). There was a high variation in earwig densities within species, with a limited sample size that reduced the statistical power of the model. The trend toward higher earwig densities in *C. sinensis* (Fig. 1b) was removed by accounting for other covariates including year and pesticide pressure (Fig. 1a, Table 2).

There was an overall effect of citrus cultivar on citricola scale densities within the citrus species *C. sinensis*; however, there were no significant paired contrasts between the cultivars. There was no effect of citrus cultivar on densities of cottony cushion scale, citrus red mite, or predatory mites (Supp Fig. S2 [online only], Supp Table 4 [online only]).

## Discussion

We found evidence of differences in mean densities across citrus species for cottony cushion scale, with higher densities in the two most commonly grown mandarin species (*C. reticulata* and *C. clementina*) than in sweet oranges (*C. sinensis*). Direct fruit damage by citrus thrips and katydids is much less prevalent in *C. reticulata* than in *C. sinensis* (Cass et al. 2019a, b; Mueller et al. 2019). The preponderance of cottony cushion scale in these mandarins thus appears to be a strong counter-example, where *C. reticulata* might be a more suitable host than *C. sinensis*. There was no effect of citrus species on the densities of the other surveyed arthropods after controlling for the effects of other covariates such as tree age and grove area. The similar pest densities suggest similar pest pressure, although more work is needed to see if similar densities beget similar effects on yield and fruit quality.

The result of higher cottony cushion scale on mandarins is striking both because cottony cushion scale appears to be a major pest of the new mandarins with frequent outbreaks recorded and because of cottony cushion scale's historical status as the target of an early, dramatically successful demonstration of classical biological control (Caltagirone and Doutt 1989). The cottony cushion scale is an invasive pest that was devastating the expanding citrus industry in California in the late 1800s. It was controlled by the introduction of two exotic, specialized natural enemies in the 1890s: the vedalia beetle *Rodolia cardinalis* Mulsant (Coleoptera: Coccinellidae) and the parasitoid fly *Cryptochaetum iceryae* Williston (Diptera: Cryptochaetidae). These have been examples of long-term, stable control of cottony cushion scale in citrus throughout the state. The vedalia beetle is active in all areas and predominant in the Central Valley including the location of this study, while the parasitoid fly favors coastal citrus (Quezada and DeBach 1973, Caltagirone and Doutt 1989, Dreistadt 2012). The higher densities of cottony cushion scale in mandarins suggest that there has been a breakdown of the vedalia beetle biological control system.

We do not know the basis for the cottony cushion scale outbreaks and presumed vedalia beetle ineffectiveness on mandarins, but present some non-mutually exclusive hypotheses. Bottom-up effects may be important, with mandarins being a better host for cottony cushion scale. For example, mandarins may provide a higher quality or more palatable food resource for cottony cushion scale (Schuman and Baldwin 2016, Erb and Reymond 2019), or a more

preferable microclimate for cottony cushion scale growth with their more bushy, higher leaf density architectural canopy structure (Lawton 1983, Denno et al. 2002, Pearson 2009). Alternatively, top-down effects may be more important, with the vedalia beetle being less effective in suppressing cottony cushion scale on mandarins. Mandarins may interfere with the efficacy of the vedalia beetle or prohibit its establishment in groves. Several non-*Citrus* host plants of cottony cushion scales have been found to be unsuitable for the vedalia beetle either because the plants themselves were unattractive or because the cottony cushion scales growing on those plants were no longer accepted as prey (Quezada and DeBach 1973, Caltagirone and Doutt 1989). Quantitative data on vedalia beetle densities were not available for the groves surveyed here, but would help to test these hypotheses.

The arthropod densities presented here describe what growers and consultants are seeing on average in their oranges versus mandarins given the grove conditions and management practices, rather than a fine-scale look at individual sampled densities that might trigger treatments. Economic injury levels are not available for any of these pests on mandarins. On navel oranges, replicated, manipulative experimental research support for a treatment threshold is available for citrus red mite (Hare et al. 1990, 1992). Hare (1988) found only minor differences in the suitability of lemons *C. limon* (L.) Burm. cv. Lisbon and the mandarin *C. unshiu* Markovitch cv. Satsuma as hosts for citrus red mite, similar to the findings reported here of similar densities on *C. sinensis*, *C. clementina*, and *C. reticulata*. Treatment thresholds for citricola scale and cottony cushion scale are based on expert opinion and experience in *C. sinensis* (Grafton-Cardwell et al. 2020). Specific thresholds for earwigs are not available in young or mature trees on any citrus species; here we did not find differences between the orange and mandarin species, although we had less statistical power due to a smaller sample size, and a lack of data for mature trees. Further work is needed for this emerging pest (Kallsen 2006). The comparable densities of predatory mites observed on mandarins and oranges may reflect the similar abundances of its main prey items on these citrus species (this study and Cass et al. 2019b).

There are some notable strengths and limitations to the ecoinformatic approach used in this study. For example, the test for citrus species effects on densities is observational not experimental. However, the scope of the data covering a broad range of growing conditions, along with the multiple covariates included in the statistical models helped to isolate the effect of citrus species from other explanatory variables. Another limitation is that the data can only cover the arthropods and citrus cultivars that are represented, for example, we do not have data on vedalia beetles, on earwigs in fruit-bearing trees, from more cultivars and older mandarin trees. However, as the data came directly from commercial groves, the model tested those factors directly relevant to the real conditions in the production region.

Analyzing the pre-existing arthropod density data collected in commercial groves as part of citrus production operations has provided an overview of arthropod densities in different citrus cultivars now commonly grown in California. For four important arthropods: citricola scale, citrus red mites, European earwigs in young trees, and predatory mites, densities did not differ significantly across citrus species. Additional work is now needed to determine whether the per-capita interaction of these pests with their different *Citrus* species hosts varies across the commercially important citrus crops. For cottony cushion scale, the higher incidence documented in mandarins provides impetus for further research.

## Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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## References Cited

- Bartlett, B. R. 1953. Natural control of citricola scale in California. *J. Econ. Entomol.* 46: 25–28.
- Bekker, R. M., E. van der Maarel, H. Bruelheide, and K. Woods. 2007. Long-term datasets: from descriptive to predictive data using ecoinformatics. *J. Veg. Sci.* 18: 457–462.
- Bernal, J. S., R. F. Luck, J. G. Morse, and M. S. Drury. 2001. Seasonal and scale size relationships between citricola scale (Homoptera: Coccidae) and its parasitoid complex (Hymenoptera: Chalcidoidea) on San Joaquin Valley citrus. *Biol. Control* 20: 210–221.
- California Department of Food and Agriculture, and California Agricultural Statistics Service. 2018. 2018 California Citrus Acreage Report. California Department of Food and Agriculture, Sacramento, CA.
- California Department of Food and Agriculture. 2019. California Agricultural Statistics Review 2017–2018. California Department of Food and Agriculture, Sacramento, CA.
- California Department of Pesticide Regulation. 2018. Pesticide use reporting (PUR). (<http://www.cdpr.ca.gov/dprdatabase.htm>) (Accessed 28 December 2019).
- Caltagirone, L., and R. Doult. 1989. The history of the vedalia beetle importation to California and its impact on the development of biological control. *Annu. Rev. Entomol.* 34: 1–16.
- Cass, B. N., E. E. Grafton-Cardwell, and J. A. Rosenheim. 2019a. Resistance of fruits from a mandarin cultivar to feeding by fork-tailed bush katydids. *J. Econ. Entomol.* 112: 2861–2871.
- Cass, B. N., L. M. Hack, E. E. Grafton-Cardwell, and J. A. Rosenheim. 2019b. Impacts of fruit-feeding arthropod pests on oranges and mandarins in California. *J. Econ. Entomol.* 112: 2268–2277.
- Congdon, B., and J. McMurtry. 1988. Prey selectivity in *Euseius tularensis* [Acari: Phytoseiidae]. *Entomophaga* 33: 281–287.
- Denno, R. F., C. Gratton, M. A. Peterson, G. A. Langellotto, D. L. Finke, and A. F. Huberty. 2002. Bottom-up forces mediate natural-enemy impact in a phytophagous insect community. *Ecology* 83: 1443–1458.
- Dreistadt, S. H. 2012. Integrated pest management for citrus, 3rd ed. UC ANR Publication 3303. University of California Agriculture and Natural Resources (UC ANR) Statewide Integrated Pest Management Program, Oakland, CA.
- Erb, M., and P. Reymond. 2019. Molecular interactions between plants and insect herbivores. *Annu. Rev. Plant Biol.* 70: 527–557.
- Flanders, S. E. 1942. Biological observations on the citricola scale and its parasites. *J. Econ. Entomol.* 35: 830–833.
- Flint, M., and R. van den Bosch. 1981. Introduction to integrated pest management. Plenum Press, New York.
- Grafton-Cardwell, E. E. 2014. The status of citrus IPM in California. *Acta Horticult.* 1065: 1083–1090.
- Grafton-Cardwell, E. E., R. A. Baldwin, J. O. Becker, A. Eskalen, C. J. Lovatt, S. Rios, J. E. Adaskaveg, B. A. Faber, D. R. Haviland, K. J. Hembree, et al. 2020. Revised continuously. UC IPM Pest Management Guidelines: citrus. UC ANR Publication 3441. University of California Agriculture and Natural Resources (UC ANR), Oakland, CA.
- Hare, J. D. 1988. Egg production of the citrus red mite (Acari: Tetranychidae) on lemon and mandarin orange. *Environ. Entomol.* 17: 715–721.
- Hare, J. D., J. Pehrson, T. Clemens, J. Menge, J. C. Coggins, T. Embleton, and J. Meyer. 1990. Effects of managing citrus red mite (Acari: Tetranychidae) and cultural practices on total yield, fruit size, and crop value of ‘navel’ orange. *J. Econ. Entomol.* 83: 976–984.
- Hare, J. D., J. Pehrson, T. Clemens, J. Menge, C. Coggins Jr., T. Embleton, and J. Meyer. 1992. Effect of citrus red mite (Acari: Tetranychidae) and cultural practices on total yield, fruit size, and crop value of ‘navel’ orange: years 3 and 4. *J. Econ. Entomol.* 85: 486–495.
- Jones, V. P. and M. P. Parrella. 1984. Intradree regression sampling plans for the citrus red mite (Acari: Tetranychidae) on lemons in southern California. *J. Econ. Entomol.* 77: 810–813.
- Kallsen, C. 2006. Earwigs flying under the radar of many citrus pest control advisors. *Topics Subtrop. Newsl.* 4: 3–4.
- Kennett, C., and D. Flaherty. 1974. Pest management of citrus red mite on citrus in the southern San Joaquin Valley. University of California Cooperative Extension Service Bulletin 27. University of California, Berkeley, CA.
- Kennett, C., D. Flaherty, and R. Hoffmann. 1979. Effect of wind-borne pollens on the population dynamics of *Amblyseius hibisci* [Acarina: Phytoseiidae]. *Entomophaga* 24: 83–98.
- Lawton, J. 1983. Plant architecture and the diversity of phytophagous insects. *Annu. Rev. Entomol.* 28: 23–39.
- Livingston, G., L. Hack, K. P. Steinmann, E. E. Grafton-Cardwell, and J. A. Rosenheim. 2018. An ecoinformatics approach to field-scale evaluation of insecticide effects in California citrus: are citrus thrips and citrus red mite induced pests? *J. Econ. Entomol.* 111: 1290–1297.
- McMurtry, J., J. Morse, and H. Johnson. 1992. Studies of the impact of *Euseius* species (Acari: Phytoseiidae) on citrus mites using predator exclusion and predator release experiments. *Exp. Appl. Acarol.* 15: 233–248.
- Mudge, K., J. Janick, S. Scofield, and E. E. Goldschmidt. 2009. A history of grafting. *Hortic. Rev.* 35: 437–493.
- Mueller, T. G., H. M. Kahl, B. N. Cass, E. E. Grafton-Cardwell, and J. A. Rosenheim. 2019. Differential impacts of citrus thrips across sweet orange and mandarin species. *J. Econ. Entomol.* 112: 2767–2773.
- Ouyang, Y., E. E. Grafton-Cardwell, and R. L. Bugg. 1992. Effects of various pollens on development, survivorship, and reproduction of *Euseius tularensis* (Acari: Phytoseiidae). *Environ. Entomol.* 21: 1371–1376.
- Pearson, D. E. 2009. Invasive plant architecture alters trophic interactions by changing predator abundance and behavior. *Oecologia*. 159: 549–558.
- Quayle, H. J. 1912. Red spiders and mites of citrus trees. Agricultural Experiment Station Bulletin 234. University of California, Berkeley, CA.
- Quezada, J. R., and P. DeBach. 1973. Bioecological and population studies of the cottony-cushion scale, *Icerya purchasi* Mask., and its natural enemies, *Rodolia cardinalis* Mul. and *Cryptochaetum iceryae* Will., in southern California. *Hilgardia* 41: 631–688.
- R Core Team. 2018. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (<https://www.R-project.org/>) (Accessed 28 December 2019).
- Romeu-Dalmau, C., X. Espadaler, and J. Piñol. 2012. Abundance, interannual variation and potential pest predator role of two co-occurring earwig species in citrus canopies. *J. Appl. Entomol.* 136: 501–509.
- Rosenheim, J. A., and C. Gratton. 2017. Ecoinformatics (Big Data) for agricultural entomology: pitfalls, progress, and promise. *Annu. Rev. Entomol.* 62: 399–417.
- Rosenheim, J. A., and M. H. Meisner. 2013. Ecoinformatics can reveal yield gaps associated with crop-pest interactions: a proof-of-concept. *PLoS One* 8: e80518.
- Rosenheim, J. A., S. Parsa, A. A. Forbes, W. A. Krimmel, Y. H. Law, M. Segoli, M. Segoli, F. S. Sivakoff, T. Zaviezo, and K. Gross. 2011. Ecoinformatics for integrated pest management: expanding the applied insect ecologist’s tool-kit. *J. Econ. Entomol.* 104: 331–342.
- Rosenheim, J. A., B. S. Higbee, J. D. Ackerman, and M. H. Meisner. 2017. Ecoinformatics can infer causal effects of crop variety on insect attack by capitalizing on ‘pseudoexperiments’ created when different crop varieties are interspersed: a case study in almonds. *J. Econ. Entomol.* 110: 2647–2654.

- Schuman, M. C., and I. T. Baldwin. 2016. The layers of plant responses to insect herbivores. *Annu. Rev. Entomol.* 61: 373–394.
- Stern, V., R. Smith, R. van den Bosch, and K. Hagen. 1959. The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. *Hilgardia* 29: 81–101.
- Tanigoshi, L. K., J. Y. Nishio-Wong, and J. Fargerlund. 1983. Greenhouse-rearing and laboratory-rearing studies of *Euseius hibisci* (Chant) (Acarina, Phytoseiidae), a natural enemy of the citrus thrips, *Scirtothrips citri* (Moulton) (Thysanoptera, Thripidae). *Environ. Entomol.* 12: 1298–1302.
- Tanigoshi, L., J. Nishio-Wong, and J. Fargerlund. 1984. *Euseius hibisci*: its control of citrus thrips in Southern Californian citrus orchards, pp. 717–724. In D. A. Griffiths and C. E. Bowman (eds.), *Acarology VI*, Vol. 2. Ellis Horwood, Limited, Chichester, United Kingdom.
- University of California Riverside. 2018. Citrus variety collection. (<https://citrusvariety.ucr.edu/>) (Accessed 28 December 2019).
- van den Bosch, R., and V. M. Stern. 1962. The integration of chemical and biological control of arthropod pests. *Annu. Rev. Entomol.* 7: 367–386.
- Wang, X., Y. Xu, S. Zhang, L. Cao, Y. Huang, J. Cheng, G. Wu, S. Tian, C. Chen, Y. Liu, *et al.* 2017. Genomic analyses of primitive, wild and cultivated citrus provide insights into asexual reproduction. *Nat. Genet.* 49: 765–772.
- Wickham, H., M. Averick, J. Bryan, W. Chang, L. McGowan, R. François, G. Golemund, A. Hayes, L. Henry, J. Hester, *et al.* 2019. Welcome to the Tidyverse. *J. Open Source Softw.* 4:1686.
- Wood, S. N. 2006. *Generalized additive models: an introduction with R*, 1st ed. Chapman and Hall/CRC, Boca Raton, FL.
- Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *J. R. Stat. Soc. B* 73: 3–36.
- Wu, G. A., J. Terol, V. Ibanez, A. López-García, E. Pérez-Román, C. Borredá, C. Domingo, F. R. Tadeo, J. Carbonell-Caballero, R. Alonso, *et al.* 2018. Genomics of the origin and evolution of *Citrus*. *Nature* 554: 311–316.