

Impacts of Fruit-Feeding Arthropod Pests on Oranges and Mandarins in California

Bodil N. Cass,^{1,3,✉} Lindsey M. Hack,¹ Elizabeth E. Grafton-Cardwell,^{2,✉} and Jay A. Rosenheim^{1,✉}

¹Department of Entomology and Nematology, University of California, Davis, CA 95616, ²Department of Entomology, University of California, Riverside, CA 92521, and ³Corresponding author, e-mail: bncass@ucdavis.edu

Subject Editor: Jana Lee

Received 29 January 2019; Editorial decision 24 April 2019

Abstract

One of the major challenges facing citrus integrated pest management (IPM) in California is the recent, sharp increase in the acreage of mandarins being planted. The current citrus IPM guidelines have been established from years of experiments and experience in oranges, with no specific guidelines for mandarins. In the absence of research into key arthropod pest effects in mandarins, the assumption that the pest management practices for oranges appropriately transfer for optimal production in mandarins has not been tested. We used a data mining or ‘ecoinformatics’ approach in which we compiled and analyzed production records collected by growers and pest control advisors to gain an overview of direct pest densities and their relationships with fruit damage for 202 commercial groves, each surveyed for 1–10 yr in the main production region of California. Pest densities were different among four commonly grown species of citrus marketed as mandarins (*Citrus reticulata*, *C. clementina*, *C. unshiu*, and *C. tangelo*) compared with the standard *Citrus sinensis* sweet oranges, for fork-tailed bush katydids (*Scudderia furcata* Brunner von Wattenwyl [Orthoptera: Tettigoniidae]), and citrus thrips (*Scirtothrips citri* Moulton [Thysanoptera: Thripidae]). *Citrus reticulata* had notably low levels of fruit damage, suggesting they have natural resistance to direct pests, especially fork-tailed bush katydids. These results suggest that mandarin-specific research and recommendations would improve citrus IPM. More broadly, this is an example of how an ecoinformatics approach can serve as a complement to traditional experimental methods to raise new and unexpected hypotheses that expand our understanding of agricultural systems.

Key words: ecoinformatics, data mining, fruit abscission, cultivar effect, variety effect

Citrus is a major part of the agricultural landscape and a high-value crop in California, supporting a >\$2 billion industry contributing 46% of the U.S. citrus production and 62% of the citrus national value (USDA, NASS 2017). The main citrus growing area is in the San Joaquin Valley where ~75% of the statewide acreage is found (Dreistadt 2012). Citrus in this region is attacked by a number of key arthropod pests, against which most growers apply three to five different pesticides throughout the growing season (Grafton-Cardwell 2015). Citrus has a year-round integrated pest management (IPM) program established from decades of experience and multiyear field experiments in sweet oranges (*Citrus sinensis*; Dreistadt 2012, Ferguson and Grafton-Cardwell 2014). In this program, growers and pest control advisors (PCAs) carefully monitor pests and diseases to make management decisions that maintain the ecosystem while minimizing pest pressure and environmental risk (Dreistadt 2012, Grafton-Cardwell 2015, Grafton-Cardwell et al. 2017).

Citrus production in California has changed substantially in recent years, with a sharp increase in mandarin acreage. From 2007 to

2016, total bearing acreage of mandarin and mandarin hybrids in California increased from 19,000 to 57,000 acres, and mandarins and mandarin hybrids were nearly 50% of the new citrus acreage planted in 2017 (CDFA 2018, CDFR and CASS 2018). There are currently no specific IPM guidelines established for California mandarins.

In California, citrus is grown exclusively for fresh market fruit, compelling growers to aggressively control for rind-scarring or -infesting pests. In the San Joaquin Valley region, several early-season pests feed directly on very young fruit, including the fork-tailed bush katydid, citrus thrips, and a complex of lepidopteran caterpillars or ‘worms’, herein ‘caterpillars’ (mostly citrus cutworm, *Egira curialis* Grote [Lepidoptera: Noctuidae]). In addition, California red scale (*Aonidiella aurantii* Maskell [Hemiptera: Diaspididae]) infests all aerial parts of the tree including fruit. Rind feeding causes fruit to abscise or creates scars that cause the fruit to be downgraded months later at harvest time to be sold for juice only, resulting in nearly complete loss of fruit value. Even within well-studied *C. sinensis*,

treatment thresholds with replicated, manipulative experimental research support for these pests are not always available or difficult to obtain. There are observational (correlative) research results for treatment thresholds for California red scale (Elmer and Brawner 1982) and citrus thrips (Rhodes et al. 1986, Rhodes and Morse 1989), supported by extensive demonstration plots (Haney et al. 1992). For caterpillars and fork-tailed bush katydids, treatment thresholds are based on industry experience. In the absence of research in mandarins, citrus growers do not know which practices might need to be changed for optimal production.

Pest life-history parameters are known to vary across other *Citrus* species. For example, *C. limon* (lemons) were demonstrated to be a better host than *C. unshiu* for egg production by the citrus red mite, *Panonychus citri* McGregor (Acari:Tetranychidae), in summer and fall (Hare 1988, Hare et al. 1990b). California red scale survival was lower on the bark of *C. unshiu* than on the bark of *C. sinensis*, *C. limon*, or *C. paradisi* (grapefruit; Hare et al. 1990a). *Citrus unshiu* and *Citrus reticulata* also supported lower California red scale densities than *C. limon*, *C. sinensis*, and *C. paradisi* (Habib et al. 1972). *Citrus nobilis* (tangerine) were less susceptible than other species to citrus leafminer, *Phyllocnistis citrella* Staint (Gracilariidae, Lepidoptera; Ba-Angood 1977). Host plants can vary in terms of antibiosis either globally (Eyles et al. 2010), in which case the densities of the pests should be expected to be different, or more locally, in specific tissues, in which case the densities might seem the same, but damage to particular tissues might vary.

Here we tested 1) whether mean densities of direct pests differed between *C. sinensis* oranges and the four major mandarin species (*C. reticulata*, *C. clementina*, *C. tangelo*, and *C. unshiu*) and 2) whether the patterns of fruit damage (scarring and fruit infestation) seen on mandarins were as expected, given mean densities of the direct pests seen there, or whether there were strong deviations from the relationships between pest densities and fruit scarring seen on *C. sinensis*. We constructed and analyzed a large database of pest management records from PCAs and commercial citrus growers in Tulare and Fresno counties in the San Joaquin Valley, CA. Results from the commercial records were compared with a complementary researcher multiple grove survey for fruit damage. Data mining or 'ecoinformatics' (Bekker et al. 2007, Kelling et al. 2009, Rosenheim et al. 2011, Soranno et al. 2014, Rosenheim and Gratton 2017) approaches such as this are emerging as important complements to answer ecological questions in agricultural systems (e.g., Krasnov et al. 2018 used this approach to assess Mediterranean fruit fly dynamics in citrus in Israel). In ecoinformatics, the data tend to be observational, pooled from pre-existing sources, cover broad spatial and temporal scales, have increased statistical power due to large sample sizes, and represent a broad range of growing conditions. Ecoinformatics is especially suited to establishing key hypotheses during the initial, highly exploratory phase of a research project. We used this approach to provide a foundation for understanding how pest dynamics are influenced by citrus species at the scale of commercial production.

Materials and Methods

Citrusformatics Database

We analyzed a subset of a large SQL server database of commercial citrus production records in California ('*Citrusformatics*', Ten2Eleven Business Solutions, LLC), described previously (Livingston et al. 2018). Briefly, the *Citrusformatics* interface was designed to increase data entry efficiency and accuracy, especially for records that were entered manually. The database included records

of scouting of pest and beneficial arthropod densities, plant nutrient status, fruit quality, pesticide applications, and yield. Data were integrated from multiple sources, including records provided by co-operating commercial citrus growers and PCAs. Agrichemical use data were supplied from growers and PCAs and accessed from the Pesticide Use Reporting (PUR) database (CDPR 2018).

Data Subset

Subsetting of the data exported from the SQL server, and all subsequent analyses were performed in R (R Core Team 2018). A commented version of the relevant code is provided in [Supp Mater \[online only\]](#). Records for 202 commercial citrus groves in Fresno and Tulare counties, CA, with pest density records, each observed for 1–10 yr (median 6 yr) were used in the analyses. These groves were surveyed in calendar years 2003–2012 with most data from the calendar years 2007–2012. Management decisions for citrus groves were made at the grove (or 'block') level, with contiguous groves referred to as a 'ranch'. The groves analyzed were from 71 ranches from six growers. Sweet oranges and mandarins in this region initiate fruit in the spring and are harvested in following winter or spring. Records were therefore organized into 976 'grove-years', with each grove-year including data from the year in which the crop was initiated and continuing until fruit harvest, which may have occurred during the subsequent calendar year. The data types used for each grove were agronomic information, scouting observations of pest densities, pesticide application records, and 'bin evaluations' of the frequency of pest-inflicted damage to the fruit rind (scarring or infestation) at harvest. Within a given grove-year, not all pests had all data types.

Grove Agronomic Data

Citrus variety, planting date, and acreage were provided by the co-operating growers. The classification of citrus varieties and evolutionary relationships among citrus species are complex (Velasco and Licciardello 2014, Wu et al. 2014); we grouped the variety types included in our analyses by citrus species, determined from the University of California Riverside Citrus Variety Collection (UCR 2018), as per [Table 1](#). Valencia orange varieties of *C. sinensis* were excluded from analyses, due to their different phenology compared with other sweet oranges. Latitude and longitude were determined from grove centroids using maps provided by growers, referenced to satellite images in Google Earth Pro (version 7.3.0.3832; Google Inc.). Median grove size was 7.1 ha (range 0.2–57.5) with a median tree age of 12 yr (range 2–103). Groves that had mixed tree ages due to partial replanting and citrus species with fewer than 5 grove-years of data were excluded from analyses. The agricultural commissioner restricts the use of pesticides in citrus groves during the bloom season until the 'petal fall' date, when an estimated 75% of the petals have dropped from the trees in a growing district. Petal fall dates for each of the four districts represented in the data set were assigned from Fresno and Tulare county agricultural commissioner records and used in analyses to normalize the phenology of crop initiation among growing years.

Pest Density Estimates

We focused here on the repeated, presence/absence sampling of the four main arthropods that directly damage the citrus fruit: caterpillars, California red scale, fork-tailed bush katydid, and citrus thrips. Pest densities were estimated for each grove from the proportion of sample units infested with the pest, with approximately 100 sample units checked per scouting, depending on the grove acreage. For citrus thrips nymphs, the sample units were individual fruit removed

Table 1. Citrus varieties represented per species assignment in the analyses

Citrus type	Citrus species	Citrus variety
Sweet orange	<i>C. sinensis</i>	'Atwood' navel
		'Barnfield' navel
		'Cara Cara' navel
		'Chislett' navel
		'Fisher' navel
		'Frost Washington' navel
		'Fukumoto' navel
		'Lane Late' navel
		'Moro Blood'
		'Navelina' navel
		'Powell' navel
		'Spring' navel
		'Washington' navel
		Other/unspecified navel
Mandarin	<i>C. reticulata</i>	'Tango'
Clementine mandarin	<i>C. clementina</i>	'W. Murcott Afourer'
Tangelo mandarin	<i>Citrus × tangelo</i>	'Clemenules'
Satsuma mandarin	<i>C. unshiu</i>	'Minneola'
		Unspecified

from the tree and inspected with a hand lens. For caterpillars and fork-tailed bush katydid, the sample units were approximately 60 × 60 cm (2 × 2 ft) areas of fruit and foliage (approximately 10–15 fruit visible per area) that were visually inspected for 30–60 s, or occasionally sampled with a sweep net or by shaking the branches. For California red scale, the sample units were trees, with the inner wood checked early in the season and outer fruit, branches, and foliage examined after the third-generation flight of male scales. One window per tree was examined for caterpillars and fork-tailed bush katydids, and usually one but up to five fruit were sampled per tree for thrips, with the sampled fruit taken from different parts of the tree when more than one fruit per tree was sampled. The number of sample units checked per grove-day was mostly 25, 50, or 100 units (range: 10–300), depending on the grove size. In larger groves, the sampled trees were spread out over each of equal-sized quadrants. 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. When two separate estimates were made for the same pest, in the same grove, on the same day (e.g., by two different PCAs on two different data sheets), the samples were combined by taking their unweighted average. When a single observation listed different types of caterpillar, these were combined additively to assume the individual insects occurred in different samples out of the total sampled units in one grove-day observation.

Daily density estimates for each pest were made by linear interpolation between consecutive observations. The density estimates were adjusted using the pesticide application records by setting pest densities to zero on the day after a spray targeting the pest, unless there was a scouting observation on that day. We assumed complete pesticide effectiveness immediately following an application for the intended pest target reported by growers/PCAs, but did not make the adjustment in cases where broad-spectrum products may also have suppressed populations of other pests. The interpolation line was kept constant on any days after an estimate up until the spray. Mean pest densities for each grove-year were then calculated using the daily estimates for the 8-wk interval following petal fall (petal fall as day 1, to day 56, inclusive) for caterpillars, fork-tailed bush katydid and citrus thrips, which damage the fruit when it is small. Mean densities for California red scale were taken as the mean

across the full calendar year, with the interpolation extending into the subsequent year if there was at least one density observation in that calendar year.

Fruit Damage Estimates

The PCAs working with one grower recorded 'bin evaluations' reporting fruit damage levels at harvest, measured as the number of fruit with visible damage (rind scarring or infestation) per top layer of fruit visible in the harvest bin after the fruit was picked and waiting to be transported to the packinghouse (other PCAs did not keep these records). On oranges, each damage type has a characteristic appearance allowing the causal agent to be identified (Grafton-Cardwell et al. 2003), although the possibility that damage morphology might differ on mandarins has not been explored. The median number of bins checked was 214 (range 2–2,038) per grove-year for each of the four direct pests: caterpillars, California red scale, fork-tailed bush katydid, and citrus thrips. Counts were pooled within grove-year when reported across several days or by different PCAs.

Damage estimates were reported as number of fruit damaged per bin, which is the metric used by growers, whereas our goal of comparing damage levels among different citrus species ideally uses the proportion of fruit damaged. It is inherently difficult to estimate the average number of fruit visible per top layer of a bin, as the fruit are packed haphazardly and are of varying sizes. The industry standard is to convert damage estimates per bin to percent fruit scarred by assuming 100 *C. sinensis* oranges and 200 mandarins (all species) visible per top layer of the bins, and then doubling the estimate to account for only the upper-facing half of each fruit being visible. Our own small survey of the number of fruit visible indicated closer to 200 *C. sinensis* oranges (range: 183–230 from five bins surveyed) and 300 *C. clementina* mandarins per top bin layer (range: 307–330 from three bins surveyed). A volume-to-surface-area calculation using the average size class ratio difference from pack-out reports is also difficult due to the variable shape and packing arrangement of the fruit. Due to this noise and uncertainty in converting damaged fruit per bin to the proportion of fruit damaged, we adopted the approach of assuming equal numbers of fruit surveyed per bin for all species (i.e., keeping the data in the provided format of fruit damaged per bin), with the awareness that this will overestimate the proportion of fruits scarred for the smaller mandarins such as *C. reticulata* by ~50%. Because our main result described below is that *C. reticulata* are less susceptible to scarring damage than are *C. sinensis*, this overestimate of mandarin scarring makes our main results more conservative.

Researcher Grove Surveys

To produce a smaller, but independent, data set that we could use to confirm or refute some of the surprising results that emerged from the commercial data set regarding fruit infestation or scarring, we evaluated fruit damage in 6 groves (3 *C. sinensis*, 2 *C. reticulata*, and 1 *C. clementina*) at the University of California Lindcove Research and Extension Center (LREC) and 14 commercial groves (7 *C. sinensis*, 5 *C. reticulata*, and 2 *C. clementina*) in Tulare and Fresno counties during late-January/early-February of 2017 (i.e., fruit that matured during the 2016 calendar year). The commercial groves were from 11 ranches managed by four different growers. In total, 17,037 fruit were evaluated from 402 trees. Approximately 25 (LREC groves) and 50 (commercial groves) fruit were examined from several branches around the full perimeter of each of 20 trees per grove. Each fruit was recorded as undamaged or with damage

by one or more of the key direct pests: caterpillars, California red scale, fork-tailed bush katydid, and citrus thrips. Scarring types were classified following Grafton-Cardwell et al. (2003) and PCA advice.

Statistical Analyses

Analyses were performed in R (R Core Team 2018). For the *Citrusformatics* data set, differences in mean estimated daily pest density per grove-year among citrus species were tested for each monitored direct pest (fork-tailed bush katydids, citrus thrips, caterpillars, and California red scale) using generalized additive mixed models (GAMM) in the *mgcv* package (version 1.8–24; Wood 2006, 2011). The response variable was the *proportion sample units infested* and the predictor variables were *citrus species*, with a beta family (logit link); a thin plate regression spline smooth for grove *latitude* and *longitude*; *crop year*, *tree age*, and *acreage* included as covariates; and *grove identifiers* nested in *ranch* as random effects. The *latitude-longitude* smooths were included to control statistically for any spatial autocorrelation. Including a term for ranch also helped toward this issue and controlled for any other differences in agronomic practices that occur at the ranch level that might have influence pest densities. Density estimates were not available for caterpillars in *C. unshiu* groves, California red scale in *C. tangelo* and *C. unshiu* groves, or fork-tailed bush katydids in *C. unshiu* groves. Where there was a significant effect of *citrus species*, pairwise contrasts were made between species by assessing the overlap of confidence intervals at an alpha level of 0.05 with Bonferroni correction.

Differences in fruit damage observed at harvest among citrus species were tested for each pest-induced damage type (caterpillar scarring, California red scale infestation, fork-tailed bush katydid scarring, citrus thrips scarring) also using GAMMs in the *mgcv* package. The response variable was *number of fruit damaged per bin*, and the predictor variables were *citrus species*, with a negative binomial family (log link); a thin plate regression spline smooth for grove *latitude-longitude*; *crop year*, *tree age*, and *acreage* included as covariates; and *grove identifiers* nested in *ranch* as random effects, weighted by the *number of bins surveyed*. Damage levels were not available for any pests on *C. tangelo*- and *C. unshiu*-harvested fruit. Where there was a significant effect of *citrus species*, pairwise contrasts were made between species by assessing the overlap of confidence intervals at an alpha level of 0.05 with Bonferroni correction.

We repeated these tests focusing on within-species effects for each of the different citrus species whenever there was a sufficient number of grove-years surveyed per citrus species. Where indicated in the results tables, the default *k*-value for the smooth was dropped from the default (10) to the minimum (3) and the *ranch* term was dropped, due to the insufficient replicate number (more coefficients than data).

To visualize how the trends in densities and damage observed for the direct pests were different in the mandarin species versus oranges, we plotted the ratio of mandarin/orange mean pest densities (x-axis) against the ratio of mandarin/orange mean fruit damage densities (y-axis) for each pest and each citrus species, where there were at least 5 grove-years with observations. In this graph, the density and damage level of each pest in oranges was normalized to ($x = 1$, $y = 1$). Pests with a lower density in mandarins than in oranges had a value of $x < 1$ and with higher densities $x > 1$. Likewise, pests with lower scarring in mandarins than oranges had a value of $y < 1$ and with higher scarring $y > 1$. If the ratio of densities to damage was similar to that seen for oranges, the point fell close to the line that has a *y*-intercept = 0 and slope = 1. Deviations from this line indicate whether the pest exhibited higher or lower scarring in mandarins given its densities relative to *C. sinensis*. Note that we

aimed here to examine the trends, so used the mean values without confidence intervals and including cases with nonsignificant effects of the overall *citrus species* predictor.

Spearman's rank correlation was used to test for a positive relationship between pest densities and damage for each citrus species using the grove-years in which a sufficient number of both measurement types was taken for each pest. There were an insufficient number of *C. reticulata* grove-years with data to test for a correlation between California red scale in-grove densities and fruit infestations at harvest. The tests were run using the *cor.test* function in the *stats* package (version 3.5.1, R core team).

The researcher grove surveys were analyzed with logistic regression (*glm* binomial family with 'logit' link function) in the *stats* package (version 3.5.1, R core team), to test for differences in the *presence of each scarring type by citrus species*. Where there was a significant effect of *citrus species*, pairwise contrasts were made between species by assessing the overlap of confidence intervals at an alpha level of 0.05 with Bonferroni correction.

Results

Overall Trends in Commercial Citrus

Caterpillar and California red scale densities did not vary by citrus species (Fig. 1a, Table 2). Fork-tailed bush katydids and citrus thrips densities did vary by citrus species, with fork-tailed bush katydids densities slightly higher in *C. clementina* and slightly lower in *C. tangelo*, and citrus thrips densities lower in *C. reticulata* than in *C. sinensis*, after controlling for the effects of tree age, grove acreage, year, location, and ranch/grove (Fig. 1a, Table 2). Fruit damage at harvest varied by citrus species for all pests examined, with damage levels in *C. reticulata* consistently lower than in *C. sinensis* (Fig. 1b, Table 3). There was little variation in pest densities and damage among citrus varieties within the citrus species (Supp Tables 1 and 2 [online only], Supp Fig. 1 [online only]).

Caterpillars

Densities of caterpillars were different among years and by latitude-longitude in 2009 and increased with grove acreage (Table 2). Scarring attributed to caterpillars varied by year and latitude-longitude in 2009, 2010, and 2011 and increased with acreage (Table 3). Scarring was lower than expected in *C. reticulata* and higher than expected in *C. clementina* given the relative densities of caterpillars in these species compared with the relative densities and scarring observed in *C. sinensis* (Fig. 1c). Among citrus varieties, scarring attributed to caterpillars was lower in 'Fukumoto' oranges than in 'Lane Late' and 'Powell' oranges (Supp Fig. 1c [online only]). There was a noisy but positive correlation between caterpillar densities and associated scarring on *C. sinensis* (Table 4).

California Red Scale

Densities of California red scale were different among years and by latitude-longitude in 2010 (Table 2). Fruit infestation levels at harvest followed similar relative trends to the in-grove density estimates and were significantly lower in *C. reticulata* and *C. clementina* than *C. sinensis* (Fig. 1c). Infestation also varied by year, grove, and latitude-longitude in years 2008–2011 (not 2012) and increased with acreage (Fig. 1b, Table 3). There was no significant correlation between California red scale grove and harvest densities on *C. sinensis* or *C. clementina* (Table 4).

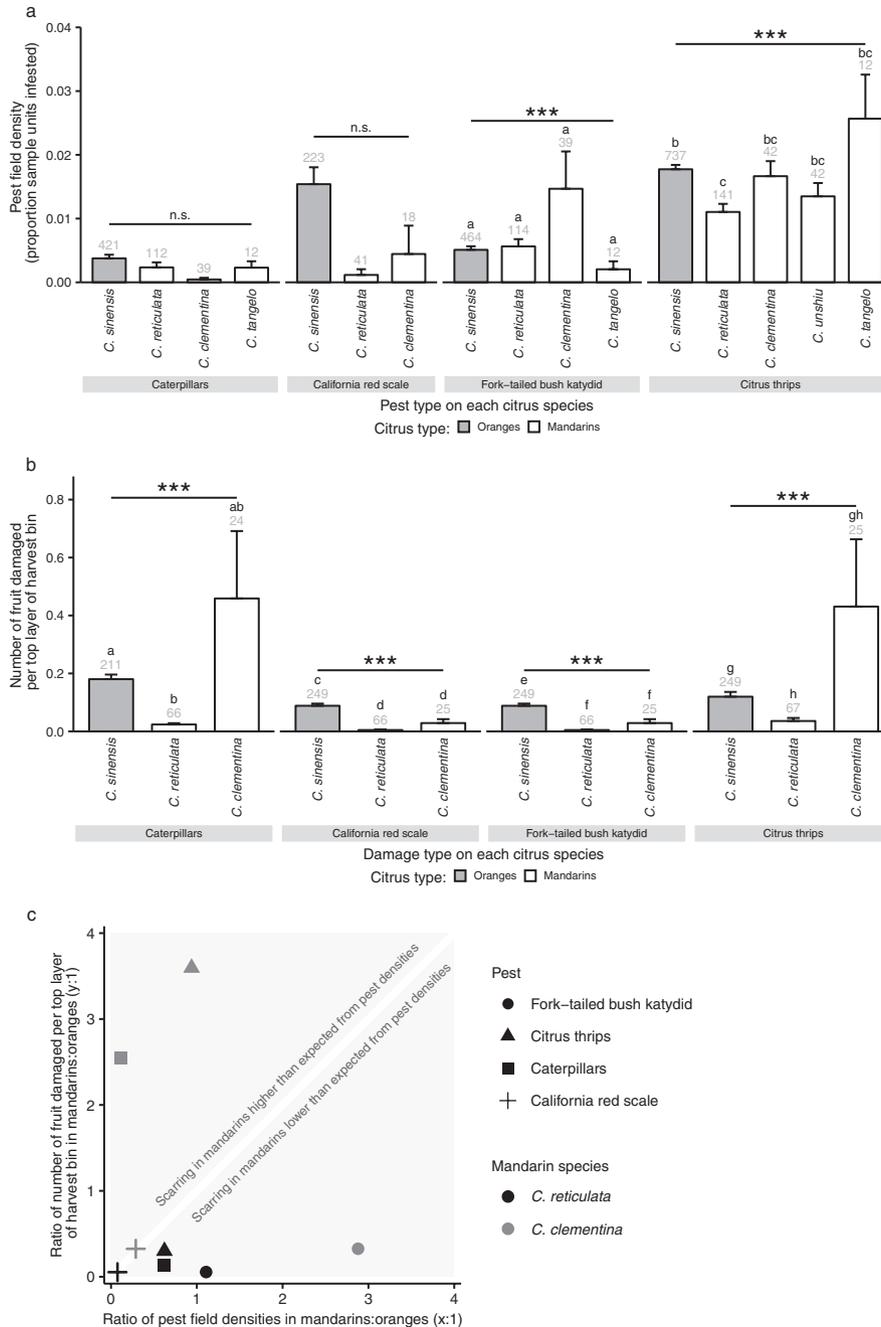


Fig. 1. Densities and damage frequencies differ in mandarin species compared with sweet oranges for the main direct pests in commercial citrus groves. (a) Mean pest densities, recorded as the proportion of sample units infested. Sampling units were fruit, visual sample windows, or trees, as appropriate for the pest type. Note that the different sampling methods used for different pests prohibit meaningful between-pest comparisons of relative densities. (b) Mean damage frequency caused by each pest, recorded as the number of fruits scarred or infested per top layer of fruit in a harvest bin. Error bars show SE. Numbers in gray above bars indicate number of grove-years. Significance of the explanatory variable *citrus species* on the response variable density or damage frequency is indicated above bars for each pest group (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, n.s. 'not significant' $P > 0.05$). Bar color indicates species of oranges (gray) and mandarins (white). Letters above bars indicate groups with overlapping confidence intervals where there was a significant effect of the explanatory variable *citrus species*. (c) Ratio of pest densities in mandarins/oranges (x-axis) and of pest scarring frequencies in mandarins/oranges (y-axis) for each pest and citrus species combination, i.e., the mean value for mandarins divided by mean value for oranges within each pest group from (a) plotted on the x-axis against the groups from (b) on the y-axis. Points falling below the diagonal indicate less damage than expected, given the observed density of the pest, whereas points falling above the diagonal indicate more damage than expected.

Fork-Tailed Bush Katydid

Fork-tailed bush katydid densities were different among years, ranches, and by latitude-longitude in 2007, 2008, 2010, 2011, 2012; increased with acreage; and decreased with tree age (Table 2). Scarring attributed to fork-tailed bush katydid varied by year, grove,

and latitude-longitude in all years (2008–2012; Table 3). Scarring was much lower than expected in *C. reticulata* and *C. clementina* given the relative densities of fork-tailed bush katydid in these species compared with the relative densities and scarring observed in *C. sinensis* (Fig. 1c). Densities were significantly lower in 'Fisher' than

Table 2. Generalized additive mixed model (GAMM)^a output for influence of different citrus species on pest densities

Pest	No. of grove-years	R ² (adj.)	Parameter	df ^b	χ ²	P value			
Caterpillars	584	0.09	<i>citrus species</i>	3	<0.1	0.9994			
			<i>year</i>	5	24.1	0.0002***			
			<i>tree age</i>	1	2.0	0.1605			
			<i>acreage</i>	1	6.3	0.0120*			
			<i>s(longitude, latitude) 2007</i>	4.6	12.1	0.0313*			
			<i>s(longitude, latitude) 2008</i>	2.0	1.9	0.3949			
			<i>s(longitude, latitude) 2009</i>	9.9	70.6	<0.0001***			
			<i>s(longitude, latitude) 2010</i>	2.7	4.1	0.2998			
			<i>s(longitude, latitude) 2011</i>	2.0	1.1	0.5877			
			<i>s(longitude, latitude) 2012</i>	2.0	0.3	0.8517			
			<i>s(grove identifier)</i>	<0.1	<0.1	1.0000			
			<i>s(ranch identifier)</i>	<0.1	<0.1	0.6307			
			California red scale	282	-0.02	<i>citrus species</i>	2	1.4	0.4932
						<i>year</i>	6	16.3	0.0124*
<i>tree age</i>	1	0.7				0.3956			
<i>acreage</i>	1	<0.1				0.9626			
<i>s(longitude, latitude)^c 2003</i>	1	0.4				0.5289			
<i>s(longitude, latitude) 2006</i>	2.0	0.2				0.9108			
<i>s(longitude, latitude) 2007</i>	2.0	1.3				0.5105			
<i>s(longitude, latitude) 2008</i>	2.0	5.1				0.0772			
<i>s(longitude, latitude) 2009</i>	2.0	4.3				0.1138			
<i>s(longitude, latitude) 2010</i>	2.0	26.6				<0.0001***			
<i>s(longitude, latitude) 2011</i>	2.0	5.5				0.0647			
<i>s(longitude, latitude) 2012</i>	2.0	0.2				0.9262			
<i>s(grove identifier)^d</i>	<0.1	<0.1				1.0000			
Fork-tailed bush katydid	629	0.17				<i>citrus species</i>	3	27.9	<0.0001***
			<i>year</i>	5	239.5	<0.0001***			
			<i>tree age</i>	1	5.6	0.0176*			
			<i>acreage</i>	1	9.0	0.0027**			
			<i>s(longitude, latitude) 2007</i>	2.0	26.0	<0.0001***			
			<i>s(longitude, latitude) 2008</i>	3.6	33.3	<0.0001***			
			<i>s(longitude, latitude) 2009</i>	5.2	8.7	0.2497			
			<i>s(longitude, latitude) 2010</i>	18.8	86.4	<0.0001***			
			<i>s(longitude, latitude) 2011</i>	8.3	31.4	0.0008***			
			<i>s(longitude, latitude) 2012</i>	15.3	87.1	<0.0001***			
			<i>s(grove identifier)</i>	0.3	0.3	0.6644			
			<i>s(ranch identifier)</i>	19.8	50.4	<0.0001***			
			Citrus thrips	974	0.39	<i>citrus species</i>	4	17.8	0.0014**
						<i>year</i>	9	173.4	<0.0001***
<i>tree age</i>	1	0.9				0.3484			
<i>acreage</i>	1	2.7				0.0978			
<i>s(longitude, latitude) 2003</i>	4.3	37.3				<0.0001***			
<i>s(longitude, latitude) 2004</i>	3.5	54.9				<0.0001***			
<i>s(longitude, latitude) 2005</i>	2.0	28.7				<0.0001***			
<i>s(longitude, latitude) 2006</i>	2.3	25.5				<0.0001***			
<i>s(longitude, latitude) 2007</i>	20.4	131.6				<0.0001***			
<i>s(longitude, latitude) 2008</i>	12.5	51.5				<0.0001***			
<i>s(longitude, latitude) 2009</i>	19.8	176.1				<0.0001***			
<i>s(longitude, latitude) 2010</i>	7.1	118.5				<0.0001***			
<i>s(longitude, latitude) 2011</i>	15.4	35.6				0.0122*			
<i>s(longitude, latitude) 2012</i>	18.6	185.7				<0.0001***			
<i>s(grove identifier)</i>	45.8	73.0	0.0002***						
<i>s(ranch identifier)</i>	30.3	92.7	<0.0001***						

^aBeta family (logit link) GAMM: *Pest density* (i.e., mean daily proportion of sample units infested) ~ *citrus species* + *year* + *tree age* + *acreage* + *s(longitude, latitude)*, bs = thin plate 'tp', by = year) + *s(grove identifier)*, bs = random effect 're') + *s(ranch identifier)*, bs = random effect 're').

^bEstimated for smooth terms.

^c*k* reduced to minimum for *s(longitude, latitude)*, bs = thin plate 'tp', by = year) term.

^d*ranch identifier* term removed due to insufficient power.

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

'Powell' variety *C. sinensis* and lower in 'Tango' than 'W. Murcott Afourer' *C. reticulata* (although confidence intervals around the mean densities overlapped). There was no significant correlation

between grove-year fork-tailed bush katydid densities and associated fruit scarring on any tested citrus species (*C. sinensis*, *C. reticulata*, and *C. clementina*; Table 4).

Table 3. Generalized additive mixed model (GAMM)^a output for influence of different citrus species on fruit damage observed at harvest

Pest	No. of grove-years	R ² (adj.)	Parameter	d ^b	χ ²	P value			
Caterpillars	301	0.93	<i>Citrus species</i>	2	46.5	<0.0001***			
			<i>year</i>	3	107.4	<0.0001***			
			<i>tree age</i>	1	<0.1	0.9455			
			<i>acreage</i>	1	5.5	0.0187*			
			<i>s(longitude, latitude) 2009</i>	20.3	229.0	<0.0001***			
			<i>s(longitude, latitude) 2010</i>	28.7	404.3	<0.0001***			
			<i>s(longitude, latitude) 2011</i>	24.1	332.1	<0.0001***			
			<i>s(longitude, latitude) 2012</i>	6.8	13.0	0.0735			
			<i>s(grove identifier)</i>	77.5	4,183.5	<0.0001***			
			<i>s(ranch identifier)</i>	15.5	1,464.8	0.3663			
			California red scale	340	0.77	<i>citrus species</i>	2	20.0	<0.0001***
						<i>year</i>	4	22.4	0.0002***
<i>tree age</i>	1	0.6				0.4472			
<i>acreage</i>	1	4.0				0.0443*			
<i>s(longitude, latitude) 2008</i>	5.5	75.0				<0.0001***			
<i>s(longitude, latitude) 2009</i>	23.7	486.3				<0.0001***			
<i>s(longitude, latitude) 2010</i>	24.1	798.6				<0.0001***			
<i>s(longitude, latitude) 2011</i>	23.1	306.0				<0.0001***			
<i>s(longitude, latitude) 2012</i>	2.0	1.8				0.4273			
<i>s(grove identifier)</i>	63.0	3,080.8				0.0003***			
<i>s(ranch identifier)</i>	25.0	5,023.2				0.6423			
Fork-tailed bush katydid	340	0.77				<i>citrus species</i>	2	19.8	0.0001***
			<i>year</i>	4	23.9	0.0001***			
			<i>tree age</i>	1	0.6	0.4543			
			<i>acreage</i>	1	3.9	0.0486*			
			<i>s(longitude, latitude) 2008</i>	5.5	76.1	<0.0001***			
			<i>s(longitude, latitude) 2009</i>	23.7	481.0	<0.0001***			
			<i>s(longitude, latitude) 2010</i>	24.1	793.5	<0.0001***			
			<i>s(longitude, latitude) 2011</i>	23.1	302.4	<0.0001***			
			<i>s(longitude, latitude) 2012</i>	2.0	1.7	0.4553			
			<i>s(grove identifier)</i>	62.8	3,058.0	0.0002***			
			<i>s(ranch identifier)</i>	25.3	5,226.3	0.6340			
			Citrus thrips	341	0.95	<i>citrus species</i>	2	21.8	<0.0001***
<i>year</i>	4	38.9				<0.0001***			
<i>tree age</i>	1	0.3				0.5930			
<i>acreage</i>	1	0.6				0.4403			
<i>s(longitude, latitude) 2008</i>	5.2	20.4				0.0014**			
<i>s(longitude, latitude) 2009</i>	18.7	86.8				<0.0001***			
<i>s(longitude, latitude) 2010</i>	13.3	38.5				0.0007***			
<i>s(longitude, latitude) 2011</i>	17.6	61.0				<0.0001***			
<i>s(longitude, latitude) 2012</i>	24.4	112.1				<0.0001***			
<i>s(grove identifier)</i>	71.3	1,593.9				0.0032**			
<i>s(ranch identifier)</i>	12.9	1,026.9				0.8516			

^aNegative binomial (log link) GAMM: *Number of fruit damaged per bin* ~ *citrus species* + *year* + *tree age* + *acreage* + *s(longitude, latitude)*, bs = thin plate 'tp', by = year) + *s(grove identifier)*, bs = random effect 're') + *s(ranch identifier)*, bs = random effect 're') + *number of bins surveyed* (weight).

^bEstimated for smooth terms.

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

Citrus Thrips

Densities of citrus thrips were different among years, groves, ranches, and by latitude-longitude in all years (2003–2012; Table 2). Scarring varied by year, grove, and latitude-longitude in all years (2008–2012; Table 3). Scarring was slightly lower than expected in *C. reticulata* and higher than expected in *C. clementina* given the relative densities of citrus thrips in these species compared with the relative densities and scarring observed in *C. sinensis* (Fig. 1c). Citrus thrips densities were higher in 'Powell' than 'Atwood', 'Fisher', 'Fukumoto', and 'Lane Late' and lower in 'Fisher' than in 'Cara Cara', 'Spring', and 'Washington' *C. sinensis* varieties (Supp Table 1 [online only], Supp Fig. 1b [online only]). There was a noisy but positive correlation between citrus thrips densities and associated fruit scarring on *C. sinensis* and *C. clementina* (Table 4).

Researcher Grove Surveys

The incidence of fruit scarring generally followed the trends observed in the grower- and consultant-generated data. Citrus species was a significant predictor of damage for all pests, with trends toward higher scarring in *C. sinensis* than *C. reticulata* and *C. clementina* in all cases; however, the confidence intervals overlapped in all paired comparisons except between fork-tailed bush katydid scarring in *C. sinensis* and *C. reticulata* (Fig. 2, Table 5).

Discussion

Pest densities and pest-induced damage to the citrus fruit varied among citrus species. Most notably, *C. reticulata*, one of the most commonly grown mandarin species (CDFA and CASS 2018), appears

Table 4. Spearman's rank correlations^a between pest densities and associated fruit damage in commercial *C. sinensis*, *C. reticulata*, and *C. clementina* groves, for grove-years that had both data types recorded for a given pest

Pest	Citrus species	No. of grove-years	Rho	S	P value
Caterpillars	<i>C. sinensis</i>	211	0.14	1,345,102	0.020*
	<i>C. reticulata</i>	65	-0.16	52,937	0.894
	<i>C. clementina</i>	24	-0.30	2,983	0.921
California red scale ^b	<i>C. sinensis</i>	65	-0.06	48,524	0.684
	<i>C. clementina</i>	8	-0.35	114	0.803
Fork-tailed bush katydid	<i>C. sinensis</i>	249	0.03	2,499,522	0.327
	<i>C. reticulata</i>	66	-0.02	48,697	0.552
	<i>C. clementina</i>	24	0.27	1,668	0.097
Citrus thrips	<i>C. sinensis</i>	249	0.28	1,859,083	<0.001***
	<i>C. reticulata</i>	67	0.20	39,858	0.048*
	<i>C. clementina</i>	24	0.50	1,158	0.007**

^aModel: mean daily pest density ~ number of fruit damaged per bin.

^bInsufficient data to test *C. reticulata*.

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

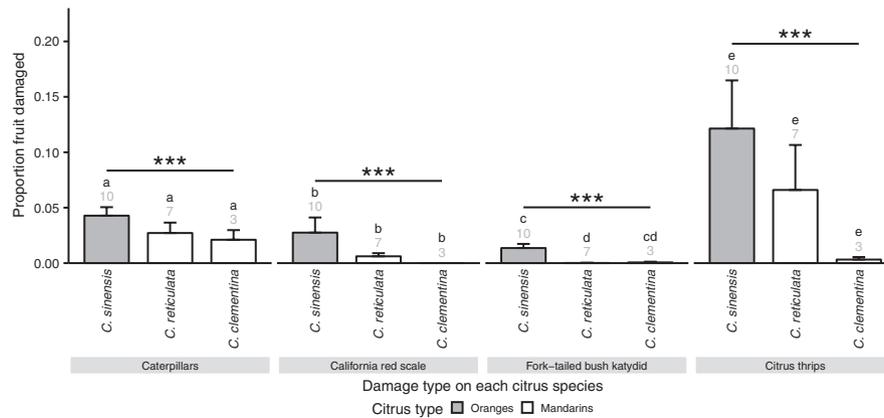


Fig. 2. Researcher grove survey of fruit damage data for the 2016 growing year, from surveyed commercial and LREC groves. Error bars show SE. Numbers in gray above bars indicate number of groves surveyed (500–1,000 fruit examined per grove). Significance of the explanatory variable *citrus species* on the response variable *damage frequency* is indicated above bars for each pest group (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, n.s. 'not significant' $P > 0.05$). Bar color indicates species of oranges (gray) and mandarins (white). Letters above bars indicate groups with overlapping confidence intervals where there was a significant effect of the explanatory variable *citrus species*.

to express full or partial resistance to the entire suite of direct pests that attack citrus. Damage levels on *C. reticulata* were consistently lower than in *C. sinensis* across all direct pests, and the true damage frequencies for mandarins are probably ca. 50% lower than the damage estimates reported in this analysis because the smaller size of mandarins compared with oranges means that more fruit were surveyed per bin sample. Thus, the remarkably low scarring observed in *C. reticulata* is probably even lower than reported here using this very conservative measure. This indicates that importing control recommendations from oranges may not be an optimal solution for developing IPM for mandarins, and there is likely an overuse of pesticides in some mandarin species.

Although the damage levels for all species may seem low overall, this is damage occurring after growers controlled for the pests, and the high value of citrus means that even low damage levels can translate to economically significant losses (Stern et al. 1959). Nonetheless, the very low fork-tailed bush katydid scarring observed in *C. reticulata* and, to a lesser extent, in *C. clementina*, raises the question of whether they are causing any economic damage to these citrus species. The low incidence of scarring was observed despite similar densities of fork-tailed bush katydids in these mandarin groves. Several hypotheses may explain why fork-tailed bush

katydid scarring is lower than expected given the densities. These include 1) an aversion by the fork-tailed bush katydids to feeding on the fruit of *C. reticulata* and *C. clementina*, so the initial fruit damage never occurred; 2) developmental recovery by *C. reticulata* and *C. clementina* from the damage, regenerating the removed tissue such that the scarring was not visible at harvest; 3) the fork-tailed katydids may feed on the fruits differently, or the growth of *C. reticulata* and *C. clementina* fruit may change the appearance of the damage, such that it was not recognized as fork-tailed bush katydid scarring; or 4) *C. reticulata* and *C. clementina* trees may be preferentially abscising fruit damaged by fork-tailed bush katydids, in favor of maturing their undamaged fruit. Citrus trees routinely drop approximately 90% of initiated fruit, even in the absence of pest damage (Goren 1993). The thinner rind of mandarins may make them more sensitive than oranges to damage, meaning more of the damaged fruit is naturally removed. These hypotheses are not mutually exclusive. In the case of the third hypothesis, fork-tailed bush katydids may still be a pest in mandarins. An assessment of total citrus yield (kilograms total fruit per hectare) and citrus quality (percent pack-out placed in fresh market grades above 'choice') could help to determine to what extent the tree is compensating for fork-tailed bush katydid damage.

Table 5. Logistic regression^a output for pest associated fruit damage in the researcher grove survey

Pest	df	χ^2	P value
Caterpillars	2	56.8	<0.001***
California red scale	2	223.4	<0.001***
Fork-tailed bush katydid	2	154.5	<0.001***
Citrus thrips	2	496.8	<0.001***

^aBinomial (logit link) GLM: *proportion fruit damaged* ~ *citrus species*.

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

In the case of citrus thrips and California red scale on fruit, the prevalence of these pests in the groves and the damage was lower in *C. reticulata*. Overall lower relative densities of pests in mandarins may, in part, be due to 1) better control measures in *C. reticulata*, e.g., if the architecture of the tree canopies allows greater pesticide coverage (which could be tested using spray cards), or if there is some difference in the ability of natural enemies to operate in mandarins; 2) pests such as California red scale having not yet built up to comparable densities in the relatively younger mandarin groves (although in the current study we controlled statistically for differences in tree age, we cannot compare beyond the represented ages of the trees); or 3) some intrinsic difference in suitability as a food for the pests, with mandarins being not as susceptible. For example, citrus species are known to vary in composition of essential oils, including limonene, a natural insecticide, and these could act as a deterrent to pests (Hollingsworth 2005, Ibrahim et al. 2008, Kamal et al. 2011). We advocate future experimental work to determine whether *C. reticulata* requires less-frequent monitoring and treatment. Our statistical model helped to control for differences in tree age, acreage of the groves, observation year, location, and grower, strengthening the inference of a causal effect of citrus species and suggesting that the differences may be due to intrinsic differences among host plants or differences in effectiveness of control measures among host plants.

Commercial citrus varieties are propagated as asexual clones classified as separate species, although many exhibit considerable interspecific hybridization (Cameron and Frost 1968). The lack of substantial variation in pest densities and damage observed here among varieties within the designated citrus species categories indicates that the species delineator is useful for generalizing these effects among the citrus varieties.

Although the primary focus of this analysis was to examine how pest densities and fruit damage vary among citrus species, the other covariates included in the GAMMs also suggest some interesting patterns. For example, year was a highly significant covariate in almost every analysis, which could be due to variation in weather conditions and phenology having strong influences on pest densities and/or fruit susceptibility. Fork-tailed bush katydid field densities were lower in older trees and smaller groves. Caterpillar densities and scarring were higher in larger groves. California red scale densities were lower in larger groves. In some cases, ranch was an important covariate in addition to latitude-longitude (e.g., fork-tailed bush katydid and citrus thrips densities), suggesting that ranch management affects those densities independent of their shared location. Future analyses could explore these factors in more detail.

The lack of significant correlations between field densities and damage levels within grove-years for some of the studied pests was surprising. For California red scale, perhaps it reflects high-density estimates made during the growing season triggering insecticide applications, resulting in cleaner fruit at harvest. For katydids and

caterpillars, it may reflect a combination of 1) previously unrecognized resistance in some citrus species (this seems to be the case for *C. reticulata*, as we have shown here, because these varieties do not have heavy scarring damage from any of the early-season chewing pests); 2) these pests generating damage on mandarins that looks different from damage on *C. sinensis*, leading to scarring miscategorization; or 3) other unidentified pests creating this damage, leading to scarring miscategorization. Ongoing experimental work is exploring each of these possibilities.

The trends observed in the commercial scarring data were supported by our own surveys of citrus groves. In particular, we confirmed the observation of lower fork-tailed bush katydid scarring levels in mandarins than oranges.

These trends of pest densities and damage in mandarins demonstrate the utility of PCA-collected data for establishing a foundation for adapting management guidelines to a new agricultural system. Drastic shifts in the citrus production landscape can lead to overuse of pesticides, as it is prohibitively expensive for researchers to perform the yield-impact studies at the scale and pace needed to keep guidelines accurate and relevant. Rebuilding major components of the IPM program to accommodate large-scale changes will be extremely costly and labor intensive if we rely solely on traditional yield-impact studies. In the case of mandarins, which are attacked by a number of different pests, this ecoinformatics approach has been useful in the initial, exploratory phase of research, to discover patterns and identify key hypotheses for subsequent experimental testing, that in this case have the potential to identify pesticide overuse. The continued maintenance of the citrus database created for this study will provide historical perspective as the landscape of citrus production in California continues to change, especially with the introduction of the Asian citrus psyllid (*Diaphorina citri* Kuwayama [Hemiptera: Liviidae]) vector of the bacterium *Candidatus Liberibacter asiaticus* that is the presumed causal agent of huanglongbing disease (citrus greening; Grafton-Cardwell et al. 2013, Grafton-Cardwell 2015). In our experience, growers and PCAs have responded positively to being involved in the research process from the outset and to recommendations arising from analyses of their own data. We expect the utility of this approach to increase as technology for in-field recording of pest monitoring data is developed and adopted (Teacher et al. 2013).

Supplementary Data

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

Acknowledgments

We are very grateful to the growers and pest control advisors who provided the data for this research project and discussions to guide research directions. We thank Jamie Nemecek, Josh Reger, and Sara Scott for assistance with the field work; Elise Hellwig, George Livingston, and Tobias Mueller for contributions to database calculations; and Hanna Kahl for comments on the manuscript. This research was funded by California Department of Pesticide Regulation contracts 11-C0089 and 13-C0064 and grant 18-PML-R001, University of California Division of Agriculture and Natural Resources competitive grant 15-3693, United States Department of Agriculture grant 2015-70006-24164, and Citrus Research Board grant 17-5500-214. The authors declare no conflicts of interest.

References Cited

- Ba-Angood, S. A. S. 1977. A contribution to the biology and occurrence of the citrus leafminer, *Phyllocnistis citrella* Staint. (Gracilariidae, Lepidoptera) in the Sudan. *Z. Angew. Entomol.* 83: 106–111.
- 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: 458–462.
- Cameron, J. W., and H. Frost. 1968. Genetics, breeding, and nucellar embryony, pp. 325–370. *In* W. Reuther, L. D. Batchelor, and H. J. Webber (eds.), *The citrus industry*, vol. 3. Division of Agricultural Sciences, University of California, Berkeley, CA.
- (CDFA) California Department of Food and Agriculture. 2018. California agricultural statistics review, 2016–2017. CDFA, Sacramento, CA.
- (CDFA) California Department of Food and Agriculture and (CASS) California Agricultural Statistical Service. 2018. 2018 California citrus acreage report. USDA's National Agricultural Statistics Service (NASS), Sacramento, CA.
- (CDPR) California Department of Pesticide Regulation. 2018. Pesticide use reporting (PUR). (<http://www.cdpr.ca.gov/dprdatabase.htm>) (accessed 8 May 2018).
- Dreistadt, S. H. 2012. Integrated pest management for citrus, 3rd ed. University of California Agriculture and Natural Resources (UC ANR) Statewide Integrated Pest Management Program Publication 3303, Oakland, CA.
- Elmer, H. S., and O. L. Brawner. 1982. Seven-year study of effects of California red scale (Homoptera: Diaspididae) on navel orange production in California's San Joaquin Valley. *J. Econ. Entomol.* 75: 6699–6700.
- Eyles, A., P. Bonello, R. Ganley, and C. Mohammed. 2010. Induced resistance to pests and pathogens in trees. *New Phytol.* 185: 893–908.
- Ferguson, L., and E. E. Grafton-Cardwell. 2014. Citrus production manual. University of California Agriculture and Natural Resources (UC ANR) Publication 3539, Oakland, CA.
- Goren, R. 1993. Anatomical, physiological, and hormonal aspects of abscission in citrus. *Hortic. Rev.* 15: 145–182.
- Grafton-Cardwell, E. E. 2015. The status of citrus IPM in California. *Acta Hortic.* 1065: 1083–1090.
- Grafton-Cardwell, E. E., N. V. O'Connell, C. E. Kallsen, and J. G. Morse. 2003. Photographic guide to citrus fruit scarring. University of California Agriculture and Natural Resources (UC ANR) Publication 8090, Oakland, CA.
- Grafton-Cardwell, E. E., L. L. Stelinski, and P. A. Stansly. 2013. Biology and management of Asian citrus psyllid, vector of the huanglongbing pathogens. *Annu. Rev. Entomol.* 58: 413–432.
- Grafton-Cardwell, E. E., B. A. Faber, D. R. Haviland, C. E. Kallsen, J. G. Morse, N. V. O'Connell, P. A. Phillips, J. E. Adaskaveg, J. O. Becker, C. J. Lovatt, *et al.* 2017. UC IPM citrus pest management guidelines for agriculture. University of California Agriculture and Natural Resources (UC ANR) Publication 3441, Oakland, CA.
- Habib, A., H. S. Salama, and A. H. Amin. 1972. Populations of *Aonidiella aurantii* on citrus varieties in relation to their physical and chemical characteristics. *Entomol. Exp. Appl.* 15: 324–328.
- Haney, P. B., J. G. Morse, R. F. Luck, H. J. Griffiths, E. E. Grafton-Cardwell, and N. V. O'Connell. 1992. Reducing insecticide use and energy costs in citrus pest management. University of California Statewide IPM Project Publication 15, Davis, 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., D. S. Yu, and R. F. Luck. 1990a. Variation in life history parameters of California red scale on different citrus cultivars. *Ecology* 71: 1451–1460.
- Hare, J. D., J. E. Pehrson, T. Clemens, J. L. Menge, C. W. Coggins, T. W. Embleton, and J. L. Meyer. 1990b. 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.
- Hollingsworth, R. G. 2005. Limonene, a citrus extract, for control of mealybugs and scale insects. *J. Econ. Entomol.* 98: 772–779.
- Ibrahim, M. A., P. Kainulainen, A. Aflatuni, K. Tiilikkala, and J. K. Holopainen. 2008. Insecticidal, repellent, antimicrobial activity and phytotoxicity of essential oils: with special reference to limonene and its suitability for control of insect pests. *Agric. Food Sci. Finl.* 10: 243–259.
- Kamal, G., F. Anwar, A. Hussain, N. Sarri, and M. Ashraf. 2011. Yield and chemical composition of citrus essential oils as affected by drying pretreatment of peels. *Int. Food. Res. J.* 18: 1275–1282.
- Kelling, S., W. M. Hochachka, D. Fink, M. Riedewald, R. Caruana, G. Ballard, and G. Hooker. 2009. Data-intensive science: a new paradigm for biodiversity studies. *BioScience* 59: 613–620.
- Krasnov, H., Y. Cohen, E. Goldshtein, O. Mendelsohn, M. Silberstein, Y. Gazit, and L. Blank. 2018. The effect of local and landscape variables on Mediterranean fruit fly dynamics in citrus orchards utilizing the ecoinformatics approach. *J. Pest. Sci.* 92: 453–463.
- 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.
- 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 8 May 2018).
- Rhodes, A. A., and J. G. Morse. 1989. *Scirtothrips citri* sampling and damage prediction on California navel oranges. *Agr. Ecosyst. Environ.* 26: 117–129.
- Rhodes, A. A., J. L. Baritelle, and J. G. Morse. 1986. Method for predicting crop response to pest attack over time: application to citrus thrips (Thysanoptera: Thripidae) scarring on navel oranges. *Bull. Entomol. Soc. Am.* 32: 153–156.
- 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., 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.
- Soranno, P. A., and D. S. Schimel. 2014. Macrosystems ecology: big data, big ecology. *Front. Ecol. Environ.* 12: 3.
- 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.
- Teacher, A. G., D. J. Griffiths, D. J. Hodgson, and R. Inger. 2013. Smartphones in ecology and evolution: a guide for the apprehensive. *Ecol. Evol.* 3: 5268–5278.
- (UCR) University of California Riverside. 2018. University of California Riverside citrus variety collection. (<https://citrusvariety.ucr.edu/>) (accessed 8 May 2018).
- (USDA, NASS) United States Department of Agriculture, National Agricultural Statistics Service. 2017. Agricultural Statistics 2017. USDA, NASS, Washington, DC.
- Velasco, R., and C. Licciardello. 2014. A genealogy of the citrus family. *Nat. Biotechnol.* 32: 640–642.
- 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. Ser. B* 73: 3–36.
- Wu, G. A., S. Prochnik, J. Jenkins, J. Salse, U. Hellsten, F. Murat, X. Perrier, M. Ruiz, S. Scalabrin, J. Terol, *et al.* 2014. Sequencing of diverse mandarin, pummelo and orange genomes reveals complex history of admixture during citrus domestication. *Nat. Biotechnol.* 32: 656–662.