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Does Use of Pesticides Known to Harm Natural Enemies of Spider Mites (Acari: Tetranychidae) Result in Increased Number of Miticide Applications? An Examination of California Walnut Orchards

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ABSTRACT Integrated pest management (IPM) offers guidelines to reduce spider mite (Acari: Tetranychidae) outbreaks by avoiding pesticides known to be harmful to the natural enemies of spider mites. However, in practice, these guidelines can be inconsistent in their effectiveness. The project examined whether California walnut (*Juglans* L.) growers, following IPM guidelines to avoid pesticides harmful to the natural enemies of spider mites, achieved lower miticide use. Significant statistical tests suggested that fields with harmful applications were 40% more likely to have a miticide application than fields without. Although the IPM guidelines achieved the goal of reducing miticide use, further analysis of other potential causal mechanisms behind outbreaks could strengthen the effectiveness of the guidelines, potentially increasing IPM adoption.

KEY WORDS biological control, integrated pest management, secondary pest outbreaks, Tetranychidae, tree nuts

A secondary pest outbreak can refer to a phenomenon where a species of minor importance attains pest status after an application of a pesticide targeting a different, primary pest species. Preventing secondary pest outbreaks is important to growers, because the need for additional pest control to avoid damage to the crop can become costly. Many agricultural extension services offer integrated pest management (IPM) guidelines to assist growers in preventing secondary pest outbreaks, particularly regarding web-spinning spider mites (Acari: Tetranychidae), which are associated with secondary outbreaks in many different crops (UC-IPM 2000). The efficacy of guidelines such as these in meeting the grower's economic goals and expectations can play an important role in increasing the adoption of IPM, thereby reducing environmental risks associated with agricultural pest management.

Although secondary spider mite outbreaks can be caused by several nonmutually exclusive mechanisms, much of the scientific literature assumes that disruption of biological control is the most important influence (Hardin et al. 1995, Hu et al. 1996, Gurr et al. 1999, Zalom et al. 2001, Prischmann et al. 2005, Hardman et al. 2006, Dutcher 2007, Stavrinides and Mills 2009). This assumption, although probably correct given the existing abundance of scientific evidence, may ignore other important mechanisms at play. Reflecting this assumption, many extension guidelines advocate that growers refrain from controlling primary pests with pesticides known to be harmful to the natural enemies of spider mites (henceforth to be referred to as "harmful pesticides") (USDA 1998; UC-IPM 2000, 2003, 2006, 2007). The goal of this study was therefore to determine whether growers who avoid these harmful pesticides have less need to treat for spider mites.

Materials and Methods

Data Sources. Data on pesticide choices, application timing, and the relative harm of the pesticides to the natural enemies of spider mites were gathered from four databases: SELECTV, Biobest, Koppert, and the Pesticide Use Reports (PUR) (Theiling and Croft 1988, Biobest 1999, Koppert Biological Systems 2005, CDPR 2010). Grower-reported pesticide product choices and application timing came from the PUR database maintained by the California Department of Pesticide Regulation (CDPR). Since 1990, regulation has required growers in California to systematically report every pesticide application on a field in a given year. The PUR database thus offers a wealth of information on real-time grower pest management decisions that can be used to accurately reflect grower experiences.

The SELECTV, Biobest, and Koppert databases were consulted to determine whether a pesticide was harmful to the natural enemies of spider mites. Each

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Table 1. Comparison of scales for ranking pesticide impacts to natural enemies between the three databases

Natural enemy database	Rank (least harm [1] to most harm [4])			
	1	2	3[a]	4
SELECTV original rank levels	(1,2)	(3)	(4)	(5)
SELECTV scaled to 1–4 range	<10	10–30	30–90	>90
Biobest	<25	25–50	50–75	>75
Koppert	<25	25–50	50–75	>75

Values are percentages; percentages can be interpreted as the percentage reduction in control capacity.

[a] A pesticide was considered harmful if it scored a rank >3.

of these databases assigned a numerical rank to the active ingredients of pesticides based on their harmful effects to a specified natural enemy. The rank reflected a range of expected percentage reduction in the control capacity of the natural enemy based on various lethal and sublethal effects of the active ingredient.

Natural Enemy Database Adjustments. The type of information varied between the three natural enemy databases. If data were available for multiple life stages of a natural enemy, then the life stage was selected with the maximum impact rank found in the database. If the databases listed multiple impacts on the natural enemies other than mortality (i.e., reducing reproductive capacity or important life cycle activities), the average rank of all the methods was used. If the database gave multiple pesticide application methods, then the rank was chosen that was assigned to the spray option. The ranking scales differed between databases. The SELECTV ranking was on a 1–5 scale, whereas the Biobest and Koppert rankings were on a 1–4 scale. For all three databases, the ranks reflected different ranges of percentage reduction in the control capacity of the natural enemy, with a rank of one representing the lowest possible impact of a pesticide to a natural enemy, and a rank of 4 or 5 (depending on the database) representing the highest possible impact. The three database were standardized to roughly equate the different rankings by combining the rankings of one and two in the SELECTV database into a single level, thus scaling SELECTV to a range of rankings from 1 to 4 (Table 1).

Case Study. California walnut (*Juglans* L.) growers were chosen as a grower subset for analysis. In 2009, there were 227,000 walnut acres in the state, valued at US$747,270,000 (USDA 2011). The primary pests of walnuts are the codling moth, *Cydia pomonella* (L.); the navel orangeworm, *Amyelois transitella* (Walker); and the walnut husk fly, *Rhagoletis completa* Cresson (Ramos 1998). Depending on the pest, they are most often treated with conventional products such as organophosphates and pyrethroids, which are thought to harm the natural enemies of spider mites (CAB International 2004, Mills et al. 2009, UC-IPM 2011).

Resolution of Analysis. The project analyzed walnut PUR data for 2000–2006 for three important growing regions: the San Joaquin Valley, the Sacramento Valley, and the Central Coast region (USDA 2007). The analysis took place at orchard field level, with the assumption that growers who divide their total acreage into multiple fields for pesticide reporting purposes do so because there is the potential for variation in pest management practices among the different fields. In addition to the assumption of independence between the fields, it was assumed that pest management practices may vary annually for any particular field, because pest pressure may change from 1 yr to the next. Based on these assumptions of independence between years and fields, the statistical analysis unit was the year-field. In total, there were 34,327 year-fields over the 7 yr. On average, the sample of year-fields represented ≈2,453 growers per year, with a mean of two orchard fields per grower, covering a total of ≈84,717 ha (≈209,341 acres).

Pesticides Harmful to Natural Enemies. A pesticide was considered harmful to natural enemies based on the numerical rank assigned to it by the databases, which took into account different lethal and sublethal effects depending on the databases. Four natural enemies of spider mites were identified as important in walnut orchards, although UC-IPM (2003) noted a variation in how dependable each was in providing effective control: Based on this variation in dependability, the western predatory mite, *Galendromus occidentalis* (Nesbitt), was considered to be the primary predator due to its high dependability, whereas the sixspotted thrips, *Scolothrips sexmaculatus* (Pergande); the spider mite destroyer, *Stethorus punctum picipes* Casey; and the minute pirate bug, *Orius tristicolor* (White) were considered less reliable secondary predators (UC-IPM 2003). To identify which pesticides were harmful to these natural enemies, the three databases were queried for the ranks they assigned to all insecticides, miticides, herbicides, fungicides, plant growth regulators, and oils reported to the PUR database by walnut growers over the 7 yr. Given the scarcity of natural enemy impact data for many pesticides used by walnut growers, the databases were queried at the genus rather than species level, over all commodities and all regions available. If there was variation in the rank levels assigned by the three databases, an average rank was used. Each pesticide was then assigned a primary rank for its impact to the western predatory mite and a secondary rank for its average impact to the remaining three secondary enemies. Given that a rank of 3 or 4 represented moderate to high negative impacts in the three natural enemy databases, each pesticide was then identified as being harmful to natural enemies if its rounded value was a ≥3 for either the primary or secondary rank.

Determination of Presence or Absence of Miticide and of Harmful Applications. For each year-field, information was gathered on whether a harmful application and a miticide application occurred at some time during the year, whether the harmful application was the miticide, and if the miticide application took place before, simultaneously, or after the harmful application. Two issues complicated the process: First, if a year-field had both harmful and miticide applications at some point, the sequential timing of the applications was important in deciding whether the miticide was potentially needed for a mite outbreak caused by the harmful application. Although the analysis could not verify any causal relationship between a harmful pesticide application and a subsequent miticide application, it could rule out all miticide applications occurring before or very near the time of harmful applications as potential responses to a harmful pesticide-induced outbreak, given the sequential ordering. Therefore, to increase the likelihood of a miticide being a response to a pesticide-induced outbreak, an occurrence of a subsequent miticide application on a year-field was only recorded if the last date of a miticide application was ≥7 d after the first date of a harmful pesticide application. The 7-d minimum limit was subjectively decided upon as a conservative measure, to ensure that the miticide application was more likely to be a response to the harmful pesticide and not a result of already existing mite pressure at the time of the harmful application. Because long-lasting residues can continue to harm natural enemies for many months throughout the growing season, no maximum day limit of effect was imposed besides the implicit year limit of the year-field unit definition (Zalom et al. 2001). Any year-fields where the last miticide application took place before or within 6 d after the first harmful pesticide application were relatively few, and were excluded from the analysis.

A second complication occurred when a miticide was considered by the three databases to be harmful to natural enemies of spider mites, or a "harmful miticide." In theory, the use of a harmful miticide could cause need for subsequent miticide applications via a secondary outbreak. If this scenario was the case for a year-field, the first application of the harmful miticide was considered to be the harmful application, and the following miticide applications were considered to be subsequent miticide applications. However, if the only harmful application for a given year-field was the miticide, without any subsequent miticide applications, then that one harmful miticide application could not be considered to be in response to a pesticide induced outbreak. In these instances, the one application of the harmful miticide was classified as a miticide application, and the year-field was included in the analysis as a field that did not use harmful pesticides but still required a miticide (Fig. 1). Following these criteria, each year-field was grouped under one of five categories: no harmful, no miticide (NHNM); no harmful, miticide (NHM); harmful, no miticide (HMN); harmful, miticide subsequent (HMs); and harmful, miticide before (HMb), the last categoryof which was excluded from analysis (Table 2).

Statistical Evaluations. Likelihood ratio, Pearson, odds ratio, and a one-sided Fisher's exact test for two-way contingency tables were used to determine whether fields without use of harmful pesticides had significantly less miticide applications. JMP software (SAS Institute 2010) was used in the analyses. In addition, a Yule's Q test, which can be interpreted as a type of correlation coefficient ranging from −1 to 1 to show strength and direction of categorical relationships, was manually done based on the JMP contingency table results.

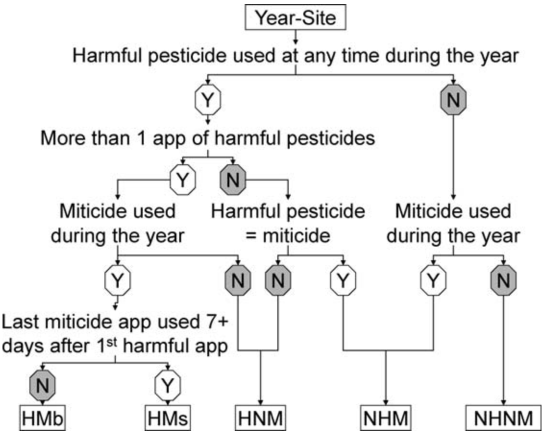

Fig. 1. Flow chart describing categorization process of each year-field for the presence or absence of harmful pesticide applications and miticide applications.

Results

Identification of Harmful Active Ingredients. One hundred and thirty-seven individual dominant active ingredients of pesticides were reported to the PUR database by walnut growers over the 7-yr time span. Nearly half of these were evaluated by at least one of the three natural enemy databases for at least one of the four natural enemies. Sixty-three percent of insecticides reported to PUR were identified as harmful, whereas 15% were considered nonharmful, and 22% were not evaluated by any of the three databases. Thirty-six percent of the miticides reported to PUR were identified as harmful, whereas 55% were considered nonharmful, and 9% were not evaluated. Two percent of herbicides reported to PUR were identified as harmful, 5% were considered nonharmful, and 93% remained unevaluated. Nine percent of fungicides reported to PUR were identified as harmful, 47% as nonharmful, and 44% were not evaluated. Sixty-seven percent of reported oils were evaluated as nonharmful, with the remaining 33% unevaluated. Finally, 20% of reported plant growth regulators were considered

Table 2. Definition and criteria for the five category options for year-fields

Category	Harmful pesticide application	Miticide application	Included in analysis
NHNM	No	No	Yes
NHM	No	Yes[a]	Yes
HNM	Yes	No	Yes
HMs	Yes[a]	Yes[b]	Yes
HMb	Yes[a]	Yes[c]	No

[a] Could potentially be a harmful miticide.
[b] If the last miticide application occurred ≥7 d after the first harmful pesticide application.
[c] If the last miticide application occurred before or within 6 d after the first harmful pesticide application.

Table 3. The number of individual dominant active ingredients reported by walnut growers to the PUR database over the 7-yr time period, the number (percentage) of these active ingredients identified as harmful or not to natural enemies of spider mites by at least one of the three databases, and the number (percentage) of these active ingredients that were not evaluated by any database

Use type of active ingredient	No. active ingredients that are			
	In PUR[a]	Harmful[b]	Not harmful[b]	Not evaluated[b]
Insecticide	41	6 (15)	26 (63)	9 (22)
Miticide	11	6 (55)	4 (36)	1 (9)
Fungicide	34	16 (47)	3 (9)	15 (44)
Herbicide	43	2 (5)	1 (2)	40 (93)
Oils	3	2 (67)	0 (0)	1 (33)
Plant growth regulator	5	1 (20)	0 (0)	4 (80)
Total	137	33 (24)	34 (25)	70 (51)

Totals are broken down by the type of use. Values in parentheses are percentages.

[a] Total number of active ingredients reported to the PUR database by walnut growers from 2000 to 2006.

[b] Total number of active ingredients evaluated by at least one of the three natural enemy databases that were considered harmful or nonharmful to mite natural enemies (percentage of column 2, the total number of PUR active ingredients).

[c] Total number of the PUR active ingredients that were not evaluated by at least one of the three natural enemy databases (percentage of column 2, the total number of PUR active ingredients).

nonharmful, and the remaining 80% were unevaluated (Table 3).

It is important to note that the pesticides not evaluated by the three natural enemy databases could have been harmful to mite natural enemies and thus unaccounted for in this analysis. However, the active ingredients not evaluated by the three natural enemy databases were usually herbicides, plant growth regulators, and fungicides, rather than arthropod controls. The excluded active ingredients that were arthropod controls were often considered to be very selective and low risk. Thus, there is potentially a high likelihood that the modes of action of these unevaluated active ingredients were not harmful to the arthropod natural enemies analyzed in this study. However, without experimental evidence, the extent of harm remains inconclusive.

Association Between Use of Harmful Pesticides and Mite Treatments. There was a total of 34,327 year-fields among all the walnut growers over the 7 yr analyzed. Three percent were excluded from analysis for having both a miticide application and a harmful application, but the miticide came before or immediately after the harmful application and thus did not qualify as a "subsequent" miticide application (HMb = 1,133). Out of the remaining 33,194 year-fields, 40% had a harmful application but no miticide application (HNM = 13,348), 31% had a harmful application and a subsequent miticide application (HMs = 10,415), 18% had no harmful or miticide applications (NHNM = 5,990), and the remaining 10% had no harmful applications, but still required a miticide application (NHM = 3,441) (Table 4).

Both the likelihood ratio test ($\chi^2 = 151.005$, df = 1, $P < 0.0001$) and the Pearson test ($\chi^2 = 149.681$, df = 1, $P < 0.0001$) were highly significant, although the Yule's Q (0.15192) was low. These three tests together revealed a significant though weak relationship between the avoidance of harmful pesticides and the lack of subsequent miticide applications. The one-sided right Fisher's exact test fine-tuned the analysis, strongly suggesting a higher probability of no miticide applications on year-fields where harmful pesticides were avoided ($P < 0.0001$). An odds ratio of 1.358267 (95% CI, 1.293141–1.426674) can be interpreted as saying that year-fields with harmful applications were 40% more likely to have a miticide application than year-fields without harmful applications.

Discussion

The highly significant results showed that growers following the existing IPM guidelines to prevent mite outbreaks by avoiding harmful pesticides are indeed less likely to need a miticide application compared with growers using harmful pesticides: only 36% of year-fields without harmful applications needed a miticide, compared with 44% of year-fields with harmful pesticides. An unanticipated result, though, can be seen if one looks solely at the year-fields with harmful pesticides: 44% needed a miticide, but 56% unexpectedly did not.

This somewhat surprising result, reflected in the low Yules Q value, can potentially be attributed to the assumptions embedded in the IPM guidelines regarding causal mechanisms behind outbreaks and the ability of natural enemies to maintain spider mites below economically damaging levels. Based on the IPM guidelines, a harmful application was defined as one that harms the natural enemies of spider mites. It did not take into account other potential causes of mite outbreaks, such as hormesis, removal or the pest's competition, or alterations in plant resources (Hardin et al. 1995, Dutcher 2007). Had the definition included

Table 4. Contingency table of the number of harmful applications and subsequent miticide applications for each year-field (percentage of count to row and column totals in parentheses separated by colon) (χ^2 value in parentheses below each count)

Year-field count (row %:column %) (χ^2)	Miticide application		
	Yes	No	Row totals
Harmful pesticide application Yes	10,415 (44:75) (24.7752)	13,348 (56:69) (17.7518)	23,763 (100:72)
No	3,441 (36:25) (62.4253)	5,990 (64:31) (44.7288)	9,431 (100:28)
Column totals	13,856 (42:100)	19,338 (58:100)	33,194 (100:100)

these potential causal factors either in addition to or instead of biological control disruption, the conclusions of this analysis could potentially have been strengthened. Further understanding of all potential mechanisms at play could therefore significantly improve the guidelines to prevent mite outbreaks, which would strengthen the efficacy of the grower's IPM tools and help to increase adoption of environmentally sustainable practices.

Recommendations. It would seem that growers would benefit from following extension guidelines if their goal is to reduce miticide applications. However, the results of this analysis point to a strong need for redirection of resources to strengthen the effectiveness of the guidelines and thus increase the potential for adoption of IPM practices. First, as proposed earlier, the guidelines could potentially be improved by increasing the knowledge of all the possible causal mechanisms behind secondary pest outbreaks, rather than solely assuming a biological control mechanism. Second, an expansion of the number and types of pesticides that are evaluated for harm to natural enemies can be invaluable to growers attempting to adopt biological control as a tool to replace or decrease pesticides. Finally, most existing literature surrounding biological control is based on studies of community ecology or laboratory-based toxicology, without incorporating the more applied considerations of the grower's economic pest pressure thresholds. To successfully answer the more applied ecological questions that can assist growers with IPM adoption, research will need to address these considerations. If future research can increase the understanding of the complex ecological reactions to pesticides, the grower will strongly benefit in being able to employ pesticides more efficiently and sustainably.

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