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Evaluation of water quality in an agricultural watershed as affected by almond pest management practices

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ABSTRACT

In the last decade, the detection of organophosphate (OP) pesticides in the San Joaquin River watershed has raised concerns about water quality. This study examined the influences of almond pest management practices (PMPs) on water quality. The Soil and Water Assessment Tool (SWAT) model was employed to simulate pesticide concentration in water as affected by different PMPs. California Pesticide Use Reporting (PUR) data were used to investigate PMP use trends. Stepwise regression analysis was performed to test the correlation between specific PMP use and pesticide concentrations in surface water and sediment. Our results showed an increasing use of reduced risk pesticides and pyrethroids on almonds. SWAT simulation over the period of 1992–2005 showed decreases in OP concentrations in surface water. High OP and pyrethroid use in dormant sprays was associated with high pesticide concentrations in water and sediment. Almond pesticide use was proved to have significant impacts on the pesticide load in the San Joaquin River watershed. The PMP which combines the use of reduced risk pesticides with no dormant spray was recommended for almond orchard use. This paper presented a novel method of studying the environmental impacts of different agricultural PMPs. By combining pesticide use surveys with watershed modeling, we provided a quantitative foundation for the selection of PMPs to reduce pesticide pollution in surface water.

1. Introduction

California produces 99% of the US almond crop, 58% of which was located in the San Joaquin Valley in 2006 (CDFA and USDA, 2006). Major pests of almonds include navel orange worm (NOW), San Jose scale (SJS), peach twig borer (PTB), and European red and brown mite. Pest management practices (PMPs), such as the application of organophosphate (OP) pesticides and oil mixtures during the dormant season, are considered effective in controlling these pests (Rice et al., 1972; UCIPM, 1985). However, the dormant period, which is from December to February, coincides with the rainy season in California potentially causing off-site movement of OP pesticides to water bodies (Zhang et al., 2005; Bacey et al., 2005; Guo, 2003; Dubrovsky et al., 1998).

OPs such as diazinon and chlorpyrifos have been routinely detected in the surface water bodies of the San Joaquin River (SJR) watershed during the rainy season (Spurlock, 2002; Domagalski et al., 1997). Studies have indicated that runoff from orchards is a source of these OPs (Domagalski et al., 1997). Although aerial drift contributes to off-site movement, surface runoff is the main pathway by which OP pesticides

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are transported to the SJR (California Regional Water Quality Control Board Central Valley Region, 2006). Furthermore, recent findings revealed adverse effects of OPs on many species dependent on surface water quality for survival, such as the California red-legged frog, California tiger salamander, Delta smelt and many birds (Miller, 2006; Ross et al., 1999; Spurlock, 2002; Werner et al., 2002). The frequent detection of OP insecticides and their toxicity to species dependent on good water quality has resulted in increased regulation of OP use.

As a result of these increased restrictions on OP use, researchers and regulators have been in search of viable alternative pest management practices. The California Department of Pesticide Regulation (Elliott et al., 2004) and UC Statewide Integrated Pest Management Program (UC IPM) have proposed several alternative PMPs to the currently used dormant OP applications (Zalom et al., 1999), such as: (1) no dormant treatment with in-season sprays as needed (no dormant use); (2) dormant oil alone; (3) bloomtime sprays for peach twig borer; (4) reduced risk pesticides (e.g. spinosad) as a dormant spray; (5) conventional non-OP pesticides (e.g. pyrethroids); and (6) pheromone mating disruption. In addition, to promote the use of reduced risk pesticides, the US Environmental Protection Agency (USEPA) Office of Pesticide Programs proposed a list of more than 170 reduced risk or OP alternative pesticide products (USEPA, 2006). Despite these efforts, however, little work has been done to quantitatively evaluate the influence of the proposed PMPs and EPA-listed products on surface water quality, especially at watershed scale.

Additionally, there is a lack of literature addressing recent changes in almond pest management practices and their influence on surface water quality. Two studies have investigated the historical changes of PMPs. Epstein et al. (2001) used the Pesticide Use Reporting (PUR) data during 1992–1997 to investigate the changes in pest management practice in almond orchards during the dormant season. They found that the use of OPs decreased both in the acreage treated and by the percent of growers applying OP products, while the use of pyrethroid, BT, oil alone, and no dormant treatment increased. Another study further confirmed the decreasing trend of dormant OP use by analyzing the PUR data from 1992 to 2000 (Zhang et al., 2005). While these two studies provided important documentation on the changes of almond PMPs, they did not, however, cover the more recent changes in the years since 2000. In addition, none of the past research has studied the influence of almond PMPs on the environment, especially on surface water quality. Therefore, the two objectives of this paper were to (1) identify the use trends of traditional and alternative PMPs from 1992 to 2005; and (2) investigate the environmental impacts of the PMPs on surface water quality.

2. Materials and methods

2.1. Study area

The SJR watershed is an important agricultural production area located in the Central Valley of California, responsible for the drainage of 19,000 km^2 of primarily agricultural lands (Fig. 1). There are about 1480 km^2 of almond orchards within the SJR watershed, on which an annual average of 55,728 kg of OPs was used during 1992–2005 (CDPR PUR database, 2006). About half of the OPs were used in the dormant season. Many of the pesticides were sprayed on orchards close to impaired water bodies, which are listed on the Clean Water 303 d list due to the detections of two OP active ingredients, diazinon and chlorpyrifos. The considerable amount of pesticide use combined with the orchard proximity to the impaired water bodies (Fig. 1) points to almond orchards as being important potential sources of agricultural pesticide runoff. Since the SJR watershed and surface water bodies support municipal, industrial and agricultural water use in addition to providing habitat for fish and wildlife species, it is crucial to reduce the risk to this watershed of OP runoff from almond orchards.

2.2. Data sources

Pesticide use information from 1992 to 2005 was obtained from the PUR database maintained by the California Department of Pesticide Regulation (CDPR, 2006). The database records pesticide use information on every application of a pesticide in production agriculture and also applications from some non-agricultural entities. The database includes information on the amount of pesticide product used, the amount of active ingredient used, the application date, the planted area and the treated area. The following measures were used to assess the use trends of PMP. (1) Total reported amount of applied active ingredient (AI) (kg of AI); (2) total area treated from all applications even if the same field was treated more than once (ha treated); and (3) number of almond growers reporting use of a particular pesticide.

This study acquired other data for watershed modeling from various databases maintained by federal and state agencies. Weather data from 1990 to 2005 were obtained from the California Irrigation Management Information System (CIMIS, 2005). Soil data were obtained from the State Soil Survey Geographic database (SSURGO) maintained by the Natural Resources Conservation Service (NRCS, 2006). Land use data was obtained from EPA's Land Use and Land Cover (LULC) spatial data set (USEPA, 2007). Measured data of stream flow, sediment load and pesticide concentration were obtained from the National Water Information System (NWIS, 2007) maintained by USGS for the monitoring site in the San Joaquin River near Vernalis, California (USGS site ID 11303500).

2.3. PUR data quality

Although the PUR database is the best database available to reflect pesticide use in California, CDPR has developed error checking procedures which identify outliers and errors in variables including rates of use, grower identification and site location identification (Wilhoit et al., 2001). An error was identified if the record was considered to be a duplicate or if the unit for treated areas was anything other than square feet or acres. Once identified as an error, the record was deleted. An outlier was identified if the use rate was greater than (1) 1.12 kg ha^{-1} (200 lbs per acre) treated; (2) 50 times the median kg per ha treated for all uses of that product on

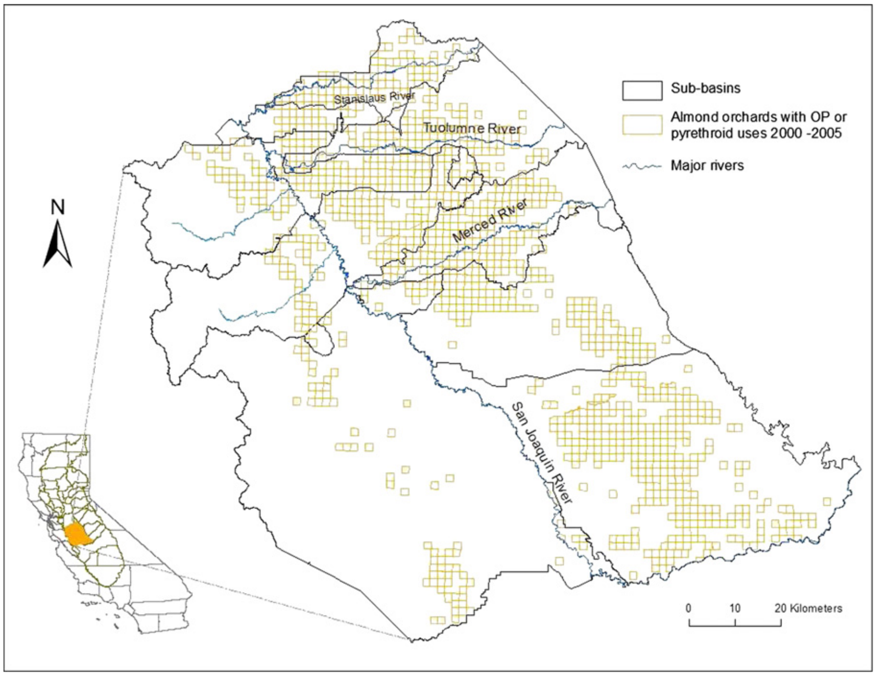


Fig. 1 – San Joaquin River Watershed.

almonds; and (3) a threshold value determined by a neural network (Wilhoit et al., 2001). Identified outliers were replaced with the median use rate (kg of AI per ha treated) of the same product on almond in the same year. For example, if a record in 1998 was identified as an outlier by the criteria described above, the use rate of this record denoted as Rate (old) will be replaced with the median rate of all the records on the same product in 1998 denoted as Rate (new). Therefore, the new value of kilograms of AI denoted as kg of AI (new) was calculated using the following equation

$$\text{kg of AI(new)} = \frac{\text{kg of AI(old)}}{\text{kg of product(old)}} \times \text{Rate(new)} \times \text{treated ha} \tag{1}$$

The data cleaning processes identified 2386 records as errors and 2694 as outliers out of total 625,875 records on almonds from 1992 to 2005. Therefore, errors and outliers account for 0.81% of the total records queried, indicating that the raw data in the database are of good quality.

2.4. *PMP scenarios*

In addition to traditionally used OP and oil combinations, pesticides used by almond growers in the past 14 years include pyrethroids, reduced risk pesticides (as identified by the Crop Protection Handbook, Meister and Sine, 2005), *Bacillus thuringiensis* (BT) pesticides, carbamates (Carb), pheromones, and other pesticides that do not belong to any of the previous groups (see Table S1 in the Supplemental Information). OPs, listed in descending order by the total amount of use during 1992–2005, included chlorpyrifos, diazinon, azinphos-methyl, phosmet, methidathion, naled, parathion, malathion, fenamiphos, methyl parathion ethoprop, dimethoate, acephate, phosalone, dicrotophos, and disulfoton. Pyrethrins and pyrethroids (PYs), in descending order of use, included permethrin, esfenvalerate, lambda-cyhalothrin, pyrethrins, cypermethrin, cyfluthrin, and tau-fluvalinate. Reduced risk pesticides included tebufenozide, methoxyfenozide, diflubenzuron, spinosad, pyriproxyfen, fenpyroximate and etoxazole, with tebufenozide and methoxyfenozide being the two most commonly used AIs. Oils included various petroleum oils, mineral oils and soybean oils. BTs included all registered strains and the encapsulated delta endotxoin of *B. thuringiensis*. Carbamates included carbaryl, methomyl, aldicarb and formetanate hydrochloride. Pheromones included (*E*)-5-decenyl acetate, (*E*)-5-decenol, *Z*-8-dodecenyl acetate, *E*,*E*-8,10-dodecadien-1-ol, *E*-8-dodecenyl acetate and *Z*-8-dodecenol.

Six almond PMPs were identified from the PUR database, labeled PMP1–PMP6 (Table 1). PMP1 is defined as the traditionally used dormant application of OPs and oil, PMP2 is a combination of OPs, PYs, and oil, PMP3 combines solely PYs and oil, PMP4 uses only oils, PMP5 only uses reduced risk controls, BT, pheromone, or controls listed under ''other'', and, finally, PMP6 eliminates dormant season applications all together, postponing pest treatment until after the rainy season. If reduced risk pesticides were used in combination with OP and PYs, the PMP was categorized into PMP1 (if with OP), PMP3 (if with PYs) or PMP2 (if with both OP and PYs).

Each of these PMPs has strengths and weaknesses in terms of effectiveness, economics, and environmental impact. While PMP1 and PMP2 are effective in controlling PTB, SJS, and aphids, their environmental impact is a problem due to the potential runoff of OPs. PMP3 eliminates OPs, but is less effective in controlling SJS. PMP4, which eliminates both OPs and PYs, is less effective in controlling both PTB and SJS. PMP5 uses reduced risk products which often are more expensive due to higher material costs and increased numbers of

Table 1 – Almond pest management practices

Pest management strategies	Code	Description
OP	PMP1	Traditional use of OPs in mixture with oil; effective for PTB, aphids and SJS.
OP + PY	PMP2	Uses of pyrethroid in combination with OP and Oil
PY	PMP3	Pyrethroid in mixture with oil, no OP application; not as effective as OPs for scale control; effective in most areas for PTB
Oil alone	PMP4	Only use oil to control European red mite eggs, brown almond mite eggs and low to medium populations of San Jose scale; this PMS cannot control peach twig borer or webspinning mites
Lower risk	PMP5	Uses of reduced risk, BT, pheromone or ''other'' pesticides as defined in Table S1 in the Supplemental Information
No dormant use	PMP6	Did not use any insecticides during dormant season, growers rely on monitoring and uses of insecticides during in-season

applications and monitoring. While BT and spinosad are effective against PTB and moderate levels of SJS, they are less effective in controlling aphids. Finally, PMP6 eliminates all pest control during the dormant season, but requires vigilant monitoring of pest pressure, and may not always be a feasible option for the grower.

2.5. *SWAT model calibration*

The Soil and Water Assessment Tool (SWAT) model was used to simulate the effects of the six PMPs on surface water quality. This model was developed to predict the impacts of land management practices on water, sediment and agricultural chemical yields at watershed scale (Neitsch et al., 2001) and has been successfully applied to simulate the hydrology of agricultural watersheds as well as their pesticide and nutrient loads (Larose et al., 2007; Hu et al., 2007). The SWAT model uses a number of submodels to predict runoff, pesticide movement, evapotranspiration, sediment transport and nutrient movement. Seven databases were constructed as inputs: soil, weather, land use, fertilizer, pesticide, tillage and urban land use. The output of the model provided information for predicting the loads of various pesticides on surface water for each year.

The hydrology and pesticide components of the SWAT model were accurately calibrated using monitoring data from the SJR watershed. A detailed description of the calibration processes was presented in our previous publication (Luo et al., in press). Daily simulations of the stream flow, sediment and pesticide loads were calibrated against monitoring data. The calibrated stream flow, diazinon and chlorpyrifos loads are shown in Figs. 2 and 3 as examples. The simulation from the hydrology components matched the actual measurements supplied by the monitoring data quite closely, with a Nash–Sutcliffe efficiency of 0.96 (Luo et al., in press, Fig. 2). Although monitoring data for pesticide loads (converted from concentration) was very limited, the simulated loads for diazinon and chlorpyrifos appeared to match well with measurement data from USGS (Fig. 3). The calibrated model was then used to predict the loads in surface water of the major OP and PY pesticides: chlorpyrifos, diazinon, permethrin and esfenvalerate, with pesticide use on almonds from 1992 to 2005. Given the non-point source nature of agricultural water pollution, the simulation was also performed with the pesticide use data for all the crops within the watershed, in order to better understand the environmental impacts of almond PMPs as compared with that of other commodities.

2.6. *Data analysis and statistical tests*

Based on the timing of applications reported in the PUR database, the PUR data were separated into two seasons: dormant and in-season. Dormant season was defined as December–February, while in-season was from March to November. Data on kilograms of AI and number of treated hectares were compiled first by each chemical group (OPs, PYs, reduced risk, BT, pheromone, other) and then grouped into each of the six PMPs. To understand the influence of the different PMPs on water quality, a stepwise regression analysis was then used to test the correlation between PMPs and the chemical concentrations predicted by the SWAT model for each season. Chemical concentrations were selected as the dependent variables, and kg of AI used by each PMP as independent variables. Two models were chosen to analyze concentrations in water and sediment, using the four major pesticides (chlorpyrifos, diazinon, permethrin and esfenvalerate), to determine the models with the best fit. PMP6 was not included in this analysis because this PMP by definition does not have kg of AI data. All the data were processed and analyzed using SAS 9.1.2 and Minitab 14.3.

3. Results

3.1. *Pesticide use trends*

During the dormant season, oil was the pesticide product with the highest kilograms of active ingredient (1.1×10^6 kg per year), followed by OPs with an average of 2.8×10^4 kg per year. Kilograms of PYs were just below OPs, increasing from 1.0×10^3 kg in 2000 to 2.4×10^3 kg in 2005. Kilograms of BT and carbamates decreased dramatically from mid 1990s to recent years. Reduce risk products showed an increase from negligible values in 2000 to 2.1×10^3 kg of AI in 2005 (Fig. 4).

Analyzing use trends by the number of hectares treated rather than by total amount offered a slightly different view, with pyrethroids and OPs changing ranks. While oil again ranked the highest (4.0×10^4 ha per year), PYs exceeded OPs since 1997 in terms of treated acreage, nearly doubling in amount from 2000 to 2005 (from 1.0×10^4 to 2.1×10^4). Hectares treated with OPs ranked third after PY, with little change over the time period (from 0.4×10^4 to 0.7×10^4). Similar to the analysis of total weights, the hectares treated with reduced risk pesticides showed a gradual increasing trend, ending

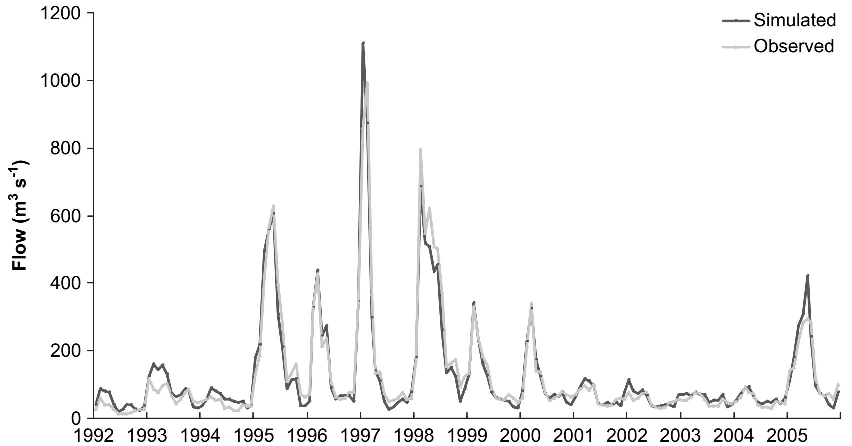


Fig. 2 – Monthly flow calibration of the SWAT model. The monthly average of stream flow rate was aggregated from daily data.

with 3.8×10^4 ha in 2005, which surpassed that of the OP group in the last year. Very few hectares were treated with BT, carbamates, or pheromones (Fig. 5).

In contrast to the chemical group trends, the trends of the almond PMPs experienced more dramatic fluctuations, as seen over the time period from 1992 to 2005 (Fig. 6). For the dormant season in 1992, the percent of growers practicing different PMPs in descending order was PMP1(69.8%) > PMP6 (17.0%) > PMP4(5.3%) > PMP5(4.9%) > PMP3 (2.2%) > PMP2(0.8%); while in 2005, the order was changed to PMP6(47.3%) > PMP3(19.3%) > PMP5 (12.9%) > PMP4 (9.9%) > PMP1(9.3%) > PMP2(1.3%) (Fig. 6). Fig. 6 shows that the use of PMP1 decreased dramatically by percent of growers, kg of AI, and treated hectares from 1992 to 2002, but increased afterwards. In its place, PMP6 has become the most popular pest management practice, in terms of percentage use among growers. In 2005, 47% of almond growers followed PMP6 compared to 17% in 1992. Use of PMP3 increased by percent of growers, kg of AI and treated hectares since 2000 and became the dominant pest management practice in 2005, second only to PMP6. Users of PMP5 decreased from 5% in 1992 to 1% in 2001 but increased to 13% in 2005. The uses of PMP5 as measured by kg of AI and treated hectares also increased in recent years. The uses of PMP2 and PMP4 did not change much over the years (Fig. 6).

For in-season pest management practices, more growers used PMP3 than PMP1 in recent years (Fig. 6). The percentage of growers using PMP3 during the in-season increased steadily, from 3% in 1992 to 35% in 2005. A dramatic increase in the use of PMP5 was observed in both kg of AI and treated hectares. In 2005, PMP5 was the most-used PMP (excluding PMP6) by kg of AI. Uses of PMP2 increased greatly in recent years and became the most-used PMP by treated hectares in 2005 (Fig. 6).

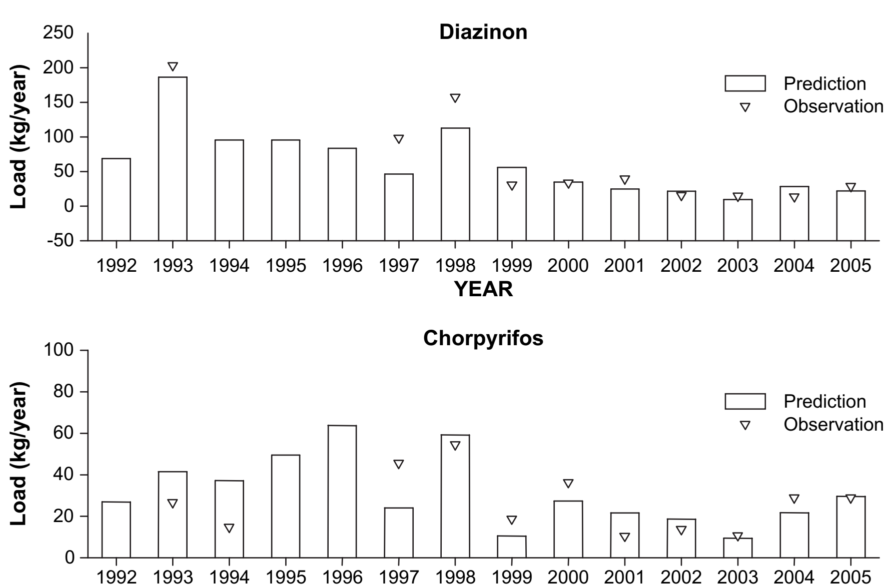


Fig. 3 – Calibration of the SWAT model for simulation of diazinon and chlorpyrifos. Adapted from Luo et al. (in press).

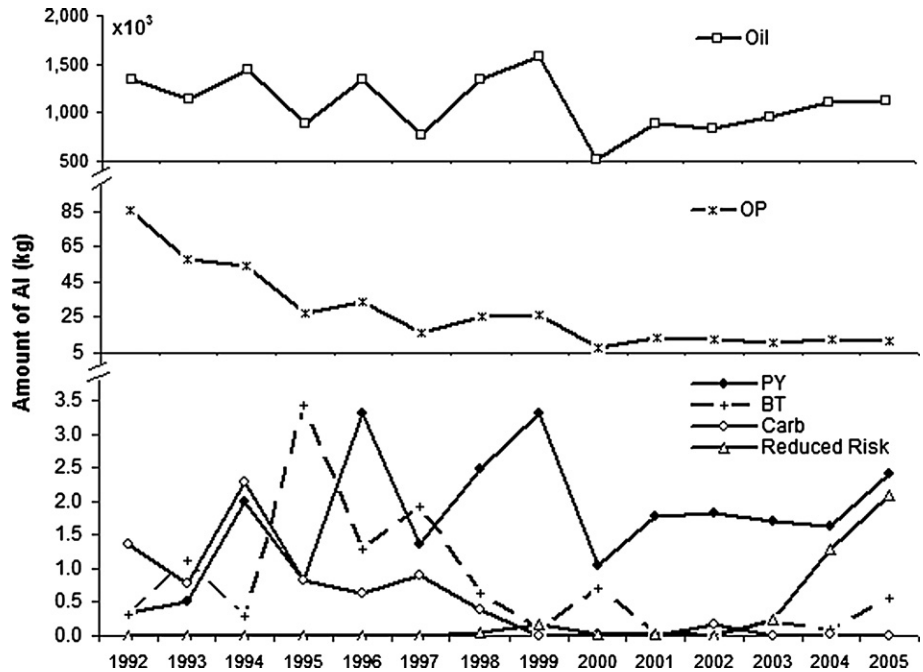


Fig. 4 – Use of pesticides on almonds by amount of AI during dormant season. OP: organophosphate; PY: pyrethroids; Carb: Carbamates; Reduced Risk: Reduced risk pesticides.

3.2. *SWAT simulation outputs*

SWAT simulation results clearly showed the temporal trends of pesticide concentrations in surface water and sediment. During 1992–2005, water concentrations decreased from 62.2 ppm to 3 ppm for diazinon and from 8.8 ppm to 1.2 ppm for chlorpyrifos (Fig. 7). Sediment concentrations of these two chemicals decreased from 15.1×10^3 ppm to 0.6×10^3 ppm for diazinon and from 73.7×10^3 ppm to 3.0×10^3 ppm for chlorpyrifos during the same time period (Fig. 7). Both water and sediment concentrations were lowest in 2003 but increased in 2002 and 2004 (Fig. 7).

Fig. 7 also shows that permethrin sediment concentrations peaked at 2.28×10^3 ppm in 1998 and 2.56×10^3 ppm in 2002, and then decreased to 0.07×10^3 ppm in 2003. Esfenvalerate sediment concentrations reached the maximum level of 1.18×10^3 ppm in 1998 and decreased to 0.13×10^3 ppm in 2003. Water concentrations of these two chemicals showed a similar pattern having maximum values in 1998 and 2002. Both water and sediment concentrations increased from 2003 to 2005.

Table 2 shows the percent of use reduction needed to meet federal and state water quality standards. Current chlorpyrifos use exceeded EPA and CDFA standards by 2.96% and 11.8%, respectively. Diazinon use exceeded EPA and CDFA standards by 1.1% and 2.7%, respectively. To meet the EPA's standard of 41 ng l^{-1} and the CDFA's standard of 15 ng l^{-1}, chlorpyrifos use needed to be reduced by 88.4% and 95.8% in the SJR watershed. Reductions of 61.6% and 78% in diazinon use were needed to meet the EPA and CDFA standards (Table 2).

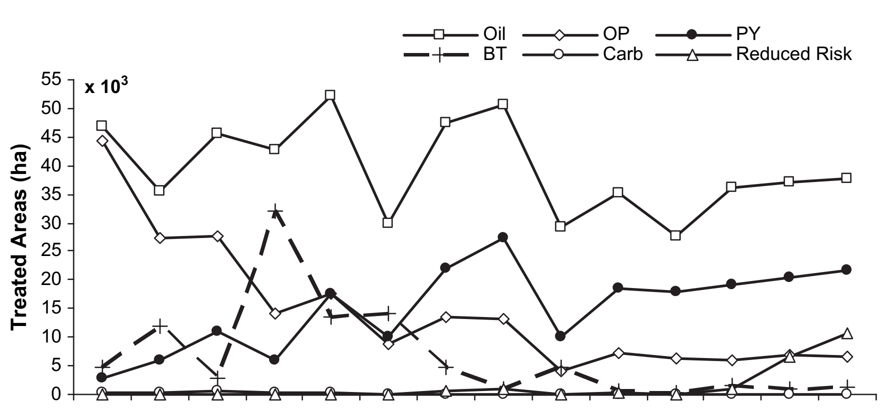


Fig. 5 – Use of pesticides on almonds by treated areas during dormant season. OP: organophosphate; PY: pyrethroids; Carb: carbamates; Reduced Risk: reduced risk pesticides.

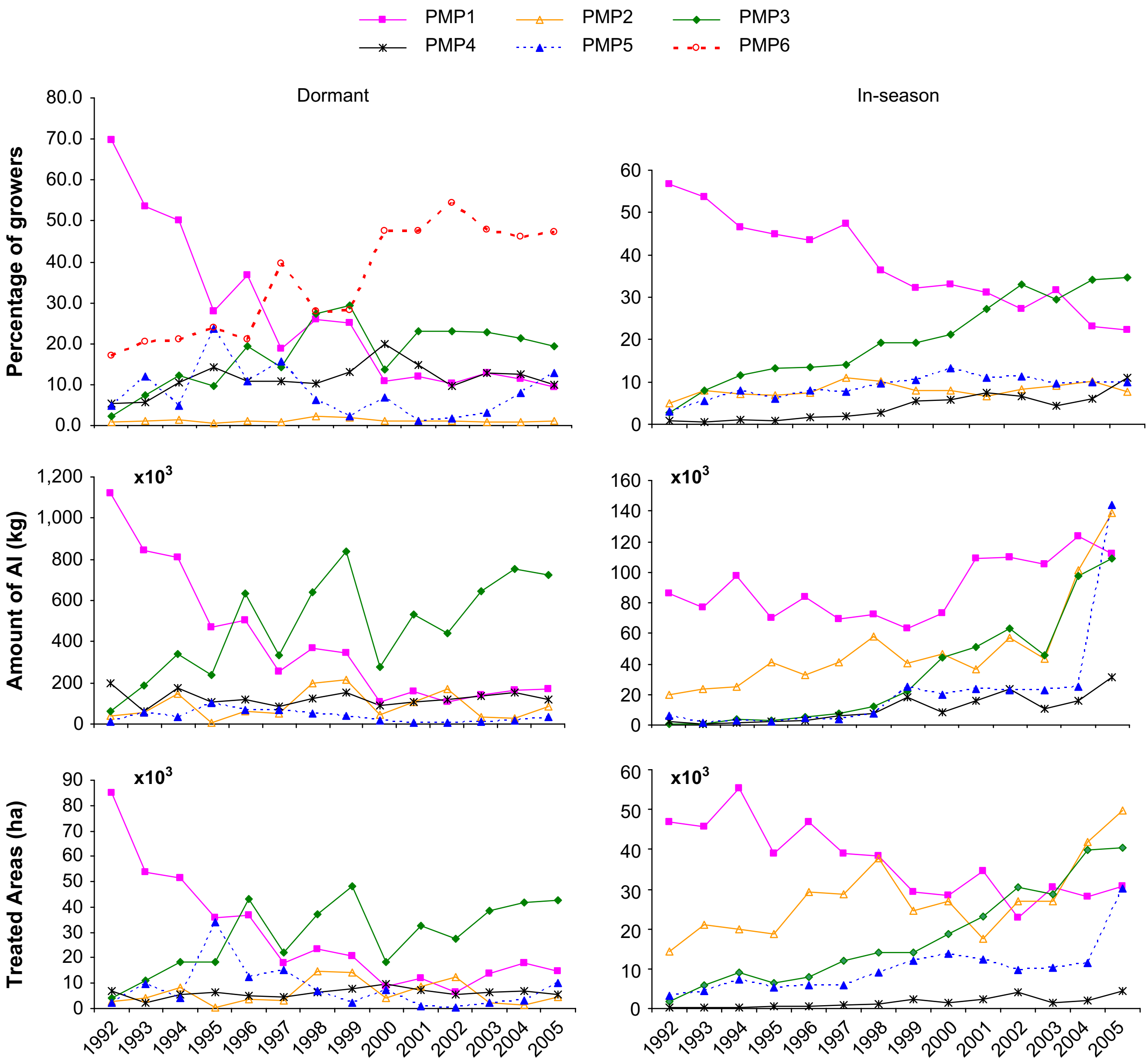


Fig. 6 – Use of different PMPs in almond by percentage of growers, amount of AI, and treated areas during dormant and in-season.

3.3. *Impacts of PMP on water quality*

The results from the stepwise regression analysis were shown in Table 3. Only significant correlations were reported. Dormant use of PMP1 was positively correlated with diazinon and chlorpyrifos concentrations in water and sediment. It accounted for 72.5% and 78.3% of the variations of diazinon and chlorpyrifos concentrations in water, and 59.7% and 66.2% in sediment (Table 3). In addition, the use of PMP1 was negatively correlated with permethrin concentration in water and sediment contributing to 12.3% and 11.0% of the variations, respectively. Dormant use of PMP2 was positively associated with permethrin and esfenvalerate concentrations in water and sediment. It accounted for 47.4% and 38.8% of the variations of permethrin and esfenvalerate concentrations in water, and 45.9% and 34.7% in sediment. In contrast, dormant uses of PMP3 were negatively correlated with diazinon concentrations in sediment (5.5%), while PMP4 was negatively correlated with diazinon in water (4.5%). Finally, PMP5 had negative correlations with diazinon and chlorpyrifos concentration in both water and sediment, explaining 8.5% and 9.9% of variations of diazinon and chlorpyrifos in water, and 13.0% and 6.8% for each chemical in sediment (Table 3).

Most in-season PMPs were not significantly correlated with any of the independent variables (Table 3). Of those that were significant, in-season use of PMP1 was negatively correlated with permethrin in water (13.8%) and sediment (11.5%), while in-season use of PMP2 had a positive correlation (17.4%) with esfenvalerate water concentration. All the models were statistically significant with *P*-values less than 0.05 (Table 3).

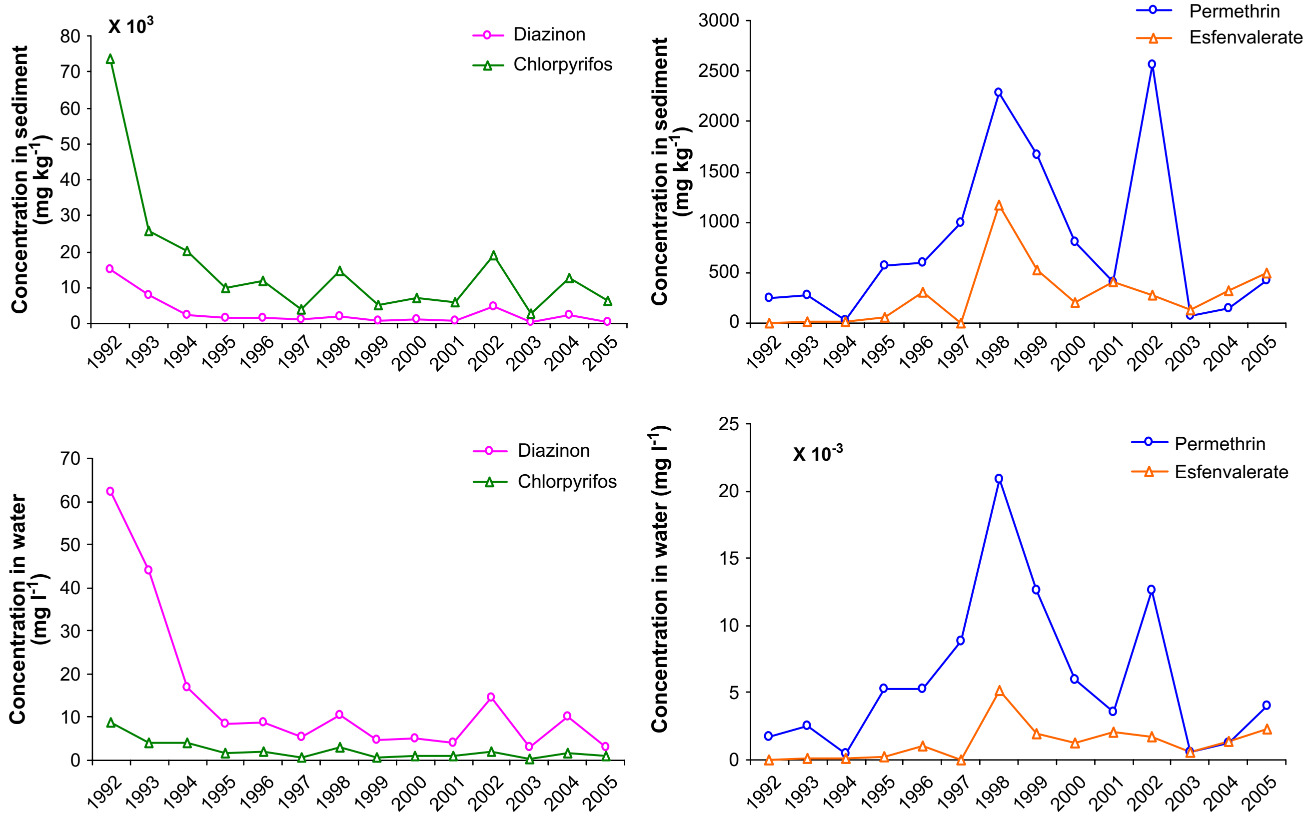


Fig. 7 – Simulated concentrations of pesticides in sediment and water.

3.4. *The contribution of almond pesticide use to surface water pesticide load*

Almond pesticide use had a significant contribution to total pesticide loads in the watershed (Fig. 8). The pesticide loads at the watershed outlet predicted by the total pesticide use of all commodities in the regions were dominated by the loads predicted from pesticide use on almonds. The temporal trends of pesticide load predicted by almond pesticide use synchronized with that predicted by total commodity use for both OP and pyrethroid pesticides. In terms of load, majority of diazinon and chlorpyrifos mass were associated with water column while majority of permethrin and esfenvalerate mass were associated with sediment. Therefore, we ran our correlation test for the OP and PY pesticides in water and sediment, respectively. Diazinon loads in water contributed by almond pesticide use were highly correlated with the total pesticide loads of all commodities, as can be seen by an R^2 value of 0.956, while the correlation for chlorpyrifos was not high with an R^2 value of 0.533 (Fig. 8). Predicted permethrin and esfenvalerate loads in sediment were also highly correlated with almonds and total commodities, with an R^2 value of 0.93 and 0.95, respectively (Fig. 8).

4. Discussion

The presence of pesticides in surface water poses potential risks to both aquatic species and human (Arias-Estévez et al., 2008). As an important source of pesticide input to surface water, agricultural pesticide use strategies should be carefully examined to evaluate their impacts on water quality.

Table 2 – Use reductions to meet water quality standards

		No exceeding (%)	5% exceeding	10% exceeding	Remark (%)
Chlorpyrifos	EPA (41 ng l^{-1})[a]	88.4	–	–	Exceeding of current use: 2.96
	CDFA (15ng l^{-1})[a]	95.8	46.4	1.1	Exceeding of current use: 11.8
Diazinon	EPA (170 ng l^{-1})[a]	61.6	–	–	Exceeding of current use: 1.1
	CDFA (100 ng l^{-1})[a]	78	–	–	Exceeding of current use: 2.7

a The EPA and CDFA criteria are four day average according to CVRWCB (2006). Percent of exceeding was calculated based on pesticide concentration from daily simulation of SWAT model and the chronic water quality standards.

Table 3 – Percent of variation in chemical concentration explained by pest management practices

Chemical concentration	Media	Dormant pest management practices					In-season pest management practices statistics					Statistics	
		PMP1	PMP2	PMP3	PMP4	PMP5	PMP1	PMP2	PMP3	PMP4	PMP5	R^2 (%)	P
		OP	OP + PY	PY	Oil alone	Lower risk	OP	OP + PY	PY	Oil alone	Lower risk		
Diazinon	Water	72.5 (+++)			4.5 (−)	8.5 (−)						85.5	< 0.001
	Sediment	59.7 (+++)		5.5 (−)		13.0 (− −)						78.3	0.001
Chlorpyrifos	Water	78.3 (+++)				9.9 (−)						88.2	< 0.001
	Sediment	66.2 (+++)				6.8 (−)						73.0	0.001
Permethrin	Water	12.3 (− −)	47.4 (++)				13.8 (− −)					73.6	0.003
	Sediment	11.0 (− −)	45.9 (++)				11.5 (− −)					68.4	0.007
Esfenvalerate	Water		38.9 (++)					17.4 (++)				56.2	0.011
	Sediment		34.7 (++)									34.7	0.008

Percent of variation (%) = sequential sum of squares of one variable/total variance.
(+): Positive correlation.
(−): Negative correlation.
The number of "+" and "−" show the strength of correlation. (+++): Percent of variance > 50%; (++) or (− −): percent of variance between 10% and 50%; (+) or (−): percent of variance < 10%.

The importance of analyzing pesticide use data and alternative pest management practices for risk assessment and effective environmental decision-making was emphasized in a recent review (Arias-Estévez et al., 2008). This paper presented the potential of combining the pesticide use surveys and watershed modeling in the adoption of lower risk PMPs to replace traditional ones.

The results of this study not only present an informative snapshot of the environmental impacts on surface water quality by almond pest management practices but also offer a basis for recommendations to further reduce impact. The regression analysis confirmed that PMPs including organophosphates and pyrethroids (PMP1, PMP2) are positively associated with their concentrations in water and sediment. While PMP3 did not have any significant association with pyrethroid concentrations, it is probable that it will in the future if PMP3 continues to increase in popularity. In contrast, the analysis showed that the PMPs using solely oils (PMP4) or reduced risk products (PMP5) had either negative association or no association with concentrations of the four representative chemicals. These results are highly relevant given impending future policy to restrict use of OP and PY pesticides due to their negative impacts on various non-target groups.

The analysis of trends on PMP use shows an optimistic future for reducing impact on water quality. PMP1 has dramatically decreased over time in terms of the percentage of growers employing it, the total kilograms of active ingredients, and the total hectares treated, while PMP2 ranked very low by all these measurements. PMP3 is the greatest concern as its use has been increasing, which could eventually increase concentrations of pyrethroids in water systems. However, recent awareness of the potential adverse effect of pyrethroids on aquatic species may result in tighter regulations on pyrethroid products, affecting growers' preferences for pyrethroid PMPs in the future. The EPA's recent decision to re-evaluate over 600 pyrethroids confirmed this surmise. While PMP4 remained relatively unchanged, PMP5 experienced great increases in use in recent years. Use of PMP6, which advises no dormant spraying and therefore causes the least negative environmental impact, has been dramatically increasing over time. Monitoring pest pressure allowed growers to take timely action to control pests and to avoid the need for blanket application of pesticides. The increasing use of PMP6 indicated that no dormant application was necessary for most of the almond orchards, although during years with high pest pressure, chemical controls were still needed. The decreased use of PMP1 together with the significant increased use of PMP5 and PMP6 indicates a promising future for reducing adverse impacts of almond pest management practices on water quality.

These results are even more promising when taken into consideration under the larger framework of agricultural non-point source pollution. The contributions to pesticide loads from almonds make up a significant proportion of the total load created by all commodities in the watershed. Therefore, the positive trends in reducing environmental impact seen by almond growers will go a long way toward reducing the overall non-point source pollution in this region. Almond

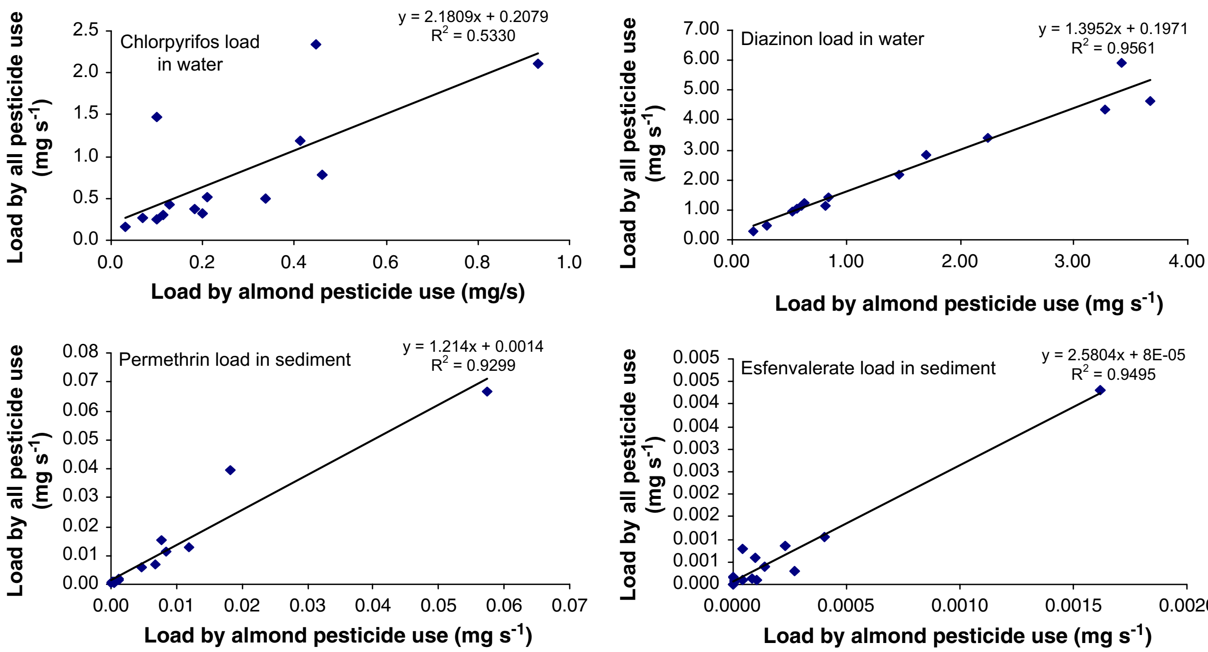


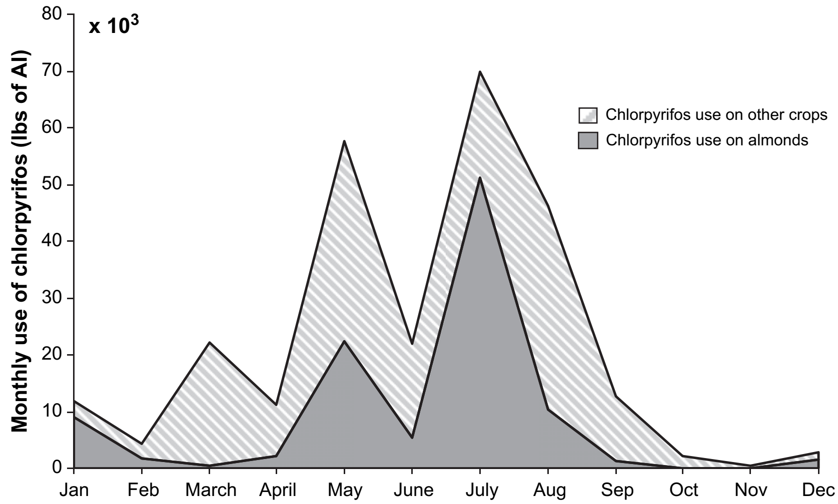
Fig. 8 – Correlation between pesticide loads predicted by uses of the pesticide on almonds and all crops.

orchards near waterways should be carefully managed with low risk pest management practices to minimize pesticide runoff. In orchards with low PWB and SJS pressure, PMP6 may be the best option for reducing impact on water quality. With careful monitoring and timely application of reduced risk pesticides during in-season, it is possible to control pests without any dormant application. It has been demonstrated that pest damage levels were not higher in the blocks with no insecticide applications than those in the conventional blocks which had dormant OP applications (Elliott et al., 2004).

The relationships between pesticide use and loads in surface water are much more complex than an intuitive thinking that ‘‘higher use resulted in higher pesticide loads’’. Pesticide loads not only depend on the amount of use, but also the landscape characteristics, soil hydrologic related properties, and many others. For example, factors such as quantity of pesticide use, physical and chemical properties of pesticides, quantity and patterns of rainfall, and timing of pesticide application affect whether or not and/or how much pesticides runoff to surface water bodies. Applications of pesticides in non-vulnerable areas may not pose environmental risks to water quality. A recent study conducted in vineyards in a northwest Spain watershed suggested that soils in these vineyards were not prone to transport fungicides and; therefore, fungicide use in these vineyards would not pose any significant risk to water supplies in the study area (Bermúdez-Couso et al., 2007). Timing of pesticide application and rainfall also play important roles. Uses of pesticides during an irrigation season may not have the same impact as the uses in a rainy season. Our data showed that OP and pyrethroid concentrations were lowest in 2003 while the total uses of these pesticides were not. The relative low concentrations were due to a combination of relatively low dormant pesticide use and low discharge in year 2003.

The percentage of the total pesticide loads that were contributed by almonds relative to other commodities in the area differs among pesticides. The differences could be explained by variation in application timing of these chemicals by almonds in comparison to other crops. Fig. 9 shows that the application timing of chlorpyrifos on almonds and other crops were synchronized while the application timings of permethrin were not. Almonds used the majority of permethrin during rainy season while other crops used the majority of permethrin during dry season (Fig. 9). These different patterns in application timing may result in different contributions of pesticide loads associated with the pesticide use on almonds. Pesticides used in rainy season are generally more prone to runoff, which explains the large contribution of almonds to total use of permethrin. There might be other reasons for the differences in almond contribution patterns among chemicals, such as chemical properties and transport pathways. Hence, further analysis is needed.

The use of the SWAT model to predict concentrations of the four representative pesticides in conjunction with use of pest management practice data presented a novel method to study the ecological footprint of growers' farming practices on water quality. It appears that almond growers are well on their way to transitioning to lower impact systems. However, outreach and education to growers and their pest control advisors can further the process through assisting in the implementation of low impact practices and supplementing chemical choices with best management practices (BMPs) that can mitigate and/or prevent negative environmental impact. As growers and policy makers are better informed as to the ecological footprints of their actions, they will be able to better transit to more sustainable practices, and the future



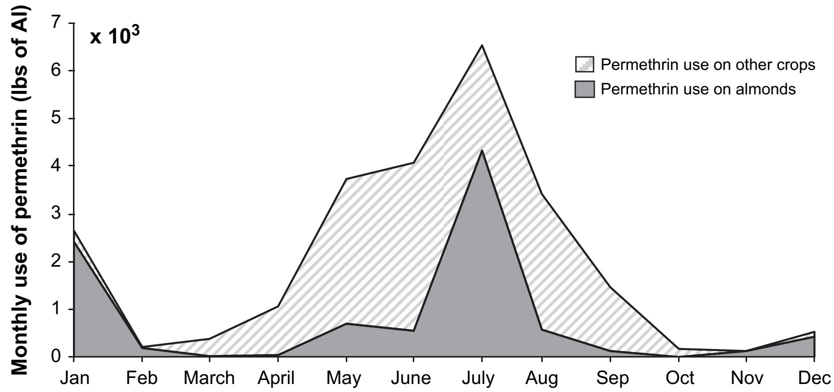


Fig. 9 – Monthly uses of chlorpyrifos and permethrin by almonds and by all commodities in the watershed.

of water quality in the San Joaquin River watershed will be better assured.

5. Conclusion

This paper presented a novel method to study the environmental impacts of different agricultural pest management practices. By combining the pesticide use surveys and watershed modeling, we revealed a promising future for the adoption of lower risk PMPs to replace traditional ones. While use of traditional dormant OP with oil (PMP1) decreased dramatically, pyrethroids in combination with OP and oil (PMP2), pyrethroids in mixture with oil (PMP3), reduced risk pesticides (PMP5) and no dormant application (PMP6) have been increasingly used. Although the decrease of dormant OP use resulted in reduced OP concentrations in water, the increasing use of pyrethroids in combination with oil (PMP3) or/and with OP (PMP2) may cause potential risk to the water quality within the SJR watershed. However, as reduced risk pesticides and no dormant application become more and more popular, it is possible to reduce water quality impact from almond orchards. Since pesticide use on almonds contributes greatly to pesticide loads in the watershed, especially for permethrin, outreach efforts are needed to promote better pest management practices and implement BMPs in almond orchards. This study suggests an optimistic future of reducing OP pesticide pollution in the SJR by adopting alternative almond pest management practices.

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Supplementary information

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.watres.2008.05.018.

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