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Assessing dormant season organophosphate use in California almonds

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Abstract

Organophosphate (OP) pesticides were recommended during the dormant season to control overwintering insects such as peach twig borer, San Jose scale, European red mite, and brown mite in California almond and stone fruit orchards. However, since 1990, dormant OP use had fallen under increased scrutiny due to surface water contamination concerns. Studies have shown positive correlation between OP use and residue load in surface water. The purpose of this study is to assess the trends and regional patterns of OP use in almond orchards, and to identify factors that may have influenced those trends, including weather, pest pressure, and use of alternatives to OP such as pyrethroid, dormant oils, and *Bacillus thuringiensis* (Bt) for the assessment of the impacts to surface water quality. Pesticide use data from the California Department of Pesticide Regulation were analyzed. Regression analyses were used to assess trends from 1992 to 2000, and a geographic information system (GIS) was used to visualize the spatial variation in pesticide use. Results from this study indicated that, statewide, dormant OP use decreased while the use of some alternatives, such as dormant pyrethroid, no dormant insecticides, and in-season pyrethroid, oil alone, and Bt, increased in the last 9 years. The significant decreasing trend of OP use was observed for the measures of kilogram per hectare crop planted, percentage of total planted hectare treated, and numbers of growers who applied dormant OP. The reduction of dormant OP use appeared in all major almond-growing counties. Correlation analyses revealed that more rain was associated with less dormant OP use. A higher percent of almond damage, or rejects, was related to higher OP use in the following dormant season and in-season periods. However, the effects of weather and percent of nut rejects can only explain small portion of the variations in dormant OP use. Therefore, in addition to weather and pest pressures, economic pressures and various outreach and extension programs may also have played a role in encouraging farmers to reduce their use of dormant OP.
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Keywords: Organophosphate; Pyrethroid; Bt; Dormant spray; Peach twig borer; San Jose scale; Almonds

1. Introduction

During the past decade, California growers used 1–0.68 million kg of OP annually during the dormant season to control overwintering insect pests. California almond orchards, which produce 99% of the US almond crop, accounted for 10–33% of the state's total dormant OP use from 1992 to 2000. Insecticides are used during winter months primarily for control of peach twig borer (PTB), San Jose scale (SJS), and European red mite and brown mite. During the early 1980s, dormant OP was recommended as an effective control for overwintering insects in almond orchards, and were considered safer to the environment and

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human health (Rice et al., 1972; UCIPM, 1985). Although OP is still effective in controlling these pests, their use has raised concerns in California due to their appearance in surface water and toxicity to aquatic species. Concentrations of diazinon in the Sacramento and San Joaquin River watersheds were documented at levels high enough to be toxic to some aquatic organisms (Ross et al., 1999; Spurlock, 2002; Werner et al., 2002). The maximum detection of diazinon reached to 0.76 ppb, while the limit for total maximum daily load was set at 50 ng/l on 4 days average (McClure et al., 2002; Guo, 2003). The major source of the OP runoff has been attributed to applications during the winter rainy season in California, typically from November to March (Domagalski et al., 1997; Dubrovsky et al., 1998; Guo, 2003).

Consequently, the California Department of Pesticide Regulation (DPR) and other organizations have been encouraging the use of alternatives to OP. Some of the alternatives included dormant pyrethroid, spinosad a microbial pesticide, oil with no other insecticide, bloom time *Bacillus thuringiensis* (Bt), as well as in-season use of OP, pyrethroid, spinosad, oil alone, and pheromones. Starting in 1997, DPR funded several projects to develop alternative methods, demonstrate their effectiveness, and encourage their adoption (CDPR, 2002). Organizations such as the University of California Sustainable Agriculture Research and Education Program (UCSAREP), the UC Statewide Integrated Pest Management Program (UCIPM), the United States Environmental Protection Agency (US EPA), the United States Department of Agriculture (USDA), and the Almond Board of California have funded similar projects (Almond Board, 2001; Swezey and Broome, 2001; UCSAREP, 2002).

The question of whether dormant OP use has decreased naturally arises, as a result of availability of non-OP insect control methods, and if the OP use decreased, what were the factors affecting the change? Pest management decisions, in general, depend on many factors including pest pressures, management strategies, weather, economics, as well as available reduced-use programs in the region. The presence and density of pests are primary considerations in pest management decisions. Weather, on the other hand, can affect pesticide use by changing insect population densities and/or by changing farmers' accessibility to use pesticides. Moreover, the availability of affordable and low risk alternatives to dormant OP can influence pest management decisions.

To determine whether dormant OP use decreased, DPR's Pesticide Use Reporting (PUR) database was used. PUR is the unique pesticide database that tracks pesticides use by location and time (CDPR, 2000), and is a powerful database for assessing pesticide use trends in California. Recent analyses of the database have shown that dormant OP use on almonds and other tree crops has declined as measured by the amount applied, area treated, and number of growers who treated from 1992 to 1997 (Flint et al., 1993; Hendricks, 1995; Epstein et al., 2000, 2001). Although it is more difficult to determine why changes in use occurred, some clues could be revealed through various statistical analyses of pesticide use along with weather and indicators of pest pressure. We also believe that government, university, or industry programs to encourage a reduction in pesticide use have played a major role, but it may be difficult to quantify this role.

The objectives of this study are to assess the use trends of dormant OP and some of their alternatives in California almonds from 1992 to 2000, to investigate possible causes for the changes, and to determine if these changes have been accompanied by use of alternatives to OP that may reduce the impacts to surface water quality.

2. Materials and methods

2.1. Study areas and data sources

Thirteen counties (Fig. 1), comprising 98% of California's almond-growing acreage, were selected for the study. These countries are Butte, Colusa, Glenn, Sutter, Tehama, Yolo (northern California); Merced, San Joaquin, Stanislaus (central California); Fresno, Kern, Madera, Tulare (southern California), and are referred to as the major almond-growing region.

The pesticide use data of 1991–2000 was obtained from DPR PUR database. The PUR contains information on nearly all production agricultural pesticide use and some non-agricultural pesticide use in California since 1990. DPR received authority to collect pesticide use from the Food Safety Act of 1989 (Chapter 1200, AB 2161). Data collected include information

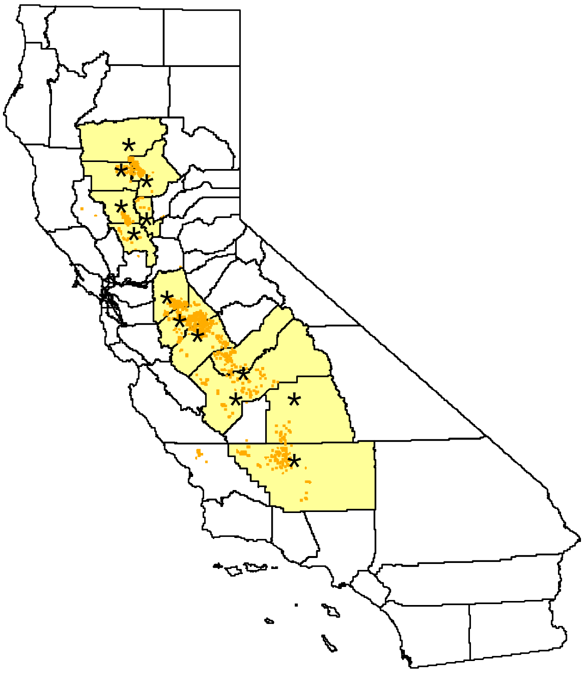

Fig. 1. Study areas—major almond-growing counties in California with light highlights. "∗" refers to the weather station locations within the county.

such as the pesticide product and amount applied, the area treated, the grower's identification code, the date of application, the specific field treated, and the application location to a square-mile section (i.e. 2.60 km^2) (CDPR, 2000). The data from field applications were aggregated to the grower and county levels for the analyses.

Although the common alternative to dormant OP use was no dormant spray (Bentley et al., 1996; CAFF/Almond Board, 1995), the main dormant pesticide alternatives to OP included pyrethroid, oils, and Bt. Other reduced-risk insecticides, such as spinosad, pheromones, and insect growth regulators, were rarely used and therefore not included in this study. There were 15, 5, 5, and 12 different active ingredients of OP, pyrethroid, oils, and Bt, respectively, reported in the PUR for almonds (Table 1). "Other insecticides" are referred to as any insecticide that did not belong to the previous groups. There were 52 reported active ingredients in this "other" category. "Oils" is a heterogeneous category and can be used as adjuvants, insecticides, fungicides, or for other purposes. In the winter season, oils are typically used as dormant insecticide applications. In this study, the category "oil alone" was defined as any non-adjuvant oil applied to fields that did not receive any application of OP, pyrethroid, carbamates, Bt, or spinosad during the defined dormant period. Dormant oil without other insecticides is one low risk alternative to dormant OP.

The dormant season was defined as December 10–March 20 of the following calendar year, while in-season use was defined as March 21–December 9 of the same year. This dormant period was chosen to capture the most common dormant applications and bloom time Bt applications. For the weather data, the winter period was defined as November 1–March 20 because weather during that period can influence arthropod survival.

Weather information was obtained from the California Irrigation Management Information System (CIMIS, 2002), which administers and collects data from more than 100 computerized weather stations throughout California's agricultural counties. Although several weather stations may be located in a county, not all the weather stations have data continuously from 1991 to 2000. The criteria for selecting the weather station in each county were (1) the proximity of the station to county almond-growing areas, and (2) continuity of data from 1991 to the present. Descriptions of each station used in the study are provided in Table 2.

Since little documentation exists to provide quantitative information about historical pest damage or pest population, we used percent nut rejects as an indicator for pest pressure. The percent of nut rejects were obtained from the Almond Board of California for each county. Most of the rejects were due to damage by PTB, navel orange worm (NOW), and ants.

2.2. Measures and methods

2.2.1. Measures of pesticide use

There are many ways to measure pesticide use and weather conditions. In this study, measures of pesticide use include kilogram of active ingredient (AI) applied, kilogram of AI per hectare crop planted (includes both bearing and non-bearing acres), cumulative hectare treated, hectare treated per hectare crop planted, percent hectare treated, and number of growers using pesticides (Table 3). The kilogram of AI per

Table 1
All reported insecticide active ingredients applied to almonds from 1992 to 2000 and their class

Active ingredient	OP	Pyrethroid	Oil	Bt
Azinphos methyl	Y			
Chlorpyrifos	Y			
Ddvp	Y			
Diazinon	Y			
Dimethoate	Y			
Disulfoton	Y			
Ethoprop	Y			
Fenamiphos	Y			
Malathion	Y			
Methidathion	Y			
Methyl parathion	Y			
Naled	Y			
Parathion	Y			
Phosalone	Y			
Phosmet	Y			
Cyfluthrin		Y		
Esfenvalerate		Y		
Permethrin		Y		
Pyrethrins		Y		
Tau-fluvalinate		Y		
Mineral oil			Y	
Petroleum distillates			Y	
Petroleum distillates, refined			Y	
Petroleum hydrocarbons			Y	
Petroleum oil, unclassified			Y	
Bacillus thuringiensis (Berliner)				Y
Bacillus thuringiensis (Berliner), subsp. *aizawai*, Gc-91 protein				Y
Bacillus thuringiensis (Berliner), subsp. *aizawai*, serotype H-7				Y
Bacillus thuringiensis (Berliner), subsp. *kurstaki* strain Sa-12				Y
Bacillus thuringiensis (Berliner), subsp. *kurstaki*, serotype 3a,3b				Y
Bacillus thuringiensis (Berliner), subsp. *kurstaki*, strain Eg 2348				Y
Bacillus thuringiensis (Berliner), subsp. *kurstaki*, strain Eg2371				Y
Bacillus thuringiensis (Berliner), subsp. *kurstaki*, strain Sa-11				Y
Bacillus thuringiensis, subsp. *kurstaki*, genetically engineered strain Eg7841 lepidopteran active toxin				Y
Bacillus thuringiensis, subsp. *kurstaki*, strain Hd-1				Y
Bacillus thuringiensis, var. *kurstaki* delta endotoxins cry 1a(C) and cry 1c (genetically engineered) encapsulated in *Pseudomonas fluorescens* (killed)				Y
Encapsulated delta endotoxin of *Bacillus thuringiensis*, var. *kurstaki* in killed *Pseudomonas fluorescens*				Y

hectare crop planted were used for more detailed regression and correlation analyses because this measure removes the effect of differences in hectare crop planted when comparing use among different counties.

2.2.2. Measures of weather

Two types of winter weather variables: temperature and rainfall were used in the study (Table 3). Three different measures were associated with temperature: cumulative chilling hours, minimum air temperature, and average air temperature. Cumulative chilling hours were the sum of hourly temperatures, T_{hr}, below the threshold temperature, T_{th}, that is

$$\text{chilling hours} = \sum_{\mathrm{hr}=A}^{B} \max\,(T_{\mathrm{th}} - T_{\mathrm{hr}}, 0)$$

Table 2
Weather station descriptions (source: CIMIS website)

Station code	Station name	Nearby city	County	Starting date	Latitude	Longitude	Elevation (ft)
2	FivePoints	FivePoints	Fresno	7 June 1982	36.336	−120.113	285
5	Shafter	Shafter	Kern	1 June 1982	35.533	−119.281	360
8	Gerber	Gerber	Tehama	22 September 1982	40.045	−122.164	250
12	Durham	Chico	Butte	19 October 1982	39.609	−121.823	130
27	Zamore	Woodland	Yolo	5 December 1982	38.808	−121.908	50
30	Nicolaus	Nicolaus	Sutter	3 January 1983	38.871	−121.545	32
32	Colusa	Colusa	Colusa	13 January 1983	39.226	−122.024	55
61	Orland	Orland	Glenn	13 May 1987	39.692	−122.152	198
70	Manteca	Manteca	San Joaquin	21 November 1987	37.835	−121.223	33
71	Modesto	Modesto	Stanislaus	25 June 1987	37.645	−121.188	35
80	FresnoState	Fresno	Fresno	3 October 1988	36.821	−119.742	339
86	Lindcove	Lindcove	Tulare	31 May 1989	36.357	−119.059	480
92	Kesterson	Gustine	Merced	13 October 1989	37.033	−120.88	75

Some weather variables included in this database are maximum, average and minimum temperatures, rainfall, wind speed and direction, relative humidity, solar radiation, soil temperatures.

Chilling hours were calculated with two different threshold temperatures, −1 and 5.5 °C, and for two different time periods (November 1–March 20 and January 15–February 15) (Table 3). Average temperature and minimum temperature during the period November 1–March 20 were used. These different temperature measures represented different ways that temperature could affect arthropods (Zalom, pers. commun., 2002).

Two different measures were associated with rainfall: total amount of rainfall and number of rain days. Both rainfall measures were calculated over the two winter season periods: November 1–March 20 and January 15–February 15. Total rainfall referred to the sum of daily rainfall in inches, while number of rain days referred to the number of days with rainfall greater than 0. Although we used weather information from only one station in each county, in most of the

Table 3
Variable descriptions

Variables	Descriptions
Kilogram	Sum of reported kilogram of active ingredient (AI) applied
Kilogram per hectare planted	Sum of kilogram of AI applied divided by hectare planted
Cumulative hectare treated	The sum of hectare treated from all applications even when the same field is treated more than once
Hectare treated per acre planted	Cumulative hectare treated divided by hectare planted
Percent areas treated	The sum of base hectare treated for all almond fields divided by hectare planted, where base acres treated of a field is the maximum of the cumulative acres treated for the field and the hectare planted for the field
Number of growers	The number of almond growers reporting use of a particular pesticide or pesticide type to DPR where a grower is distinguished by the last seven characters of the grower_id
Dormant 30° chilling hours	The sum of hourly temperatures in Fahrenheit, T_{hr}, below the threshold temperature 30 °F during the period November 1–March 20, that is chilling hours $= \sum_{\mathrm{hr}=A}^{B} \max(30 - T_{\mathrm{th}}, 0)$
Dormant 40° chilling hours	The sum of hourly temperatures below 40 °F during the period November 1–March 20
January 30° chilling hours	The sum of hourly temperatures below 30 °F during the period January 15 and February 15
January 40° chilling hours	The sum of hourly temperatures below 40 °F during the period January 15 and February 15
Rainfall	Sum of the daily rainfall in inches during the period November 1–March 20
Rain days	Number of the days that had any rainfall during the period November 1–March 20
Average temperature	Daily average temperature during the period November 1–March 20
Minimum temperature	Daily minimum temperature during the period November 1–March 20

All measures of pesticide use and almond acres planted are from the PUR.

almond-growing regions, the within-county variation in weather is fairly small.

Occasionally, CIMIS data had missing or erroneous values. We replaced these missing or erroneous values with interpolated values. For daily average temperature, we interpolated using a straight line from the value on the day previous to a set of missing or erroneous values to the value on the first day after that set. The daily rainfall for any missing or erroneous value was set to the average rainfall during its month using valid daily rainfall data reported for that month. For the hourly temperature data, we did not use linear interpolation if there were more than six consecutive hours of missing or erroneous data because the daily temperature pattern usually follows a cyclical pattern. If there were more than 6 h of erroneous data, the cumulative chilling hours for that day was treated as missing. If there were 6 h or less of erroneous data, we estimated the missing hourly temperatures with linear interpolation. We then calculated the cumulative chilling hours for each day estimating the missing daily cumulative chilling hours using linear interpolation.

2.2.3. Experimental design and statistical analyses methods

The PUR data were a census of production agricultural pesticide use in California, covering all applications of all pesticides. We used the county as the basic unit for the assessment because of interest expressed by the agricultural community, and because there may be significant differences between counties. These differences are due not only to climatic differences but also to the variations of pest management recommendations by regional farm advisors.

Regression analyses were used to examine pesticide use trends, while correlation analyses were used to investigate the associations among temperature, rainfall, nut rejects, and the different pesticide types using data aggregated at county level. The regression slopes and the percent changes based on the linear regression slope were used to compare the trends use among counties from 1992 to 2000.

Correlations were performed for dormant and in-season insecticide use, as measured by kilogram per hectare planted, percent almond nut rejects and winter weather variables. For the latter two variables, data from the same year of pesticide use and data from the previous year were examined. Region-wide measures of temperature, rainfall, and percent rejects were calculated as weighted sums of the county level measures, using acres planted in almonds as the weighting factor. For example

$$R_{\text{region}} = \frac{\sum_c A_c R_c}{\sum_c A_c}$$

where R_{region} is the region-wide rainfall, A_c the almond acreage in county c and R_c is the rainfall in county c.

A GIS was used to visualize the spatial distribution of the pesticide use trends in California among counties (Zhang and Wilhoit, 2001). The GIS is a computer system designed to retrieve, store, analyze and display spatial data and is a powerful tool for understanding the spatial distributions and patterns of OP use.

2.3. Data quality

Despite the extensive error checking of the PUR data before it gets into the database, errors still occasionally appear. For this study, we performed additional error checking and data cleaning on several PUR variables. These variables include rates of use, grower identifications and site location identification. These error checking procedures are described more completely in Wilhoit et al. (2001).

Unusually high rates of use (kilogram of AI per hectare treated) were replaced with the median rate for that pesticide product on almonds. A rate of use was considered unusually high if it was greater than (1) 224 kg of AI per hectare treated, (2) 50 times the median kilogram of product per hectare for all uses of that product on almonds, or (3) a value determined by a neural network (Wilhoit et al., 1999, 2001).

The effect of replacing outlier rates with median rates on total kilogram of AI used statewide was less than 6.5% for all years. For most counties, the percent difference between total actual reported kilogram of chemicals with total kilogram in which outlier values were replaced with values calculated from median rates was less than 10% and most of these were in 1992 and 1993. Less than 0.55% of the PUR records had an extremely high rate of use for each year from 1992 to 2000 when we compared the original data with the cleaned data. This percentage was less than 1% for all years and counties of interest except in three situations, the highest being 3.5% error rate in Tehama in 1999.

The data cleaning procedures for grower identifications had no effect on number of growers for all years after 1992 in all counties except for Stanislaus, Sutter, and Yolo Counties. The error rate in these three counties varied between 0.05 and 3.5% in different years. In 1992, the statewide error rate was 0.68%. In contrast, the data cleaning procedures on site location identification had a fairly large effect on the apparent number of almond fields. The years with the largest number of errors were from 1995 to 1999, with 7 to 14% change in the number of fields statewide. The years with the fewest number of errors were 1994 and 2000, with only 0.1% change in number of fields for all counties.

The almond acreage calculated from the PUR using the data cleaning procedures differed from the almond acres reported by California Agricultural Statistical Service (CASS) between 0.14 and 4.0% each year between 1993 and 2000 except that, in 1992, the PUR calculated acres planted were 16% higher than the CASS acres. In general, the PUR data are of good quality for the analysis when we aggregate at the grower, county, and state levels.

3. Results

3.1. Trends and patterns of pesticide use

3.1.1. Dormant season

Statewide, almond dormant OP use decreased each year at 0.099 kg/ha crop planted, which was a 80% reduction from 1992 to 2000 (Fig. 2). A similar decrease was found when pesticide use was measured by percent areas treated and number of growers (Fig. 2). This decrease, as measured by kilogram of AI per hectare crop planted, was statistically significant statewide and for each major almond county except Sutter. When measured by hectare crop treated, this decrease was statistically significant for all the counties in the region. Above 0.112 kg/ha planted annual reduction of OP use was found in the counties of Fresno, Kern and Stanislaus, while below 0.067 kg/ha planted annual reduction was found in the counties of Sutter and Yolo (Fig. 3a). The annual decrease for the other counties was between 0.067 and 0.112 kg/ha planted (Fig. 3a).

In contrast, the use of the main alternative practice to dormant OP, no treatment with insecticides, increased from 1992 to 2000 (Fig. 2). From 1992 to 1994, dormant OP was by far the most commonly used insecticides to control overwintering almond pests. During this period, OP was applied to 40–50% of the almond acreage (Fig. 2, CDPR, 2001). In 1992, dormant OP was used on over 20 times more areas than pyrethroid or oils alone, and nine times more acreage than Bt (Fig. 2). In 2000, both dormant season pyrethroid (16% of the total almond acreage) and Bt were used on more almond areas than OP (Fig. 2). In 1992, no dormant insecticide use was 35% of the total almond areas, but by 2000, 57% areas received no dormant treatments (Fig. 2).

The use of dormant pyrethroid, another alternative to dormant OP, generally increased by all measures from 1992 to 2000 (Fig. 2). The annual statewide increase use was 0.0022 kg/ha planted almonds. In kilogram per hectare treated, the increase was statistically significant statewide at 150%, and in four out of 13 major almond-growing counties showed statistically significant increases (Fig. 3b). The counties with the largest percent increase of dormant pyrethroid were Fresno, Kern, Madera, and Tulare (Fig. 3b) in the San Joaquin Valley. On the other hand, the use of dormant pyrethroid declined in Sutter, Yolo, Glenn, and Butte in the Sacramento Valley (Fig. 3b).

Interestingly, use of dormant oil alone increased as measured by percent areas treated and number of growers, but fluctuated from year to year in kilogram per hectare crop planted (Fig. 2). Kern County had the largest percent increase, and Glenn, Yolo, and Madera had the largest percent decrease in dormant oils alone. However, there was no significant overall trend in the use of bloom time Bt, another alternative to OP, by any measure during the entire period 1992–2000 (Fig. 2). The use of Bt increased statewide from 1992 to 1995, but generally decreased after that.

3.1.2. Growing season

In-season almond OP use decreased statewide from 1992 to 2000 as measured by kilogram of active ingredients per planted hectare almond, percent areas treated, and number of growers (Fig. 4). Most of the reduction occurred between 1997 and 2000. Statewide, a statistically significant 34% reduction of OP use occurred from 1992 to 2000, which is

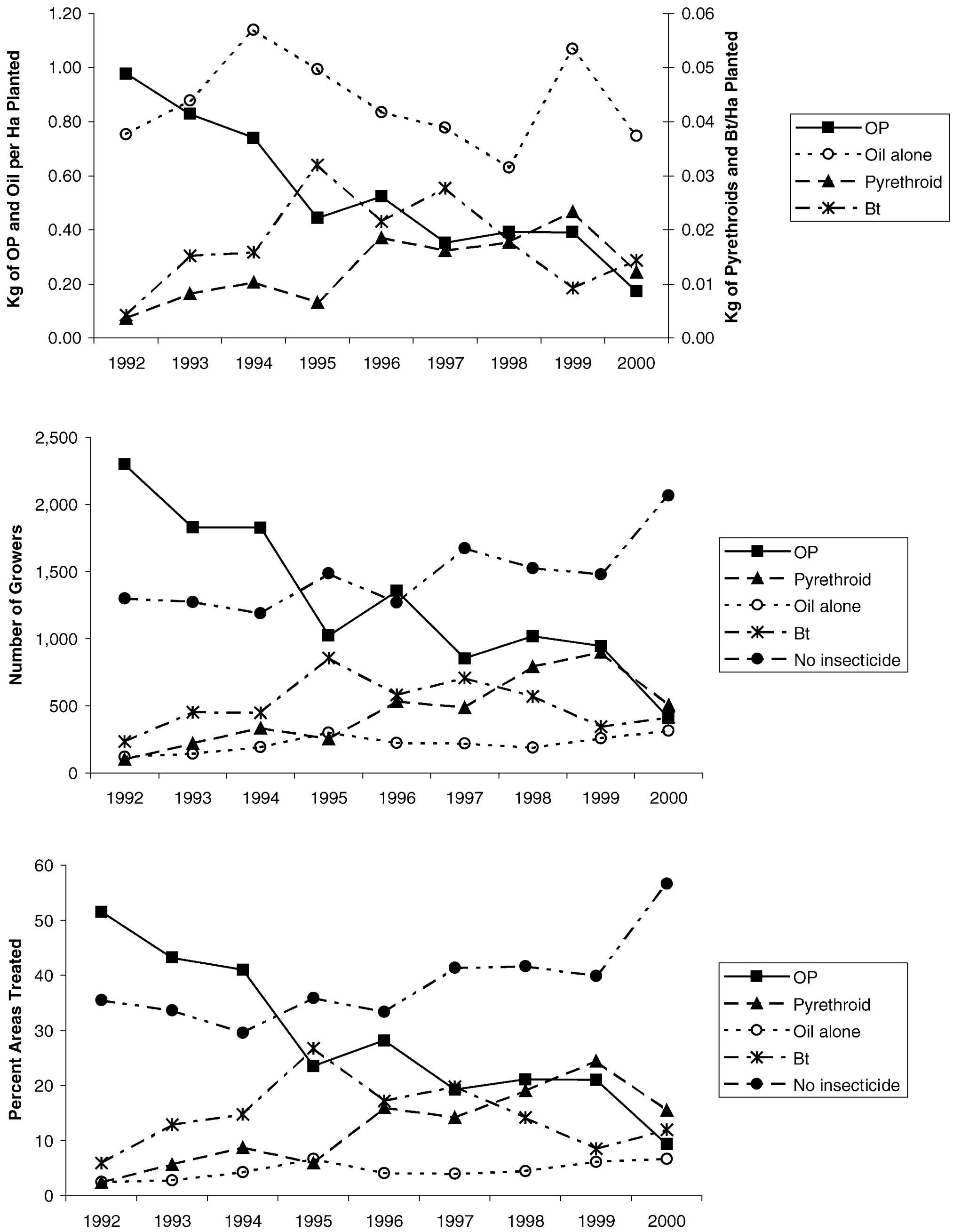

Fig. 2. Kilogram of AI per hectare almond planted, percent of almond areas treated and number of almond growers using various dormant season insecticide practices.

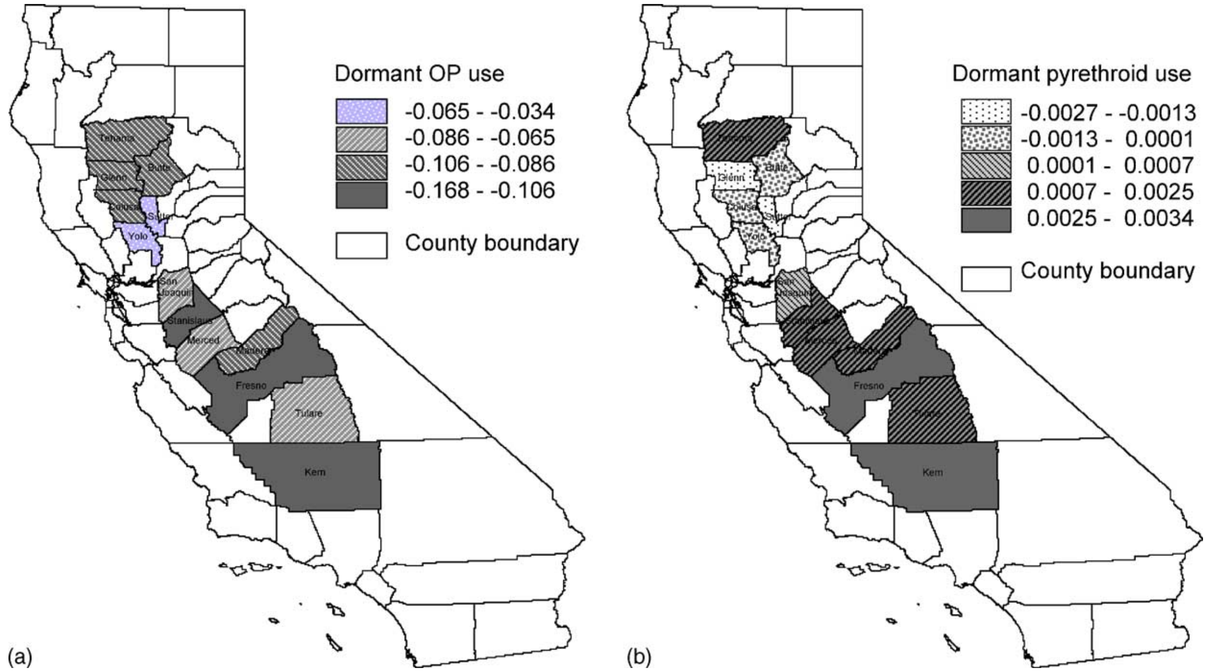

Fig. 3. (a) Trend of OP use between 1992 and 2000 in California almond-growing counties during the dormant season. (b) Trend of pyrethroid use between 1992 and 2000 in California almond-growing counties during the dormant season. The different shadings represent different levels of slopes (change per year).

equivalent to an annual reduction of 0.041 kg/ha crop planted. The decreases were significant for six out of the 13 major almond-growing counties. The counties with significant percent reduction of in-season OP use were Colusa, San Joaquin, Stanislaus, Merced, Madera, and Fresno, and their annual reductions were 0.034, 0.056, 0.055, 0.070, 0.108, and 0.080 kg/ha crop planted, respectively (Fig. 5a), while the almond yields did not change significantly (Almond Board, 2001).

Although there were variations in use, the in-season use of pyrethroid, oil alone, and Bt showed a general increased trend from 1992 to 2000 in all measures (Fig. 4). In-season pyrethroid increased by 120% or annual increase of use at 0.002 kg/ha planted, and oils alone annual increase of use at 0.02 kg/ha planted in the period of 1992–2000. The percent area treated and number of growers using no in-season insecticides fluctuated from year to year. Counties with significant percent increases of in-season pyrethroid were Kern, Madera and Merced (Fig. 5b). The in-season increase of pyrethroid use mostly occurred in San Joaquin Valley counties while counties in Sacramento Valley had no significant changes.

3.2. Relationship between weather and pesticide use

The correlation of pesticide use and the winter weather showed that, for the major almond-growing region, reduction of dormant OP and oil alone uses was related to increased amount of winter rainfall and warmer temperature (Table 4). The use of dormant pyrethroid or Bt was the opposite to the dormant OP when they were related to winter rainfall and temperature. These patterns were similar from county to county. However, there were fewer significant or consistent patterns in correlations between winter weather and in-season insecticide use. The correlation of pesticide use with the previous year winter weather showed consistent results as for the same year winter weather.

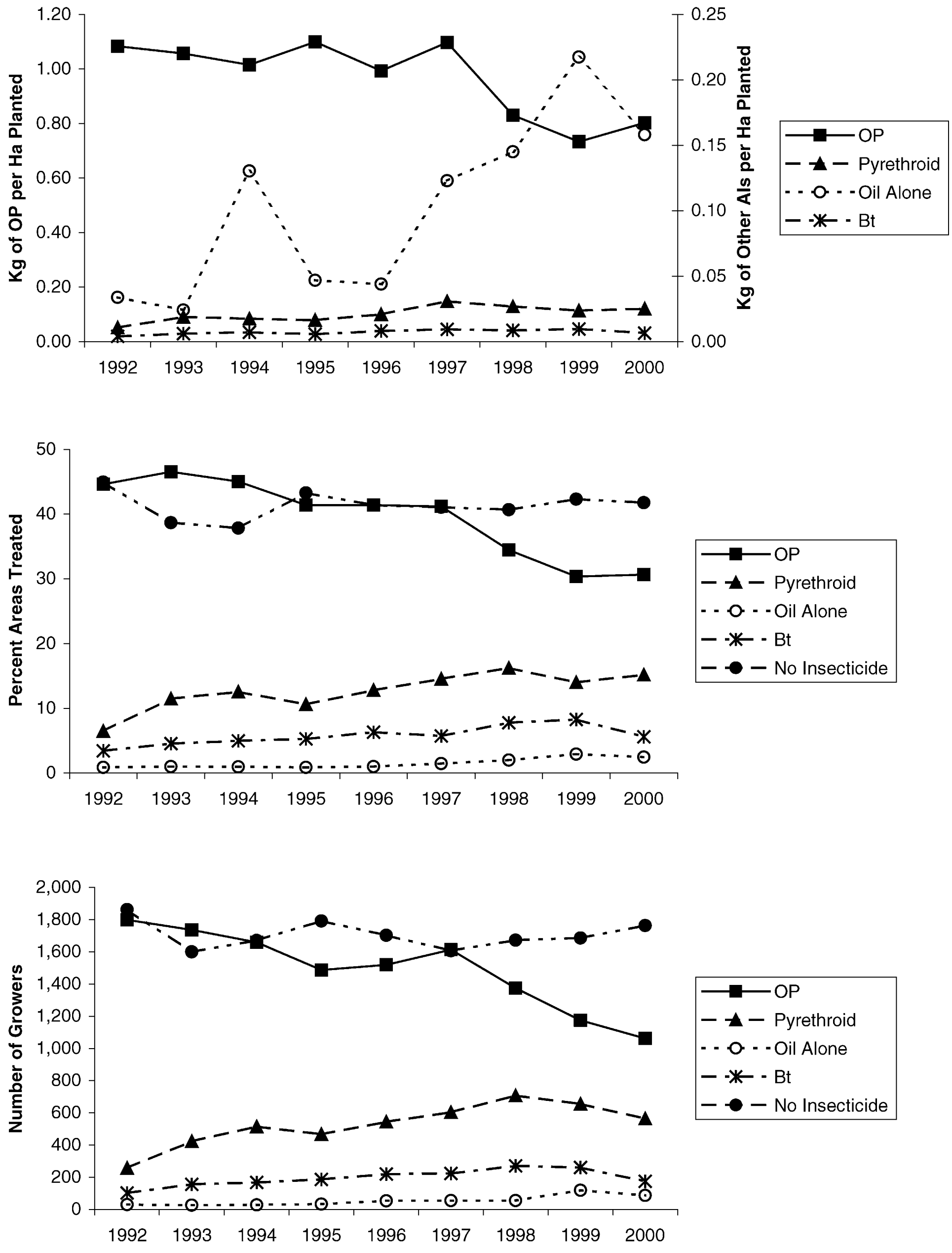

Fig. 4. Kilogram of AI per hectare almond planted, percent of almond areas treated and number of almond growers using various in-season insecticide practices.

The relationships between in-season insecticide use and previous year's winter weather were similar to the relationships with dormant insecticide use, except for Bt. In-season Bt use was positively correlated with previous year's winter rainfall and temperature, and nearly all correlations were statistically significant for most individual counties. The use of Bt appeared to be more weather-dependent than other pesticides.

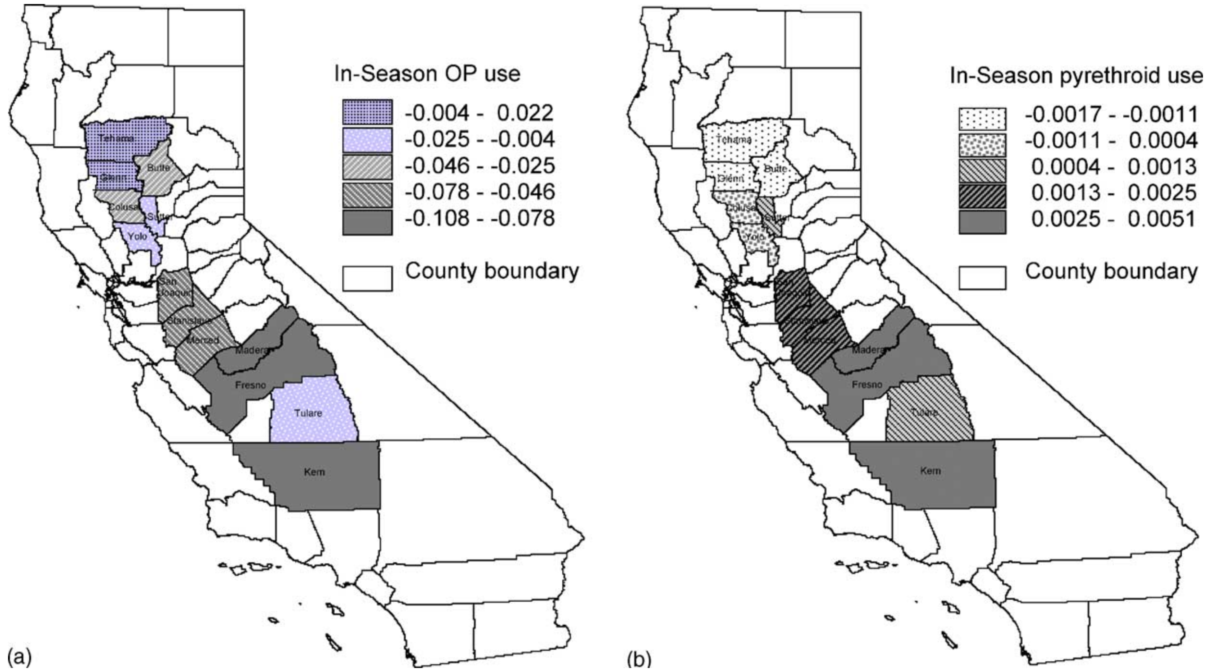

Fig. 5. (a) Trend of OP use between 1992 and 2000 in California almond-growing counties during the growing season. (b) Trend of pyrethroid use between 1992 and 2000 in California almond-growing counties during the growing season. The different shadings represent different levels of slopes (change per year).

3.3. Relationship between percent almond rejects and pesticide use

Using nut rejects as an indicator for pest pressure, we found no correlations between the percent nut rejects and dormant OP use. However, a positive sign was observed for the correlation in nearly all the 13 counties. This positive sign suggests that pest densities and populations were considered when using OP. For the use of pyrethroid, there were statistically significant positive correlations between percent rejects and the next year's dormant pyrethroid use in the major almond-growing region ($r = 0.82$, $P < 0.05$) and in Butte County ($r = 0.78$, $P < 0.05$). The results indicated that the use of dormant pyrethroid increased when higher nut rejects were observed in the harvest. In Glenn County, farmers seemed to respond the higher nut rejects with increased dormant oil use ($r = 0.8$, $P < 0.05$). In San Joaquin County, farmers reduced dormant Bt use when the higher nut rejects were observed ($r = -0.73$, $P < 0.05$).

For the growing season, there were statistically significant positive correlations between percent nut rejects and the following year's growing season OP use in Colusa County ($r = 0.76$, $P < 0.05$); pyrethroid use in Butte County ($r = 0.76$, $P < 0.05$), and Bt use in Glenn County ($r = 0.93$, $P < 0.01$), all in the Sacramento Valley. Farmers responded to the higher nut rejects by applying more in-season OP in Colusa County, by applying more in-season pyrethroid in Butte County, and by applying more in-season Bt in Glenn County.

3.4. Relationships among pesticide use variables

3.4.1. Within-season associations in pesticide use

The largest negative correlation was found between dormant OP and dormant pyrethroid. This relationship was strongest in Kern and Fresno counties, which indicated that the reduction of OP use in both counties was clearly replaced by pyrethroid. The reduced OP use was replaced by Bt use in San Joaquin County,

Table 4
Counties with significant positive and negative correlations between their dormant insecticide use and several weather measures, and among dormant insecticide use

OP	Pyrethroid	Bt	Oil alone[a]
Chilling hours			
Kern: chill40j (+0.73*); Madera: chill40j (+0.83*); San Joaquin: chill40j (+0.77*), chill40j (+0.71*)	Tulare: chill40 (+0.90*)	Madera: chill40 −0.78*); San Joaquin: chill40j (−0.70*); Sutter: chill40j (−0.77*); Yolo: chill40 (−0.72*), chill40j (−0.73*)	Almond region: chill40(+0.70*), chill30j (+0.81**), chill40j (+0.71*); Butte: chill30 (+0.72*), chill40 (+0.72*); San Joaquin: chill40j (+0.82*); Stanislaus: chill30 (+0.81*)
Temperature			
Almond region: tave (−0.70*)	Tulare: tmin (−0.88*)	Madera: tmin (+0.71*), tave (+0.67*); Sutter: tmin (+0.73*); Yolo: tmin (+0.72*), tave (+0.75*)	Almond region: tmin (−0.74*) tave (−0.73*); Butte: tave (−0.82**); San Joaquin: tmin (−0.68**)
Rain			
Madera: dayj (−0.69*); San Joaquin: dayj (−0.80*)	Tulare: fallj (+0.82*)	Butte: fall (+0.68*), fallj (+0.69*); Glenn: fall (+0.93**), day (+0.80**); San Joaquin: dayj (+0.69*); Sutter: fallj (+0.77*), dayj (+0.81*); Tehama: fall (+0.95**), day (+0.64*), fallj (+0.79*)	Almond region: fall (−0.79**); Madera: fallj (−0.67*); San Joaquin: fall (−0.82**), day (−0.75*)
OP			
	Fresno (−0.92**); Kern (−0.76*)	San Joaquin (−0.88**)	Madera (+0.85**)
Pyrethroid			
		Sutter (−0.81*)	Kern (+0.67*); Stanislaus (+0.86**); Tehama (+0.81*)
Bt			
			Tulare (−0.88**)

A positive correlation between use and chilling hours is a negative correlation between use and temperature. The almond region covers the 13 counties where most almonds are grown. Numbers in parentheses are the correlation coefficients.

[a] Temperature measures— chill30: 30° chilling hours; chill40: 40° chilling hours; chill30j: January 30° chilling hours; chill40j: January 40° chilling hours; tmin: minimum temperature; tave: average temperature. Rain measures—fall: dormant rainfall; day: dormant raindays; fallj: January rainfall; dayj: January raindays.

* Significance level: $P < 0.05$.

** Significance level: $P < 0.01$.

and was accompanied by reduced oil use in Madera County (Table 4). The replacement of any other alternatives among the counties was not as clear.

The reduction of in-season OP was likely replaced by other alternatives such as pyrethroid, oils alone and Bt. These other uses were positively correlated among themselves (Table 4). The use pattern varied in different counties except that the use pattern in most northern San Joaquin Valley counties was similar to that in the region-wide. From the state viewpoint, the reduced OP use was accompanied by increased Bt use, while Bt use may be selected over the pyrethroid use.

3.4.2. *Between-season associations in pesticide use*

Statewide, the reduced use of OP was associated with the reduced use of OP in-season, but related to the increased use of in-season pyrethroid, oil alone, and Bt (Fig. 2, Table 5). The increased use of dormant pyrethroid was related to reduced in-season OP use and increased in-season pyrethroid, oil alone, and Bt use. A reduction of dormant OP use did not cause an increased use of dormant OP in the following year; rather it was related to an increased use of dormant pyrethroid in the following year (Table 5). The correlations between dormant OP and next year's in-season insecticide use were similar to that between dormant

Table 5
Counties with statistically significant correlations between their dormant insecticide use and in-season use and the following year's dormant use

	Dormant OP	Dormant pyrethroid	Dormant Bt	Dormant oil alone
In-season				
OP	Butte (+0.75*), Colusa (+0.81*), Merced (+0.81**), San Joaquin (+0.73*), Yolo (+0.76*)	Almond region (−0.68*)		Madera (+0.80*)
Pyrethroid	Almond region (−0.79*), Butte (+0.73*), Kern (−0.71*), Madera (−0.72*), Stanislaus (−0.75*)	Almond region (+0.71*), Kern (+0.97**), Yolo (−0.83*)		Madera (−0.75*)
Bt	Fresno (−0.74*), Glenn (+0.78*), Madera (−0.70*), Stanislaus (−0.71*)	Merced (+0.86**), Fresno (+0.87**)	Madera (+0.78*)	Madera (−0.72 *)
Oil alone	Fresno (−0.66*), Stanislaus (−0.80**)	Almond region (+0.69*), Fresno (+0.76*), Merced (+0.81**), San Joaquin (+0.85**), Sutter (+0.96*)	Stanislaus (+0.78*)	
Next year's				
Dormant OP	Fresno (+0.91**), Merced (+0.97**), Stanislaus (+0.79*), Almond region (+0.83*)	Almond region (−0.91*), Fresno (−0.89**), Kern (−0.86**), Madera (−0.85**), Merced (−0.86**), Stanislaus (−0.84**)	Stanislaus (−0.79*), Sutter (+0.80*)	
Dormant pyrethroid	Almond region (−0.78*), Fresno (–0.86**), Kern (−0.86**), Madera (−0.72*), Yolo (+0.89*)	Fresno (+0.81*) Kern (+0.92**)	Tehama (+0.76*)	San Joaquin (−0.74*)
Dormant Bt		Tulare (−0.90*)		
Dormant oil alone	Madera (+0.83*)	Kern (+0.71*), Madera (−0.78*), Tulare (+0.99**), Yolo (+0.97**)		Colusa (+0.86**), Madera (+0.71*)

Pesticide use is measured by kilogram of AI per acres planted for the each pesticide type. Numbers in parentheses are the correlation coefficients.

* Significance level: $P < 0.05$.

** Significance level: $P < 0.01$.

OP and the same year's in-season insecticide use. Similarly, the correlations between dormant pyrethroid and the next year's in-season insecticide use were similar to that between dormant pyrethroid and the same year's in-season insecticide use (Table 5) for most counties.

In analyzing the percent of growers who used dormant OP, we found that the percent of growers who continued to use dormant OP from 1 year to the next declined from 67% in the 1993 to 29% in 2000 (Fig. 6). The percent of growers who switched from dormant OP in 1 year to no dormant insecticides in the next year increased from 18% in 1993 to 38% in 2000. The percent of growers who switched to other insecticides fluctuated from year to year but remained around 20% in the last decade (Fig. 6).

Similarly, the growers who used reduced-risk alternatives to dormant OP did not use more in-season insecticides. The percent of growers who used dormant and in-season OP, decreased from 56% in 1992 to 43% in 1999. An average 35% of growers who used dormant OP applied no in-season insecticides in the last decade. The percent of these growers that applied in-season pyrethroid, increased from 8% in 1992 to 26% in 1998. The in-season pesticide use among growers who applied dormant pyrethroid was similar,

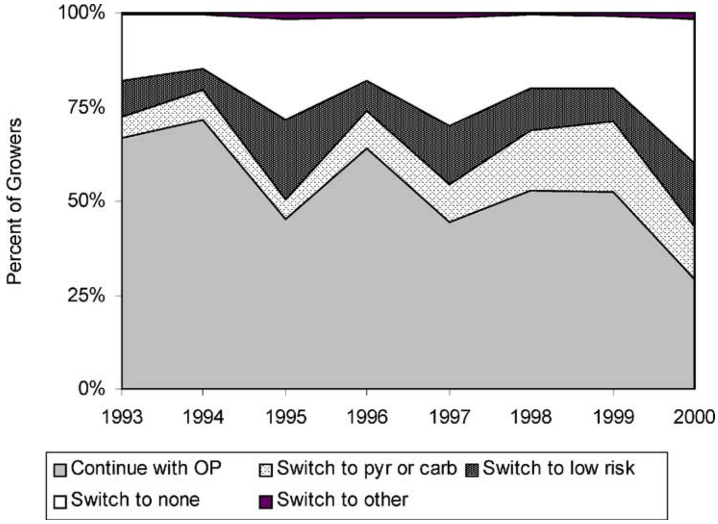

Fig. 6. The percent of almond growers each year in California that used dormant OP in the previous year and continued to use dormant OP in the current year; the percent that switched from dormant OP the previous year to (1) a dormant pyrethroid or carbamate, (2) a low risk pesticide (oil or Bt only), (3) no dormant insecticide, or (4) some other insecticide or combinations of insecticides.

except that the percentage using no in-season insecticides was less and the percentage that used in-season pyrethroid remained around an average of 25% from 1992 to 1998. The growers who used bloom time Bt treatments applied less in-season OP and pyrethroid and used more in-season Bt than growers who applied dormant OP and pyrethroid. The growers who used bloom time Bt treatments also increased the use of in-season Bt, from 19% in 1992 to 40% in 1999. These growers also increased the use of in-season pyrethroid, but not other alternatives. About 50% of growers who used only dormant oils applied no in-season insecticides and about 65% who used no dormant insecticides applied no in-season insecticides. However, the growers who used no dormant insecticides applied more in-season pyrethroid and less in-season OP.

4. Discussion

The significant declining trend of dormant OP use on almonds, whether it was measured by kilogram per planted hectare or by percent areas treated, illustrates the profound changes in pest management strategies in the California almond farm community (Grieshop and Raj, 1992; CDPR, 2001; Epstein et al., 2000, 2001; Swezey and Broome, 2001). The decrease of dormant OP use is probably a result of many complex factors (Hendricks, 1995; Flint et al., 1998; Epstein et al., 2001). Since almond production has been rather stable (CDFA, 2001) and the almond damage rate as measured by nut rejects stayed fairly constant during the last decade (Almond Board, 2001), these trends suggest that either the chemical alternatives to OP use were successful and/or almond growers focused on strategies that were less reliant on pesticides (Hendricks, 1995; National Research Council, 1996; Committee on the Future Role of Pesticide in US Agriculture, 2000; Thrupp, 2001). The reduced-risk and use programs funded by the government and universities may have played a role in the reduction of dormant OP use in California (Ehler and Botrell, 2000; Epstein and Bassein, 2002).

Given the almond production over the last decade (Almond Board, 2001), the decrease in dormant OP use was probably not due to growers who use OP leaving almond production and new growers starting production using alternatives. We found instead that growers were switching from using dormant OP to alternative practices (Fig. 4). In addition, growers were not generally replacing dormant OP use with in-season OP (Table 5).

The increased use of pyrethroid may be due to the inexpensive price, and the availability of the pesticide in the region. It also can be applied at the same times as dormant OP. However, the trends of Bt use are less clear-cut than the OP or pyrethroid trends. Bt use is affected by several factors. Growers spray Bt at bloom time (from February to March) to control peach twig borer, and at hull split (in July) to control navel orange worm. Despite its expense, growers sometimes favor Bt because it does not disrupt natural enemy populations or cause mite outbreaks, and because of its very low mammalian toxicity. It is understood that Bt cannot control a wide range of pests. Therefore, the fluctuation of using Bt may be explained by growers' choices of pesticides, weather patterns and the existing pests.

The most widely used alternative to dormant OP in recent years was no dormant insecticide. This may be because in some areas the overwintering pests were not a big problem or that in-season pesticide applications were sufficient to maintain almond productivity. In addition, it is possible that some growers find that they do not need to spray every year to get adequate control of wintering pests. The poorer economic conditions in the late 1990s could have also led growers to cut back on expenses such as pesticide applications. However, applying no dormant insecticides does not necessarily mean they are doing nothing else to control these pests. In fact, innovative farm practices, such as orchard sanitation and conserving beneficial arthropods in farm fields have been reported as effective ways to reduce the use of more hazardous pesticides (Hendricks, 1995; Bentley et al., 1996; Ruano et al., 2003). Growers who understand ecological farming principles and apply their local knowledge to farm pest management can often use less pesticide to achieve similar productivity (Thrupp, 2001). It is clear that the DPR and other agencies have promoted such an integrated approach in various projects during the 1990s (Swezey and Broome, 2001; Thrupp, 2001; CDPR, 2002) for the transition of developing new concepts of reducing/applying no dormant pesticide use.

The decline in OP use is good news for the many government agencies working to reduce OP surface water runoff. Although the relationship between dormant OP use and residues of OP in surface water depends on many factors, such as coincidence of rain and applications, distance from a river, and method of application, in general, one would expect less dormant OP use to result in less OP in surface water (Guo, 2003). Previous studies of OP runoff suggested that dormant OP use was a major source for surface water contamination (Domagalski et al., 1997; Dubrovsky et al., 1998).

There are several possible ways that temperature could affect arthropod populations. Some species may be able to survive long periods of relatively cold weather but not a short time at temperatures below some threshold. In this case, there might be no relationship between high cumulative chilling hours and mortality but a strong relationship between minimum temperature and mortality (Tables 4 and 5). On the other hand, some species may have the opposite reaction in which mortality increases with long periods of relatively cold temperatures but mortality is not affected by brief periods of very cold temperatures (Zalom, pers. commun., 2002). Some species such as peach twig borer may be most sensitive to weather in late January or early February because they sometimes emerge from their protective environments during that period. During the growing season, temperatures above or below optimal levels will slow the development of arthropods, which will affect the timing of different events. For peach twig borer in almonds, population size is probably not as important as timing of larval emergence relative to almond hull split.

Rainfall can have several possible effects on arthropod populations, but can limit application in field accessibility. For example, high rainfall creates muddy fields, making it difficult to get spray equipment into a field and possibly resulting in fewer dormant applications (Table 4). Some growers may respond to outreach from various agencies discouraging OP use during rainy periods due to surface water pollution concerns. There are additional social factors that will affect grower decisions such as what their neighbors do, what they have done in the past, and whom they trust to provide advice. Judging by conversations with various almond growers and industry leaders, the most important factors affecting grower decisions are probably market considerations, including commodity prices and pesticide costs (Chris Heinz, pers. commun., 2003).

Although correlation does not imply causality, it can tell us whether hypothetical causal explanations are consistent with observed relationships. For example, because we know it is difficult to spray in muddy fields, we expect a negative correlation between rainfall and dormant pesticide use. Consistent with our expectation, most correlations between rainfall and dormant OP or oil use were indeed negative. For reasons stated earlier, we might also expect colder winter temperatures to result in lower pest populations—and therefore less pesticide use—later in the same year or in the following year. The temperature accounted for about 50% of the variation in dormant pyrethroid use and about 70% of the variation of in-season Bt use (Table 4).

Percent rejects accounted for about 30% of the variation in dormant OP use and about 65% of the variation in dormant pyrethroid use in the following year. This suggests that growers may respond to finding higher rejects in their fields by applying more pesticides the next year. But when more insecticides were applied, percent rejects from the treated orchards were only somewhat lower. These results are not surprising because there are two conflicting effects involved in this relationship. First, growers may apply more pesticides in "problem" areas—areas with higher reject rates, leading to a positive correlation between percent rejects and pesticide use. Second, pesticide applications should reduce pest populations, which would lead to a negative relationship between rejects and pesticide use. Therefore, it is likely that the correlation between rejects and pesticide use in the period from 1992 to 2000 was weak.

The relationships among the uses of different insecticide types suggest that pyrethriods were generally replacing OPs at the county and region-wide level. To more fully understand the relationship between the uses of different insecticide types requires analysis at the field level.

Reduced dormant OP use does not necessarily mean that overall risk from pesticides has been reduced (Zalom et al., 2001). Lower dormant OP use could result in more pest damage, leading to more pesticide use later. For example, certain secondary pest populations previously suppressed by OP use could build up over time, causing economic damage. This has been the case in some San Joaquin Valley stone fruit orchards, which have seen an increase in katydids (*Scudderia furcata*) and cucumber beetles (*Diabrotica undecimpunctata*) since stopping OP use (California Tree Fruit Agreement, 2003). In addition, the use of dormant pyrethroid has increased and these chemicals carry their own set of environmental risks (Werner et al., 2002). Pyrethroid can disrupt natural enemy populations, causing outbreaks of mites or other secondary pests, thus potentially increasing in-season pesticide use (UCIPM, 2002). Some pyrethroid also pose hazards to bees and certain aquatic species, such as the fat head minnow (Werner et al., 2002).

Although nearly everyone considers Bt a reduced-risk alternative to dormant OP, it is in itself not a complete substitute because Bt controls only peach twig borer. Replacing dormant OP with Bt could result in increased scale and mite populations, which may then cause growers to use, for example, in-season OP to control scales or propargite (a probable carcinogen) to control mites (UCIPM, 2002).

The grower level analyses suggested that growers who used lower risk dormant season alternatives did not tend to use more OP or pyrethroid later, either in the in-season following the dormant season or in the following dormant season. This finding could mean that stopping OP use has not significantly worsened pest problems, and that alternatives to OP are working. To be conclusive, other analyses should be conducted to examine pesticide use patterns at the field level of resolution.

Although, we recognize that transport of pesticides by surface runoff during rainfall events is a major process contributing to pesticide contamination in rivers, dependence of pesticide load in surface water on precipitation and pesticide use has been well established (Larson and Gilliom, 2001; Guo, 2003). Guo (2003) reported that pesticide use and precipitation are two major environmental variables dictating the dynamics of pesticide transport into surface water in a watershed. Therefore, the decreasing trend of OP use should inevitably reduce the pesticide load in surface water to balance the agriculture and environment. This research allows further progress to be made in OP use reduction on other orchard crops in California. If almond crop grows in elsewhere with similar pest pressures and weather conditions, the finding in this research will apply as well.

5. Conclusions

This study clearly depicts the decline of dormant OP use in California almonds in the 1990s and showed that other alternatives were working successfully. These findings were demonstrated at the regional, county and grower levels. Although pyrethroid and Bt were the main replacement of OP, the degree and magnitude of the replacement varied from county to county. The reduction of OP use would reduce the impact to surface water quality. However, whether using the alternatives could reduce the risk of surface water contamination was unclear because the ecological risk of using pyrethroid has been recently documented.

It is also clear that a majority of almond growers practiced using various pesticide types to consciously or unconsciously avoid environmental impacts. While the factors of pest pressure, availability of pesticides, and weather patterns are important, we acknowledge that other variables such as pesticide and commodity prices ($3210 t^{-1} in USDA report (2001)), pesticide resistance, pest population size, and grower perceptions could also affect pesticide use trends in almonds. These data are needed to paint a complete picture of pesticide use trends and grower decision-making in almonds, and to assist efforts to promote sustainable agriculture.

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