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An Ecoinformatics Approach to Field-Scale Evaluation of Insecticide Effects in California Citrus: Are Citrus Thrips and Citrus Red Mite Induced Pests?

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Abstract

Experimental approaches to studying the consequences of pesticide use, including impacts on beneficial insects, are vital; however, they can be limited in scale and realism. We show that an ecoinformatics approach that leverages existing data on pesticides, pests, and beneficials across multiple fields can provide complementary insights. We do this using a multi-year dataset (2002–2013) on pesticide applications and density estimates of two pests, citrus thrips (*Scirtothrips citri* (Moulton [Thysanoptera:Thripidae])) and citrus red mites (*Panonychus citri* McGregor [Acari: Tetranychidae]), and a natural enemy (*Euseius* spp. predatory mites) collected from citrus groves in the San Joaquin Valley of California. Using correlative analyses, we investigated the long-term consequences of pesticide use on *S. citri* and *P. citri* population densities to evaluate the hypothesis that the pest status of these species is largely due to the disruption of natural biological control—i.e., these are induced pests. We also evaluated short-term pesticide efficacy (suppression of citrus thrips and citrus red mite populations immediately post-application) and asked if it was correlated with the suppression of *Euseius* predator populations. Although the short-term efficacy of different pesticides varied significantly, our dataset does not suggest that the use of citrus pesticides suppressed *Euseius* densities or worsened pest problems. We also find that there is no general trade-off between pesticide efficacy and pesticide risk to *Eusieus*, such that highly effective and minimally disruptive compounds were available to citrus growers during the studied time period.

Key words: ecoinformatics, induced pest, nontarget impact, *Scirtothrips citri*, *Panonychus citri*

The traditional approach to evaluating the efficacy and nontarget impacts of pesticides involves laboratory experiments or field experiments that employ small, replicated plots (Macfadyen et al. 2014a). In many regions of the world, such experimental testing is mandated by government regulators (e.g., by the U.S. Environmental Protection Agency or the European Food Safety Authority) or commissioned by growers who want to verify the effectiveness of new products (Warner 2008). This approach has proven highly effective to evaluate the direct effect of a pesticide on arthropod mortality (Macfadyen et al. 2014b). However, laboratory or semi-field experiments have several important drawbacks. First, logistical constraints mean that these experiments are typically not large enough or performed for long enough to reproduce field conditions (Rosenheim et al. 2011, Macfadyen et al. 2014a). This creates a mismatch between the spatial and temporal dynamics that can occur in the experiment and those that may actually occur in the field. Specifically, a number of factors may be overlooked, including: 1) long-term indirect effects of a pesticide application on the health of pests or natural enemies (Desneux et al. 2007), 2) recolonization of the pest population (Trumper and Holt 1998), or 3) disruption of the natural enemy community (Macfadyen et al. 2014a). For these reasons, traditional field experiments are ill-suited to test the hypothesis that some damaging herbivores in agriculture are 'induced pests' (sensu Prokopy and Kogan 2009)—i.e., herbivores that rarely are economically damaging under natural conditions, but which become damaging due to control practices that harm their natural enemies (also called 'secondary pests'). Previously proposed solutions to these issues center on improvements in the design and analysis of semi-field studies (Macfadyen et al. 2014a). Yet, even semi-field experimental approaches lack realism in that various factors may differ between an experiment and pesticide applications by growers, including spray equipment, environmental conditions, and the precise chemical mixture applied. We propose using farmer data as a complementary tool to improve the evaluation of pesticide efficacy, nontarget impacts, and the possibility that some herbivores become induced pests in commercial agriculture.

Two types of data are regularly collected on pests and pesticide use in fields: pest density scouting and pesticide use reports. Pest density scouting is often conducted by private pest management consultants and may include estimates of pest densities before and after a pesticide application. Pesticide use reports are detailed records of the pesticides applied that are maintained by consultants or growers, including the rate and identities of the pesticides applied. In some localities such as California, New York, and some European countries, reporting of agricultural pesticide applications to regulatory agencies is mandatory (e.g., the California Department of Pesticide Regulation [CDPR], http://www.cdpr.ca.gov/docs/legbills/calcode/030201.htm#a6626). When used in combination, these pest density estimates and pesticide use records represent an enormous and largely untapped resource to evaluate pesticide efficacy and nontarget impacts at the commercial scale. Relative to experimental approaches, this ecoinformatics approach has the advantages of enhanced statistical power and high dimensionality that allows researchers to resolve subtle treatment effects and investigate a rich array of hypotheses (Rosenheim et al. 2011, Rosenheim and Gratton 2017).

Although pesticide use has been examined at the field and landscape scale (Meehan et al. 2011, Larsen, 2013, Campbell et al. 2015, Larsen and Noack 2017), only a few studies have utilized pest control reports and pesticide or other chemical use data to evaluate effects of conventionally applied pesticides on pest population densities (Gross and Rosenheim 2011, Steinmann et al. 2011, Lu et al. 2012). Steinmann et al. (2011) found that in walnut orchards, applications of pesticides that were thought to have substantial negative impacts on natural enemies were associated with a 40% increase in the need for applications of miticides later in the same growing season. Gross and Rosenheim (2011) found that early-season pesticide use in cotton can generate monetary losses due to subsequent outbreaks of secondary pests. Lu et al. (2012) demonstrated that the use of Bt cotton allowed Chinese farmers to reduce their use of broad-spectrum insecticides to control *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), resulting in increased predator populations and improved control of aphid pests. Ecoinformatics studies to date have generally focused on crop yield, while there is a need to expand the approach to other areas of agricultural entomology that normally rely on experiments, such as pesticide efficacy and nontarget impacts.

We use a database (Citrusformatics) compiled from pest control advisor reports and pesticide use reports on citrus cultivars from eight growers and 249 groves in the San Joaquin Valley of California. California citrus production was valued at $2.12 billion in 2016 (USDA, National Agricultural Statistics Service, https://www.nass.usda.gov/), and pesticide use in this region is substantial (California Department of Pesticide Regulation 2016; http://www.cdpr.ca.gov/docs/pur/purmain.htm). Our Citrusformatics database includes density estimates for multiple pest species and records the use of a wide range of pesticides. Here we analyze data from 2003 to 2012 for two citrus pests, one natural enemy, and many different compounds. The herbivores we focus on are major economic pests of citrus production: the citrus thrips, *Scirtothrips citri* (Moulton) (Thysanoptera: Thripidae), and the citrus red mite, *Panonychus citri* (McGregor) (Acari: Tetranychidae). Citrus thrips create their primary economic damage by feeding on young citrus fruits, creating scarring that causes fruit quality downgrading at harvest (Tanigoshi and Moffitt 1984, Rhodes and Morse 1989, University of California 2012). Citrus red mites cause foliar damage that can change fruit size and depress yield (Hare et al. 1990, 1992). Both of these pests can be difficult to control due to natural physiological defenses, pesticide resistance, and disruption of natural enemies (Grafton-Cardwell et al. 1999a, 2008). Citrus red mite is thought to be especially prone to exhibit rapid increases in density following the use of broad-spectrum compounds, including especially the organophosphate, carbamate, and pyrethroids pesticides, and the hypothesized loss of natural enemies (Grafton-Cardwell et al. 1995). Citrus thrips populations at one long-studied site in the San Joaquin Valley were significantly elevated during an extended period from the early 1970s until 1997, during which use of broad-spectrum insecticides was heavy, but thrips populations subsequently declined dramatically with the broad adoption by the citrus industry of more selective pesticides (e.g., insect growth regulators and spinosyns; Morse and Grafton-Cardwell 2017). Insecticides are, however, still used commonly to bring citrus thrips below its economic threshold (Khan and Morse 2006). *Euseius* spp. (Acari: Phytoseiidae) predatory mites contribute to control of both citrus thrips and citrus red mites (Grafton-Cardwell and Ouyang 1995, Grafton-Cardwell et al. 1999b), but because *Euseius* is a generalist, feeding on plant sap, pollen, and many small arthropods (Grafton-Cardwell and Ouyang 1996), its densities are not tightly coupled with citrus thrips or citrus red mite densities.

We extend the ecoinformatics approach to address two questions for which we do not have clear prior expectations. First, we ask what are the long-term consequences of pesticide use on populations of citrus thrips, citrus red mites, and *Euseius* spp. predatory mites at the spatial scale of entire commercial citrus blocks? Clearly, under an integrated pest management program for a focal set of pests, we seek to use control methods, including pesticides, in ways that will not disrupt control of other pests. Has this been achieved in California citrus? Second, we ask what is the relationship between pesticide efficacy for citrus thrips and citrus red mite control and the risk to *Euseius* natural enemies? Long-term use of pesticides is well known to cause the evolution of resistance, and the use of broad-spectrum pesticides can cause the disruption of natural enemies that can worsen pest problems (Pimentel et al. 1992). It is clear that some pesticides that are effective for citrus thrips and citrus red mite control are also toxic to *Euseius* (e.g., formetanate, dimethoate, beta cyfluthrin, and spinetoram; Grafton-Cardwell et al. 1995, Khan and Morse 2006, Grafton-Cardwell et al. 2017). Indeed, there seems to be a widespread belief among farmers growing many different crops that more efficacious pesticides are also more broad-spectrum (Kouser and Qiam 2013). If this is so, then farmers may face a difficult trade-off between achieving the level of pest suppression that they seek versus preserving the ecosystem services provided by their resident populations of natural enemies. Nevertheless, the general relationship between efficacy and risk to natural enemies is unknown. Thus, we ask the question: are the pesticides that show the highest efficacy in short-term pest suppression also those posing the greatest risks to natural enemies?

Methods

Overview

We gathered data from two private pest management consultant groups and the CDPR to evaluate pesticide efficacy. These data are a subset of the SQL server Citrusformatics database describing pests, pesticides, fruit quality, and yield for commercial citrus production in California. The consultant data include scouting reports for two pests and a shared natural enemy: citrus thrips and citrus red mite, and predatory mites in the genus *Eusieus*. We carried out two main analyses: 1) first, we examined whether long-term (multi-year) use of pesticides increase average infestation levels of citrus thrips or citrus red mites, and 2) second, we examined the relationship between pesticide efficacy against thrips and mites and negative nontarget impacts on densities of predatory mites in the genus *Euseius*.

Cultivars and Groves

Our dataset was derived from 249 groves located in California's San Joaquin Valley (Fresno and Tulare counties) and distributed among 83 separate ranches (clusters of groves) and sampled between 2003 and 2012. The groves are composed of both navel oranges (79% of groves) and various mandarin varieties (21% of groves) planted between 1961 and 2010 (average: 1997; SD = 12 yr). Mean grove size was 14.0 ha (SD = 10.2; range 1.4–55.0 ha)

Pests and Predatory Mites

Each of the pests was scouted by the consultants at variable intervals, depending on the pest life history and the management style of the consultant. Citrus thrips were sampled approximately bi-weekly after petal fall, from March or April to the end of June. Sampling involved checking 25–300 fruit per grove, depending on the size of the grove. Consultants recorded the proportion of fruit infested with one or more citrus thrips individuals. Citrus red mite was scouted by evaluating between 25 and 100 leaves (top and bottom) for the presence of any number of adult female mites. The proportion of infested leaves was recorded. Predatory mites were counted as follows: 1) a branch terminal from deep inside the tree canopy was taken that bore young, succulent foliage; 2) the terminal was brought into the sunshine, and the undersides of five leaves were examined to count the number of *Euseius* (*Euseius* respond to the light by moving rapidly across the leaf surface, making them easy to count); 3) five terminals were sampled per 20-acre citrus block; and 4) the average number of mites per terminal, rounded to the nearest integer value, was used as our measure of *Euseius* density.

Citrus red mite densities were occasionally recorded using density categories (low, medium, and high) instead of presence or absence sampling. Given our limited sample sizes, these data records were valuable, and we translated these records into a corresponding proportion infested. This was possible because in some cases, the same grove was sampled on the same day using both presence or absence sampling and the density categories. For each density category, we therefore calculated the average presence or absence infestation level from all dates where both record types were available. We then substituted those averages for each of the corresponding density category records.

Pesticides

Pesticide use data were downloaded from the Pesticide Use Reporting database managed by the CDPR. This database includes all insecticide and acaricide sprays applied to each grove from 2003 to 2012. Information on the date of application, the active ingredients, other compounds (e.g., surfactants), and the use rate of each compound is included. We utilized information on the active ingredients only. Through discussions with the consultants we determined the likely targets for each of these sprays. Management practices ranged from a strong reliance on biological control in combination with pesticides viewed as being 'softer' for natural enemies to frequent applications of less selective pesticides, providing substantial variation for our analysis. A majority of citrus thrips and citrus red mite applications were made as tank mixes, with multiple active ingredients sprayed together.

Long-Term Effects of Pesticide Use

To assess the hypothesis that pesticide use could worsen long-term pest problems or suppress populations of natural enemies, we examined correlations between pesticide use and multi-year average densities of citrus thrips, citrus red mites, and *Euseius* predators. To capture the disruptive potential of each pesticide, we used two previously published metrics of the negative impacts of particular insecticides on natural enemies. Using two different metrics allows better cross validation. First, we used the University of California Statewide Integrated Pest Management Program (UCIPM) qualitative selectivity ratings (http://www.ipm.ucdavis.edu/PMG/r107300811.html), which is tailored to citrus production in California. We converted these qualitative ratings to a numeric scale and multiplied persistence time by the breadth of natural enemies impacted. Following the UCIPM terminology, if a compound affects only one type of natural enemy it received a '1', and two or more natural enemies received a '2'. Short persistence times received a '1', short to intermediate a '2', intermediate a '3', and long a '4'. Higher scores indicate higher risk to natural enemies. Second, we used the SELECTV database (Theiling and Croft 1988), which is intended to be applicable to any crop. The SELECTV database estimated pesticide impacts on natural enemies from a literature review of published experimental studies and extrapolated impacts from similar compounds in cases where no studies were available for a given compound. The SELECTV database relies on a broad geographic range of studies; however, it may not necessarily be an accurate reflection of local conditions. Reassuringly, the two measures of pesticide use were positively correlated across the citrus groves studied here (consultant group 1: $N = 83$, $R^2 = 0.69$, $P < 0.0001$; consultant group 2: $N = 165$, $R^2 = 0.82$, $P < 0.0001$).

We examined the long-term effects of pesticide use on pests and *Euseius* by correlating the average yearly total natural enemy impact score of pesticide applications in each grove with the average infestation level of citrus thrips and citrus red mites and the average densities of predatory *Euseius* mites. Averages were taken across all years from 2003 to 2012 for which we had observations. We chose to analyze effects on average densities of pests and *Euseius* rather than using panel data modeling methods because panel data methods require complete cases—i.e., all replicates would require the same number of repeated observations, whereas in our dataset different groves were sampled for different numbers of years. The natural enemy impact scores of all the pesticides used in a grove were summed to give a natural enemy impact score for each grove each year and then averaged across all years. Infestation levels of citrus thrips and citrus red mites, and densities of *Euseius* mites were averaged over the year, and then averaged across all years for each grove. For citrus thrips and citrus red mite, we excluded from this particular analysis all sprays that targeted these pests. This reduced the potential for spurious correlations between the infestation level of pests and sprays targeting those pests. Note that compounds were sprayed in almost every year for other pests such as fork-tailed katydids (*Scudderia furcata* Brunner von Wattenwyl [Orthoptera: Tettigoniidae]), citrus cutworms (*Egira curialis* [Grote] [Lepidoptera: Noctuidae]), California red scale (*Aonidiella aurantii* [Maskell] [Hemiptera: Diaspididae]), and citricola scale (*Coccus pseudomagnoliarum* [Kuwana] [Homoptera: Coccidae]), which are known to affect citrus thrips, red mites, and *Euseius* mites. For predatory *Euseius* mites, we included sprays targeting any pest.

Quantifying Short-Term Pesticide Efficacy

We measured pesticide efficacy by calculating the proportional change in infestation pre-application to post-application (calculated as [proportion infested post-application − proportion infested pre-application]/proportion infested pre-application) by using the nearest sampling dates to the application. Both citrus thrips and citrus red mites were sampled during the same seasonal period, from March to July. To measure pesticide efficacy against citrus thrips, we utilized a window of 7 d before or after a pesticide application. This interval was lengthened to 14 d for citrus red mite. These values were selected to compensate for the differing generation times and sampling frequencies among the pests, as well as the slower acting nature of some acaricides. Note that this analysis focuses specifically on pesticides that targeted citrus thrips or citrus red mites, whereas our previous analysis, which asked whether citrus thrips and citrus red mites are induced pests, specifically excluded thrips- and red mite-targeted applications and instead considered pesticides applied to control other pests.

Statistical Analyses

For our correlational analyses regarding long-term pesticide use, we used a linear mixed model to account for the possible confounding influence of ranch. Each grower has multiple ranches that include clusters of groves. These ranch units potentially have spatial autocorrelation or similarities in uncharacterized management practices. To remove this effect, we modeled ranch as a random effect in our model using the lme4 package (Bates et al. 2015) in R. To describe the influence of long-term pesticide use on arthropod densities, we report R_β^2, a standardized measure of association between the fixed predictors (in this case, just one—pesticide use) and the response variable (arthropod densities) in linear mixed models (Edwards et al. 2008).

Results

Long-Term Effects of Pesticide Use

We found no evidence that pesticide use in citrus groves from 2003 to 2012 was associated with worsening pest status of either citrus thrips or citrus red mites. For citrus thrips, we instead found significant negative correlations between long-term average UCIPM natural enemy impact scores of pesticide sprays and the average thrips fruit infestation levels (Fig. 1A and B), suggesting that insecticides directed at other pests were contributing to the suppression of citrus thrips populations. Populations of citrus red mites were uncorrelated with the UCIPM pesticide use metric (Fig. 1C and D). Results were similar using the SELECTV pesticide use metric, although statistically significant suppression of citrus thrips was found only for data gathered by one of the two consultant groups (Supp Fig. 1 [online only]). Neither the UCIPM nor the SELECTV pesticide use metric was significantly correlated with mean *Euseius* spp. densities (Fig. 2 and Supp Fig. 2 [online only]). Thus, we found no evidence that the putatively disruptive effects of pesticides on *Euseius* spp. or other natural enemies were worsening the pest status of either citrus thrips or citrus red mites. Furthermore, although mean densities of both pests varied substantially across citrus groves (Fig. 1), few groves exhibited mean densities above the thresholds at which pesticide applications are generally recommended to avoid economic losses (5% fruit infested for citrus thrips on navel oranges; 8 mature females per leaf for citrus red mite, corresponding to at least 95% of leaves with adult female mites present; Zalom et al. 1985, University of California 2012), suggesting that control was generally effective.

Efficacy and Nontarget Impacts

A GLM of the effect of the presence or absence of each of 16 pesticides applied singly or, more often, within a given pesticide tank mixture on the proportional change in citrus thrips densities pre- to

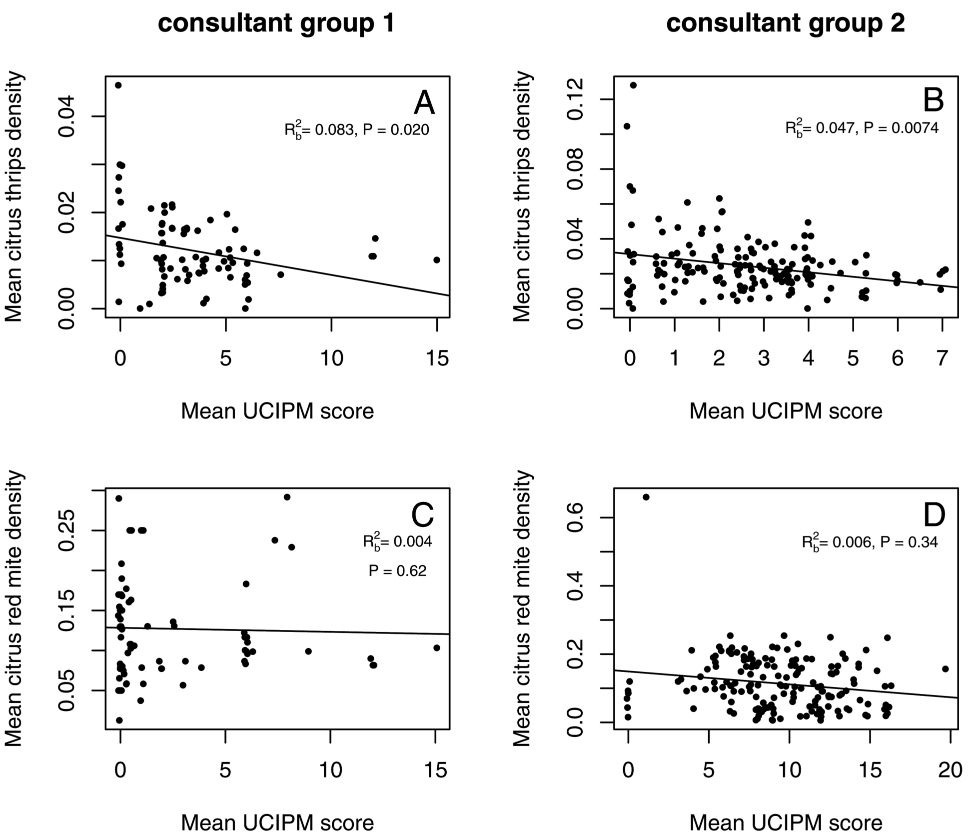

Fig. 1. Relationship between mean UCIPM natural enemies impact scores and the long-term mean infestation levels of citrus thrips and citrus red mites. Lines shown are simple linear regression fits. Summary statistics for effect of pesticide use index in linear mixed models: (A) citrus thrips for consultant group 1 (N = 85, UCIPM metric estimate = −0.000768 ± 0.000322, R_β^2 = 0.083, P = 0.020); (B) citrus thrips for consultant group 2 (N = 164, UCIPM metric estimate = −0.00206 ± 0.00076, R_β^2 = 0.047, P = 0.0074); (C) citrus red mites for consultant group 1 (N = 83, UCIPM metric estimate = 0.00111 ± 00.00220, R_β^2 = 0.004, P = 0.615); (D) citrus red mites for consultant group 2 (N = 165, UCIPM metric estimate = −0.00146 ± 0.00154, R_β^2 = 0.006, P = 0.343).

post-application revealed a range of negative coefficients (indicating materials whose average effect is to increase the efficacy of an application) and positive coefficients (indicating materials that decreased the efficacy of an application), three of which were significant: cyfluthrin, chlorpyrifos, and imidacloprid (Table 1). The same model for citrus red mites with 14 pesticides also revealed a range of positive and negative effects, seven of which were significant, with significant negative effects (efficacy enhanced) for spirotetramat, pyriproxyfen, chlorpyrifos, spinetoram, and hexythiazox, and significant positive effects (efficacy reduced) for malathion and oil (Table 2).

Neither UCIPM nor SELECTV natural enemies impact scores were significantly correlated with efficacy in short-term pest suppression (citrus thrips—SELECTV: $F = 0.78$, df = 14, $P = 0.39$; citrus thrips—UCIPM: $F = 0.41$, df = 14, $P = 0.57$; citrus red mites—SELECTV: $F = 0.89$, df = 12, $P = 0.364$; citrus red mites—UCIPM: $F = 0.07$, df = 12, $P = 0.79$). Thus, at least for this example in California citrus, our analyses provide no support for the idea that farmers face an unavoidable trade-off between short-term pesticide efficacy and preserving a key natural enemy.

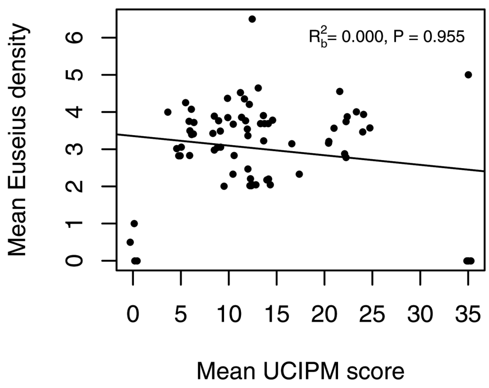

Fig. 2. Relationship between mean UCIPM natural enemies impact scores and the long-term mean density of *Euseius* spp. predatory mites. Line shown is a simple linear regression fit. Summary statistics for effect of pesticide use index in linear mixed models: $N = 74$, UCIPM metric estimate = 0.00125 ± 0.02200, $R^2_\beta = 0.000$, $P = 0.955$.

Discussion

Our results suggest that the integrated pest management practices used in California citrus during 2003–2012 achieved a key desired goal: compatible management practices for different pests. When pest densities were viewed as long-term (multi-year) averages, we found no evidence that heavier use of pesticides thought to be harmful to natural enemies caused a worsening of problems with either citrus thrips or citrus red mites (Fig. 1 and Supp Fig. 1 [online only]). Thus, we find no support for the hypothesis that citrus thrips or citrus red mites are induced pests (Morse and Zerah 1991, Morse and Grafton-Cardwell 2017). Long-term disruption might have been a reasonable expectation, given that citrus foliage has a thick waxy layer that is known to absorb lipophilic pesticide materials and protect them from weathering, resulting in highly persistent residues (Nigg et al. 1981). These persistent residues may cause long-term suppression of natural enemies (Rosenheim and Hoy 1988). Nevertheless, we found no evidence that *Euseius* spp. predatory mites suffered long-term suppression in citrus groves receiving heavier pesticide use. Instead, at least for citrus thrips, pesticides being applied to control other pests were apparently contributing to the suppression of citrus thrips as well. Potentially contributing to the resilience of biological control in citrus groves, some key natural enemies have evolved resistance to some insecticides (Rosenheim

Table 1. Generalized Linear Model (GLM) model output for influence of different pesticides on short-term suppression of citrus thrips populations[a]

Pesticide[b]	Intercept ± SE	N[c]	T	P	SELECTV impact score	UCIPM impact score
Spinosad	−0.379 ± 0.288	71	−1.31	0.19	12.2	3
Spinetoram	−0.363 ± 0.243	147	−1.49	0.14	35.8	3
Spirodiclofen	−0.272 ± 0.794	2	−0.34	0.73	9.5	3
Spirotetramat	−0.235 ± 0.469	13	−0.50	0.62	47.5	1
Malathion	−0.079 ± 0.384	19	−0.21	0.84	25	6
Formetanate	−0.066 ± 0.307	271	−0.22	0.83	31.3	8
Dimethoate	−0.047 ± 0.297	51	−0.16	0.87	44.8	8
Hexythiazox	−0.027 ± 0.208	64	−0.13	0.90	25	2
Fenpropathrin	0.037 ± 0.158	150	0.23	0.82	25	8
Oil	0.159 ± 0.266	343	0.60	0.55	35.8	2
Abamectin	0.198 ± 0.350	16	0.57	0.57	28.5	3
Pryiproxyfen	0.264 ± 0.324	37	0.81	0.42	5	4
Cyfluthrin	0.292 ± 0.144	253	2.03	0.04*	47.5	8
Acetamiprid	0.664 ± 0.577	4	1.15	0.25	47.5	8
Chlorpyrifos	0.968 ± 0.323	39	3.00	0.003**	23.6	4
Imidacloprid	1.617 ± 0.433	15	3.73	0.0002***	39.3	6

Global model: $N = 111$, $F = 3.49$, $P < 0.001$. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

[a]Multiple regression results and impact scores for citrus thrips. Negative regression coefficients indicate compounds whose presence in a pesticide application, most of which were tank mixes, increases the efficacy of that application, whereas positive regression coefficients indicate compounds whose presence decreases efficacy. Active ingredients in the applications that are known to be effective against citrus thrips and those that are not effective are included because of the potential for indirect effects involving natural enemies. To aid in interpreting the intercepts: the average efficacy across all treatments was −0.697, meaning that infestation levels dropped by 69.7% on average, and the mean proportion of fruits infested with citrus thrips pre-spray was 0.12 ± 0.07 (SD; range 0.028–0.28), well above the action threshold of 5% fruit infestation (University of California 2012).

[b]Pesticide names shown in italics are included in the University of California Pest Management Guidelines for control of citrus thrips (http://ipm.ucanr.edu/PMG/r107301711.html).

[c]Number of times the indicated pesticide was applied when citrus thrips were present.

Table 2. GLM model output for influence of different pesticides on short-term suppression of citrus red mite populations[a]

Pesticide[b]	Intercept ± SE	N[c]	T	P	SELECTV impact score	UCIPM impact score
Spirotetramat	−1.883 ± 0.829	31	−2.27	0.02*	47.5	1
Pyriproxyfen	−1.779 ± 0.441	86	−4.04	<0.0001***	5	4
Chlorpyrifos	−1.456 ± 0.543	40	−2.68	0.0076**	23.6	4
Abamectin	−1.313 ± 0.834	11	−1.58	0.12	28.5	3
Spinetoram	−0.946 ± 0.429	134	−2.21	0.03*	35.8	3
Spinosad	−0.816 ± 0.496	47	−1.65	0.10	12.2	3
Hexythiazox	−0.742 ± 0.266	76	−2.79	0.005**	25	2
Formetanate	−0.300 ± 0.292	236	−1.03	0.30	31.3	8
Cyfluthrin	−0.237 ± 0.218	167	−1.09	0.28	47.5	8
Fenpropathrin	−0.191 ± 0.202	211	−0.95	0.34	25	8
Dimethoate	−0.069 ± 0.375	41	−0.18	0.86	44.8	8
Imidacloprid	0.014 ± 0.410	29	0.03	0.97	39.3	6
Malathion	0.693 ± 0.328	32	2.11	0.04*	25	6
Oil	0.982 ± 0.340	368	2.89	0.004**	35.8	2

Global model: $N = 110$, $F = 2.42$, $P < 0.01$. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

[a]Multiple regression results and impact scores for citrus red mites. Negative regression coefficients indicate compounds whose presence in a pesticide application, most of which were tank mixes, increases the efficacy of that application, whereas positive regression coefficients indicate compounds whose presence decreases efficacy. Active ingredients in the applications that are known to be effective against citrus red mites and those that are not effective are included because of the potential for indirect effects involving natural enemies. To aid in interpreting the intercepts: the average efficacy across all treatments was −0.115, meaning that infestation levels dropped 11.5% on average; the mean proportion of leaves infested with citrus red mites pre-spray was 0.23 ± 0.13 (SE; range: 0.07–0.63), indicating that growers are using thresholds for treatment far below the University of California recommendations (University of California 2012).

[b]Pesticide names shown in italics are included on the University of California Pest Management Guidelines for control of citrus red mites (http://ipm.ucanr.edu/PMG/r107400111.html).

[c]Number of times the indicated pesticide was applied when citrus red mites were present.

and Hoy 1986, Grafton-Cardwell and Ouyang 1993). Another contribution to the apparently compatible use of pesticides in the groves represented in our database was the generally modest intensity of overall pesticide use. Because some pesticides were applied as tank mixes, there are two ways to summarize pesticide use intensity: as the number of separate applications per year, where a tank mix of two pesticides would still be counted as a single application, versus where a tank mix of two pesticides would be counted as two different applications. Using either approach, pesticide use appears to have been moderate overall (number of applications per block per year, with tank mixes considered as a single application: consultant group 1: mean = 1.80 ± 0.79 [SD] [range: 1.0–5.0]; consultant group 2: mean = 1.77 ± 0.59 [range: 1.0–3.8]; number of applications with each active ingredient in a tank mix counted separately: consultant group 1: mean = 2.73 ± 1.18 [SD] [range: 1.0–6.0]; consultant group 2: mean = 3.37 ± 1.15 [range: 1.0–6.67]). There is concern, however, that insecticide use may escalate substantially as the Asian citrus psyllid *Diaphorina citri* (Kuyawama) (Hemiptera: Liviidae), the vector of huanglongbing disease, becomes fully established (Grafton-Cardwell et al. 2013). This could pose future challenges for the continuing compatibility of pesticide use in California citrus.

We find also that the efficacy of compounds and risk to natural enemies are not correlated. In this analysis, our efficacy data are more precise than our metrics of expected impacts on nontarget beneficial insects. Future research should directly measure or more accurately model both the positive impacts (efficacy) and the negative impacts (nontarget impacts) of sprays at grove-level resolution. Tools based on spatial information systems can help improve the measurement of nontarget impacts, such as the PURE online assessment (Zhan and Zhang 2012). Nevertheless, our results highlight a conclusion of importance for citrus pest management in California: from an ecological perspective, growers have available pesticide active ingredients that are simultaneously highly effective and very low risk. Although farmers growing other crops may express the belief that more selective products are less efficacious (Kouser and Qiam 2013), in California citrus there is a recognition that some highly selective materials are also highly effective (B. G. Grafton-Cardwell, personal communication).

Short-Term Efficacy of Insecticides

Our analyses also provide some insights that may be valuable for citrus growers into which pesticides are providing more effective short-term suppression of citrus thrips and citrus red mites. Although efficacy is typically measured in small, replicated experimental field trials, our commercial-scale data provide a picture of realized efficacy under actual commercial production conditions. Our analysis of citrus thrips suppression contrasted densities observed within 1 wk before and 1 wk after an application. Given this narrow time frame, effective pest population suppression should be expected and was observed: the average application was associated with a 69.7% decrease in the proportion of infested fruits (Table 1). Nevertheless, one widely used material, cyfluthrin, which is listed as an option on the University of California Statewide IPM website (http://ipm.ucanr.edu/PMG/r107301711.html), was associated with significantly less effective treatments; this may be a reflection of resistance (Khan and Morse 1998). The continued widespread use of cyfluthrin may reflect its value in controlling another pest, the fork-tailed bush katydid, *S. furcata*, which is often targeted at the same time as citrus thrips with tank-mixed applications. Two other materials, chlorpyrifos and imidacloprid, which are used to control other citrus pests, were also associated with significantly less effective suppression of citrus thrips, although sample sizes were smaller for these materials (Table 1). Chlorpyrifos use is declining steeply due to tightening regulatory restrictions, but use of imidacloprid may rise sharply as the Asian citrus psyllid invades. Our results suggest that we should be vigilant regarding potentially disruptive effects of imidacloprid on citrus thrips population control.

Our analysis of citrus red mite suppression used a broader time window around the date of an application—density estimates were taken from up to 2 wk before and 2 wk after an application. Given this broader time frame, weaker mite population suppression might be expected and was observed: the average application was associated with only an 11.5% decrease in the proportion of infested leaves (Table 1). Most materials appeared to play similar, moderately helpful roles in suppressing the population growth rates of citrus red mites. The one striking exception was the use of oil. Oil is widely used, either singly or as an adjuvant to improve coverage and absorption of other materials (e.g., abamectin, spinetoram, spinosad, and pyriproxyfen), and in our data set across a large number of observed applications (n = 368) was clearly associated with a loss of citrus red mite control (Table 2).

Conclusions

We demonstrate that ecoinformatics may be a valuable complementary tool for studying pesticide efficacy, and that it can address novel questions that integrate efficacy with nontarget effects. The diversity of compounds and tank mixtures used on crops across the globe is overwhelming, and the efficacy and nontarget effects associated with their use cannot be addressed solely by experimental approaches. Greater use of ecoinformatics can accelerate the study of pesticide efficacy and integrate it with risk, ultimately helping to enhance pest control and reduce unnecessary pesticide use.

Supplementary Data

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

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