Department of Pesticide Regulation
Environmental Monitoring Branch
1001 I Street
Sacramento, California 95812

Modeling pyrethroid uses and conservation practices in agricultural areas of California

Yuzhou Luo, Ph.D.
Research Scientist IV

11/13/2017

1 Introduction

Pyrethroid insecticides are applied to a variety of crops throughout California. Due to their aquatic toxicity, off-site movement of these chemicals into surface water is of concern. Monitoring studies and toxicity tests in early 2000 showed pyrethroid-related sediment toxicity in agriculturally influenced areas of California (Amweg et al., 2005; CCWQP, 2006; Starner et al., 2006). As a result of the monitoring, impaired water bodies for pyrethroids have been included in the 303(d) list since 2006 (SWRCB, 2006). Conservation practices, often called best management practices or BMPs, are increasingly required to prevent and mitigate pesticide exposure to aquatic ecosystems. In 2008, U.S. Environmental Protection Agency (USEPA) stipulated label changes with updated spray drift language for all pyrethroid products used on agricultural crops (USEPA, 2008a). The label changes include requirements on spray buffer zone, vegetative filter strip (VFS), and other conditions for agricultural applications of pyrethroid products.

Since BMP effectiveness cannot be tested in all field conditions, USEPA suggested modeling strategies for the development and implementation of watershed management plans (USEPA, 2008b). As a part of an ecological risk assessment (ERA) for agricultural uses of pyrethroids, Pyrethroids Working Group (PWG) modeled label-required mitigations of spray buffer zone and VFS (Giddings et al., 2015). A similar ERA was conducted by USEPA Office of Pesticide Programs, Environmental Fate and Effects Division (EFED) (USEPA, 2016), where only spray buffer was considered. However, the worst-case conditions before the BMP implementation were not modeled, so the effectiveness of the required mitigation practices and other potential BMPs cannot be evaluated. In addition, the ERAs only simulated the maximum application rates and frequencies permitted in pyrethroid product labels. Actual application methods should be considered for comparison with monitoring data in surface water, such as the database compiled by PWG (Giddings et al., 2016).

This study develops a modeling system for both baseline simulation and scenario analysis of pesticide applications in agricultural settings. Pesticide Registration Evaluation Model (PREM) developed by the Surface Water Protection Program (SWPP) is selected as the core model.

PREM covers landscape- and water-phase processes for pesticide risk assessments. But it's not sufficient for BMP evaluations which require additional modeling capabilities such as alteration of default parameter values in field scenarios and consideration of pesticide attenuation during the transport from treated areas to receiving water bodies. A conceptual model is first proposed for risk assessment on agricultural uses of pesticides to aquatic ecosystem. Additional modeling capabilities for BMPs are introduced and coupled with PREM. The resulting system is used to evaluate the observed sediment toxicity of pyrethroids and potential conservation practices. The current study only demonstrates spray buffer zone and VFS as required for agricultural uses of pyrethroids, but other BMPs such as vegetated drainage ditch (VDD) and sediment basin are considered in the modeling system and the simulation capabilities can be evaluated in the future.

Specifically, this study simulates the use, off-site movement, and environmental concentrations of pyrethroids in agricultural areas of California. To be consistent with the commonly available monitoring data, pyrethroids applications to rice paddy and for vector control are not considered here. Application methods and BMPs to be simulated include [1] baseline simulation for the worst-case conditions, with the maximum application rates and frequencies permitted in product labels, and before the implementation of any mitigation practices, [2] spray buffer and VFS specified in the updated spray drift language (USEPA, 2008a), and [3] actual application methods reported in the Pesticide Use Reporting (PUR) database. Table 1 lists the proposed model simulations, in comparison with the ERAs by PWG and USEPA. Based on results of model application and evaluation, future research needs for better understanding and modeling on pesticide management practices also will be investigated.

Table 1. Proposed model simulations for pyrethroid uses in agricultural areas of California

Simulations	This study	PWG	USEPA
Baseline simulation (worst-case conditions)	X		
Baseline + spray buffer	X		X
Baseline + VFS	X		
Baseline + spray buffer + VFS	X	X	
Baseline + spray buffer + VFS + actual application methods (current conditions)	X		

Note: spray buffer and VFS (vegetative filter strip) follow the requirements in the label changes with updated spray drift language (USEPA, 2008a).

2 Modeling approach

2.1 Model development

A conceptual model (Figure 1) is developed for risk assessment of pesticide agricultural uses to aquatic ecosystem. The model extends the FIFRA tier-2 modeling settings (10-ha agricultural field and 1-ha receiving water) by introducing potential conservation practices. Figure 1 demonstrates typical BMPs in agricultural areas: in-field practices (*e.g.*, reduced application rate, cover crop), spray drift management, tailwater treatments including vegetative filter strips (VFS), vegetated drainage ditch (VDD), and sediment basin. These practices are selected to represent major mitigation mechanisms in agricultural settings: [1] to reduce spray drift, [2] to reduce water runoff and soil erosion, and [3] to facilitate infiltration and sediment settling by increasing hydraulic retention time and decreasing peak flow rate.

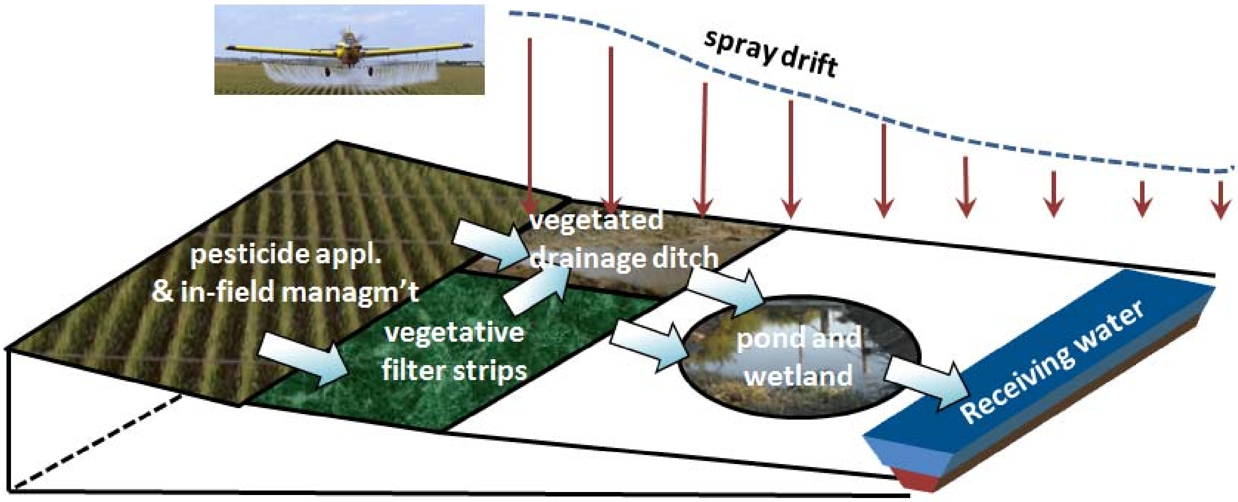


Figure 1. Conceptual model for risk assessments of pesticides to aquatic ecosystem with options of conservation practices in agricultural areas

The conceptual model considers the representation of BMP combinations and geographic or hydrological variability. First, BMPs can be enabled and disabled according to field conditions and management plans. For example, the USEPA 2008 label changes for all pyrethroid products used on agricultural crops could be mathematically represented with the options for spray buffer and VFS while disabling other practices. In addition, flow distribution between BMPs and flow non-uniformity within a BMP can be defined by a user. This option is included for better representation of BMP operations in field conditions. For example, White and Arnold (2009) observed about half of flow in a VFS handled by 10% of the VFS area. Three sections in a vegetative treatment system are considered in this study: [1] a section with low-rate overland flow (defined by runoff fraction over the entire treated field, f_1, and simulated as VFS), [2] a section with high-rate overland flow (f_2, simulated as VFS), and [3] a section with channelized flow (f_3, simulated as VDD). Summation of f's should be either 0% or 100% of the runoff from the entire treated field, with 0 indicating no vegetative treatment system in action. The f_3=0 suggests a VFS-only system, f_1=f_2=0 is for VDD-only system, and the settings of [f_1>0 and f_3>0] could be used for representing grassed waterways.

Numerous environmental models have been developed for pesticides, but none sufficiently covers all relevant processes in pesticide off-site movement from treated areas, and subsequent fate/distribution in aquatic systems (Figure 1). An integrated modeling system is developed based on the existing modeling capabilities in PRZM and VVWM, which have been incorporated in the PREM version 5 (Luo, 2017b). Therefore, PREM itself is capable of simulating pesticide behaviors over the treated area with pesticides and in a receiving water body. In addition, effects of in-field BMPs can be evaluated in PRZM by altering soil properties and surface parameters. For example, cover crop and residue management can be represented by adjusting curve numbers, erosion factors and Manning's surface roughness. Irrigation management can be simulated with PRZM parameters for irrigation period, timing, type, rate, and leaching. VVWM, compared to its previous version EXAMS (Exposure Analysis Modeling System), provides more options for characterizing various water bodies. For example, VVWM or its algorithm has been used for simulating rice paddies (Young, 2012) and aquatic sites (Luo, 2017b) receiving pesticides. In the modeling system, sediment basin will be evaluated by VVWM with appropriate dimension and hydrological settings.

Additional modeling capabilities are required for representing transport mechanisms between a treated field and its receiving water. Specifically, AgDrift v2.1.1 (USEPA, 2017b) and VFSMOD v4.3.1 (Sabbagh et al., 2010) are integrated into the PREM for evaluating the effects of spray drift management and filtration systems (VFS and VDD), respectively. AgDrift is the USEPA official tool for modeling off-site deposition of pesticides from agricultural applications. By following the USEPA guidance (USEPA, 2013a), AgDrift is used in this study to update two PREM input parameters, application efficiency and drift fraction, to represent the requirements and restrictions presented in spray drift management (*e.g.*, buffer distance, wind speed, nozzle size). VFSMOD is widely used for designing and evaluating VFS's. As an event-based model, VFSMOD is dynamically coupled with PREM for continuous daily simulations during the 30-year period of 1961–1990. Generally, VFSMOD will run for each simulation day and update edge-of-field fluxes (water, sediment, and pesticides) to represent the mitigation effects by the user-specified VFS. Updated fluxes are sent back to PREM for subsequent simulations in sediment pond or receiving water (Figure 2). VFSMOD was not originally developed for channelized flow in VDD. However, a recent study demonstrated successful application of VFSMOD for predicting mitigation effects on runoff, suspended sediment, and chlorpyrifos in vegetated ditches in Salinas, California (Phillips et al., 2017). In the modeling system, therefore, the same approach is applied to evaluating pyrethroid fate and transport in VDD.

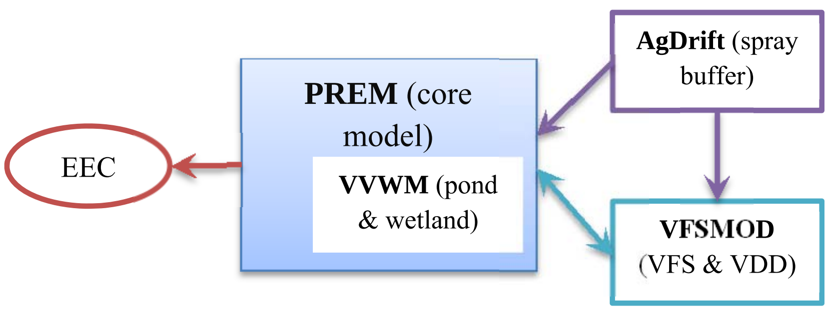


Figure 2. Model integration for pesticide risk assessments with conservation practices.

In this study, BMP modeling is designed for scenario-based, continuous simulations under the FIFRA Tier 2 modeling framework. Similar to registration evaluations, a proposed management practice will be simulated with prescribed modeling scenarios and weather data for the 30-year period of 1961-1990 (while the active period for a BMP can be defined, *e.g.*, perennial or certain seasons only). Therefore, pesticide residues from the previous runoff event and remaining in a mitigation structure, such as a VFS, will be continuously modeled during the dry period and in the next runoff event. This is different for most of the previous BMP modeling efforts which were developed for site-specific, event-based simulations. It's expected that the modeling results provide screening-level analysis on the mitigation effectiveness, with limited data available from the data requirements for pesticide registration (USEPA, 2007). Note that the actual effectiveness of a BMP may be dependent on more factors such as effects of spatial variability and long-term operations (Liu et al., 2017).

2.2 Simulation design

There are 25 pyrethroid active ingredients registered for use in California, and this study only considers six of them: bifenthrin, cyfluthrin, cypermethrin, esfenvalerate, lambda-cyhalothrin, and permethrin. This selection is based on their agricultural uses and historical monitoring results. Two more chemicals, deltamethrin and fenpropathrin, were evaluated in the ERAs by PWG and USEPA. Deltamethrin is mainly used in urban areas of California (CVRWQCB, 2017) and not included in the current DPR agricultural monitoring (Deng, 2017a). For fenpropathrin, the highest concentration observed in agriculturally influenced sites of California is 64 ng/L (Giddings et al., 2015), which does not exceed the lowest chronic aquatic-life benchmark (USEPA, 2017a).

Two types of model simulations are conducted in this study: baseline simulation and scenario analysis (Table **1**). The same modeling approach has been applied in the DPR's risk assessment for urban/residential uses of fipronil and bifenthrin (Budd and Luo, 2016; Luo, 2017c). Baseline simulation is to capture the worst-case conditions of pyrethroid uses in agricultural areas. Baseline simulation is based on the maximum rates and frequencies and other conservative settings of pesticide applications permitted in the product labels. Developed as a foundation for further evaluation of mitigation effectiveness, in addition, baseline simulations don't consider conservation practices (*i.e.*, no spray buffer, no VFS). Therefore, baseline simulation results are expected to overestimate monitoring data.

After baseline simulation, the integrated modeling system is used for scenario analysis by evaluating conservation practices. In this study, spray buffer and VFS, by individual practices and their combined effects, are tested according to the updated drift spray drift language for pyrethroid agricultural labels (USEPA, 2008a). The basic assumption in scenario analysis is that the required practices are implemented in an idealized condition, reflecting the maximum effectiveness. Scenario analyses are conducted for two purposes: (1) to quantitatively evaluate the effects of conservation practices on applied mass and environmental concentrations of a pesticide. For this purpose, relative changes of applied mass and EEC to the baseline simulation results are reported by comparing modeling results before and after the implementation of conservation practices. (2) to assess risk to aquatic ecosystems, by comparing the predicted concentrations with water quality criteria to determine if the scenario is sufficient to meet the criteria.

With PUR data for California, in addition, the actual application methods of pyrethroid products can be determined. For some pesticides, annual cumulative application rates in most of fields would be less than the maximum value permitted in the labels which have been assumed in the previous ERAs and baseline simulations in this study. The observed, reduced uses of pyrethroid will be considered as a conservation practice and simulated in the scenario analysis for representing more realistic conditions of pyrethroid uses in agricultural areas of California. With all these practices applied, the modeling results for pyrethroids are expected to be comparable to the monitoring data in recent years after the label changes.

Risk assessment in this study is based on the modeling results of organic carbon (OC) -normalized concentrations in sediment (μg/kg[OC]). Previous studies showed that partitioning coefficients used in modeling are associated with great variability on both the definition and values. Model-predicted concentrations in aqueous phases (*i.e.*, freely dissolved concentration in water column and in pore water) are very sensitive to the input values of the coefficients. However, the predictions for concentrations in sediment were generally invariant with different coefficient values (USEPA, 2016). For pyrethroids, in addition, the most sensitive species are usually sediment-dwelling organisms. The associated toxicity values are most likely measured as pesticide concentrations in sediment, then may be converted to the form of freely dissolved concentration by assuming local instantaneous equilibrium. The use of concentrations in sediment also avoids the potential problem with water concentration based risk assessment that the same toxicity value is proposed for both water column and pore water.

Modeling results are reported as the 1-in-10-year peak concentration ("peak EEC") and the 1-in-10-year 21-d moving average concentration ("21-d EEC") of pyrethroids in sediment, in OC-normalized format (μg/kg[OC]). The peak EEC will be compared to monitoring data for validating the baseline simulation and scenario analysis. It's expected that the peak EEC will overestimate the observation within one magnitude, *i.e.*, the ratio of prediction/observation within 1–10X. The 21-d EEC is compared to the chronic toxicity endpoints in sediment for risk characterization. The similar approach was used in the ERAs by PWG and USEPA (Giddings et al., 2015; USEPA, 2016).

3 Input data

3.1 Pyrethroid agricultural uses and usage

Pyrethroid products were reviewed by PWG and USEPA, and summarized as use patterns and application methods in a model-ready format (Giddings et al., 2015; USEPA, 2016), with the maximum application rate, the maximum number of application per year/season, and the minimum application interval. The data for use patterns relevant to California are used in this study (Table 2). Other model input data for pesticide applications are set as the PREM defaults (Luo, 2017b). For example, the date for the first application is assumed as the date of crop emergence as defined in the USEPA tier-2 crop scenarios.

Table 2. Application methods derived from product labels for risk assessment

Crop(s)	Application interval (days)	Spray method, rate (kg[AI]/ha), and frequency
Bifenthrin		
Almond	15	Airblast, (0.2242×2) + (0.1121×1)
Cole crops, grapes, lettuce	7	Aerial, 0.1121×5
Corn	14	(Aerial, 0.1121×2) + (Ground, 0.2242×1)
Cotton	3	Aerial, 0.1121×3
Cyfluthrin		
Alfalfa	5	Aerial, 0.049×8
Almond *	-	Aerial, 0.049×1
Grapes	14	Aerial, 0.056×4
Citrus	7	Airblast, 0.112×2
Cole crops, melons, tomato	7	Aerial, 0.056×12
Corn	7	Aerial, 0.049×4
Cotton	3	Aerial, 0.056×6
Lettuce *	7	Aerial, 0.056×4
Wheat	3	Aerial, 0.043×2
Cypermethrin		
Alfalfa	7	Aerial, 0.056×3
Almond *	7	Aerial, 0.056×5
Citrus	14	Airblast, 0.056×4
Cole crops, tomato	4	Aerial, 0.056×6
Corn	3	Aerial, 0.056×4
Cotton	3	Aerial, 0.056×6
Corn	-	Ground, 0.056×1
Grapes, Lettuce *	7	Aerial, 0.056×6
Wheat	14	Aerial, 0.056×5
Esfenvalerate		
Almond	5	Airblast, 0.112×4
Cole crops	1	Aerial, 0.056×10
Corn, cotton, tomato	3	Aerial, 0.056×10
Lettuce *	5	Aerial, 0.056×7
lambda-cyhalothrin		
Almond *	5	Airblast, 0.045×5
Alfalfa	3	Aerial, 0.0336×4
Citrus	3	Airblast, 0.0448×6
Cole crops, tomato	5	Aerial, 0.0336×12
Corn	3	Aerial, 0.0336×4
Cotton	3	Aerial, 0.0448×5

Crop(s)	Application interval (days)	Spray method, rate (kg[AI]/ha), and frequency
Lettuce *	5	Aerial, 0.034×10
Melon	5	Aerial, 0.0336×6
Wheat	5	Aerial, 0.0336×2
Permethrin		
Alfalfa	30	Aerial, 0.2242×4
Almond	10	Airblast, 0.3362×3
Grapes	10	Aerial, 0.3362×8
Corn	7	Aerial,0.1681×3
Cole crops	5	Aerial, 0.2242×4
Lettuce	7	Aerial, 0.2242×4
Tomato	5	Aerial, 0.2242×4

Notes: Most of the application data are taken from the USEPA ERA. Additional use patterns for almond and lettuce, marked with an asterisk (*), are from the PWG ERA.

3.2 Pyrethroid agricultural uses in California, bifenthrin as an example

Actual application methods are based on the PUR database, using bifenthrin as an example. PUR data for individual agricultural applications of bifenthrin during 2001–2015 are retrieved and summarized for the entire state and by application methods.

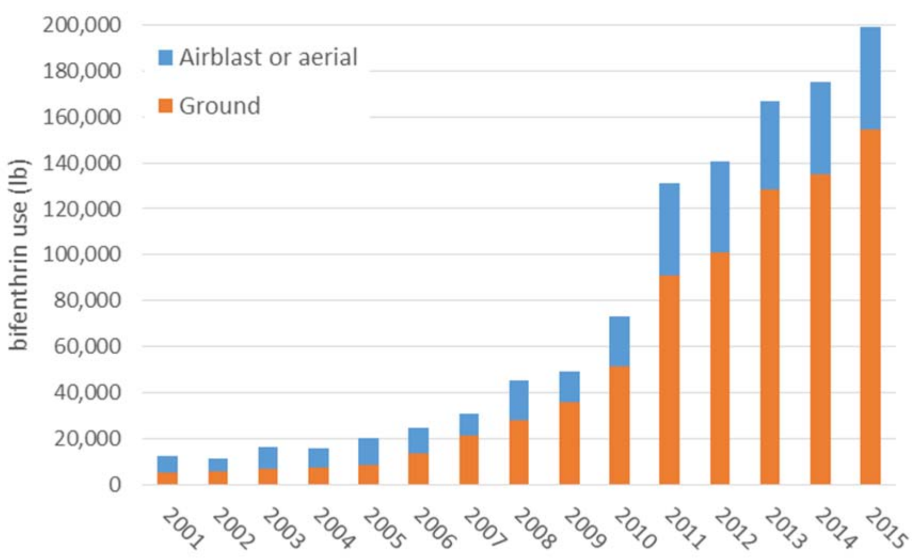


Figure 3. Agricultural uses of bifenthrin in California during 2001–2015 (~0.4% additional uses reported as other spray method, not displayed in the figure)

Agricultural uses of bifenthrin in California have been increased by ~16X during last 15 years (Figure 3). For the approximate 200,000 single application events of bifenthrin reported in the PUR, observed application rates, as either medians or the 90th percentiles by crops and spray methods, generally followed the label rates in Table 2. There is no sufficient information to spatially locate each application within a field; therefore, annual cumulative application rates in a field are conservatively estimated as the sum of all application rates reported in the field in a year. For all fields treated with bifenthrin during 2001–2015, the median cumulative application rate is 0.12 kg/ha, or equivalent to one ground application by following the label rate, while the 90th percentile of cumulative application rate is 0.45 kg/ha.

For the crops to be modeled for bifenthrin, the actual cumulative application rates can be further converted to application frequency (Table 3). To generally match the observed cumulative rate (as the 90th percentiles), the number of applications (Table 2) is adjusted, while the rate, interval, and spray method keep constant. Taking lettuce as an example, more realistic application method is estimated as "Aerial, 0.1121kg/ha×3" to be consistent with the observed annual cumulative application rate of 0.36 kg/ha. This reflects a 40% reduction compared to the application method "Aerial, 0.1121×5" in Table 2. In addition, applications of bifenthrin are observed in a wider window compared to that assumed as the date of crop emergence by PREM. In order to incorporate actual application methods in model simulations, therefore, multiple model runs are needed by varying the date of the first application monthly (specifically, the first days of months within the proposed application window), and the highest EEC from the multiple model runs is reported as the final result. For example, 12 model runs will be conducted for lettuce with the days of the first application from Jan 1st to Dec 1st, and 8 runs for cotton from Mar 1st to Oct 1st (Table 3). The same approach was used in modeling bifenthrin outdoor uses in residential areas of California (Luo, 2017c).

Table 3. Actual annual uses of bifenthrin for selected crops during 2001–2015

	Cumulative rate (90th percentile), kg/ha		Estimated application method for modeling	Months with applications
	All treated fields	by airblast or aerial		
Almond	0.47	0.49	Airblast, 0.2242×2	Mar–Oct, Dec
Cole crops	0.37	0.37	Aerial, 0.1121×3	Jan–Dec
Grapes	0.25	0.12	Aerial, 0.1121×1	Apr, Jun–Aug
Lettuce	0.39	0.36	Aerial, 0.1121×3	Jan–Dec
Corn	0.25	0.25	Aerial, 0.1121×2	Jan–Dec
Cotton	0.25	0.25	Aerial, 0.1121×2	Mar–Oct

Note: PUR data for broccoli are used to represent the application rate and frequency for cole crops.

3.3 Monitoring and toxicity data

Monitoring data were analyzed for statewide conservative estimates to representing the contamination levels of pyrethroids in agricultural areas of California. According to the simulation design (Section 2.2), monitoring data are separated into two groups, representing the historical (before the label changes) and current (after the label changes) conditions. The label changes were required in 2008, and here it's assumed that it takes 2–3 years before all labels in the channels of trade reflected the new mitigation statements and training had reached the majority of commercial applicators (Winchell et al., 2017). Therefore, the monitoring data before 2012 are used for representing historical conditions, and data of 2012 and after for current conditions.

Monitoring data from California Environmental Data Exchange Network (CEDEN, 2017) are used in this study. CEDEN data from two programs "Central Coast Cooperative Monitoring Program for Agriculture" and statewide "Irrigated Lands Regulatory Program" are retrieved for representing agriculturally influenced areas in California, including 1904 records during 2004–2016 (as of this study, only one sample was in 2016, and 2015 data may not be complete). The other available data source is the PWG-compiled nationwide data for pyrethroids (Giddings et al., 2016), which has been used in the ERAs by PWG and USEPA. The same data analysis processes are conducted to CEDEN data and PWG data. Results showed that, for the historical conditions (before 2012), the results from PWG data are very similar to those from CEDEN data. For 2012 and after, PWG data are not sufficient for percentile calculations. Therefore, CEDEN data are used in this study for consistency.

Representative concentrations are calculated as the 90th and 95th percentiles for each pyrethroid in each period (Table 4). The same approach was used in the previous ERAs by PWG, USEPA, and DPR (Luo, 2017a), but improved in this study by evaluating the relevance of a monitoring site to pyrethroid uses. For each pyrethroid, specifically, if a monitoring site has no detection, it's identified as an irrelevant site and all its measurements for the corresponding chemical are removed before percentile calculations. Relevance analysis is conducted due to the fact that percentiles as representative concentrations could be statistically "diluted" by using data from *all* sites including those drained from areas with relative low uses of pyrethroids (*i.e.*, less-relevant sites). Taking whole-water samples of bifenthrin as an example, the detection frequency was reported as 19.2% with all data in the PWG database (Giddings et al., 2015), while DPR's agricultural monitoring study reported higher frequency of 56% with more relevant sites (evaluated by SWPP's Surface Water Monitoring Prioritization Model) (Deng, 2017b). With site relevant analysis, the representative concentrations (as the 90th and 95th percentiles) in this study are significantly higher than those in the ERAs by PWG and USEPA (Giddings et al., 2015; USEPA, 2016).

Table 4. Monitoring data summary for concentrations of pyrethroids in sediment (μg/kg[OC])

	2004–2011		2012–2016	
	90th percentile	95th	90th	95th
bifenthrin	3533	8139	2152	2961
cyfluthrin	713	1161	264	383
lambda-cyhalothrin	1320	2041	1038	1658
cypermethrin	430	1115	183	250
esfenvalerate	684	1428	657	1165
permethrin	3172	5919	278	5280

Criteria for model validation are also established based on the monitoring data as percentiles. For example, Giddings et al. (2015) expected systematic over-predictions in the modeled EECs at the high (90th and 95th) percentiles of monitoring data, and USEPA (2016) expected the EEC and the 90th percentile monitored concentration of each chemical within one order of magnitude difference of each other. As mentioned in the simulation design, it's expected in this study that the modeled peak EEC will overestimate the percentiles by 1–10X.

To be consistent with monitoring data analysis and model simulation, chronic toxicity endpoints for benthic invertebrates are used in this study (Table 5), as defined by PWG, USEPA, and Central Valley Regional Water Quality Control Board (CVRWQCB). The *H. azteca* 10-d median LC50s (Amweg et al., 2006) are also displayed for comparison. By considering the toxicity endpoints as the target water quality criteria for pyrethroids in sediment, one can roughly estimate the required reduction of environmental concentrations to meet the criteria. For example, the required reductions of bifenthrin based on the 95th percentile of the historical conditions are 97.2% (=1-230/8139) for PWG endpoints or 99.9% for USEPA (1-6.25/8139).

This study only considers monitoring data for pyrethroids in sediment. Water quality criteria are also presented as dissolved concentrations, *e.g.*, CVRWQCB water quality objectives and USEPA aquatic life benchmarks. For evaluations with these criteria, POC (particulate organic carbon) and DOC (dissolved organic carbon) concentrations are needed to convert whole-water concentrations to dissolved concentrations. Compiled data for whole-water concentrations of pyrethroids together with POC and DOC are not available at this time.

Table 5. Benthic invertebrates most sensitive chronic endpoints for the selected pyrethroids (µg/kg[OC])

	(Giddings et al., 2015)	(USEPA, 2016)	(CVRWQCB, 2015), 5th percentile	*H. azteca* 10-d median LC50 (Amweg et al., 2006)
Bifenthrin	230	6.25	423	520
Cyfluthrin	270	22	774	1080
Lambda-cyhalothrin	70	7.75	617	450
Cypermethrin	700	7.7	932	380
Esfenvalerate	400	176	2166	1540
Permethrin	1100	1025	6075	10830

Notes: Some of the USEPA data (bifenthrin, lambda-cyhalothrin, and permethrin) were originally reported as dry-weight (dw) based concentration, and converted by the author to organic-carbon (OC) based values with a OC fraction of 4% (*i.e.*, USEPA standard pond scenario). CVRWQCB water quality objectives were presented as dissolved concentrations with the unit of ng/L, and converted to µg/kg[OC] by KOC (SPME) values in Table 6.

3.4 Physiochemical properties

The same set of physiochemical properties and environmental fate data are used for both baseline simulation and scenario analysis. Model input values for the selected pyrethroids (Table 6) are mainly retrieved from the USEPA ERA, with the following changes:

1) As the primary modeling approach in this study, KOC based on the liquid-liquid extraction (LLE) methodology is used for both land- and water-phase simulations. The values of LLE-based KOC are taken from USEPA modeling studies (USEPA, 2013b, 2016).
2) KOC from solid phase microextraction (SPME) is also tested as a secondary modeling effort for water-phase simulations (while land phase is always by LLE-based KOC). SPME-based KOC values are taken from Chickering (2014).

3) As mentioned in the DPR's comments on the USEPA ERA (CDPR, 2017), the input value of anaerobic metabolism half-life for lambda-cyhalothrin (6,084 days) is too high. This study uses a value of 426 days (3X of the median value of available data: 57.7, 142, 6320 days) according to a previous USEPA study (USEPA, 2013b).
4) Foliar degradation is assumed stable according to the USEPA guidance for model input data (USEPA, 2009). It was set as 35 days by USEPA and 3.5 days by PWG for all pyrethroids.

Table 6. PREM input parameters for physiochemical properties of the selected pyrethroids

	Bifenthrin	Cyfluthrin	Lambda-cyhalothrin	Cypermethrin	Esfenvalerate	Permethrin
MWT	422.9	434.29	449.86	416.3	419.9	391.3
VP	1.8e-7	1.8e-8	1.56e-9	1.7e-9	4.7e-7	1.48e-8
SOL	1.4e-5	2.32e-3	5e-3	9e-3	6e-3	5.5e-3
AQPHOT	49	0.7	13	36.2	9	94
AERO	169.2	72.68	52.0	219	225	211
HYDRO	Stable	Stable	Stable	210	Stable	Stable
AERO_W	466.2	44.58	47.87	23.5	80.4	56.7
ANAER_W	650.2	25.59	421	53.1	138.3	193
KOC (LLE)	236,750	184,864	333,200	141,700	251,717	76,800
KOC (SPME)	4,228,000	3,870,000	2,056,000	3,105,000	7,220,000	6,075,000

Notes: MWT (g/mol) = molecular weight, VP (torr) = vapor pressure, SOL (ppm) = water solubility, AQPHOT (day) = aqueous photolysis half-life (HL), AERO (day) = aerobic soil metabolism HL, HYDRO (day) = hydrolysis HL, AERO_W = aerobic aquatic metabolism HL, ANAER_W (day) = anaerobic aquatic metabolism HL, KOC (L/kg[OC]) = organic carbon (OC) normalized soil adsorption coefficient, LLE = liquid-liquid extraction, and SPME = solid phase microextraction.

4 Modeling results

4.1 Drift fraction

The requirement of spray buffer zone is part of the 2008 USEPA label changes with updated spray drift language for all pyrethroid products used on agricultural crops (USEPA, 2008a). The label changes required 150 ft buffer zone for aerial applications and 25 ft buffer zone for airblast and ground applications. In addition, requirements on wind speed and direction, temperature inversion, droplet size are also specified. Drift fractions of pyrethroid uses are calculated by AgDrift 2.1.1 for the USEPA pond. Other model input parameters are selected according to the USEPA guidance on modeling off-site deposition of pesticides via spray drift for ecological assessments (USEPA, 2013a). For comparison, default values of drift fractions without spray buffer zone are also provided. For application efficiency, to be consistent with USEPA guidance (USEPA, 2009) and the ERAs by PWG and USEPA, this study uses the values of 0.95 for aerial and 0.99 for airblast and ground applications.

Table 7. Drift fraction for agricultural applications of pyrethroid products (calculated for the USEPA pond)

	With required spray buffers (USEPA, 2008a)		Default drift fraction without buffer (USEPA, 2013a)
	AgDrift model settings	Drift fraction	
Aerial	Drop size distribution (DSD): ASABE medium; wind speed: 15 mph	0.037 (150 ft)	0.125
Airblast	Orchards: spare (Young, Dormant)	0.015 (25 ft)	0.042
Ground	Boom height: high; DSD: ASABE fine to medium/coarse; data percentile: 90th	0.007 (25 ft)	0.062

By introducing spray buffer zones and other spray drift requirements, AgDrift modeling results (Table 7) with the USEPA 2008 label changes showed significant reductions (by 65–90%) of drift fractions compared to default values. For airblast and ground applications, the drift fractions used in this study are consistent with those calculated in the USEPA ERA. For aerial application, the value used in this study (0.0373) is higher than that in the USEPA ERA (0.031), but similar to a previous USEPA modeling study (0.036) (USEPA, 2012). The drift fractions calculated by USEPA or this study are higher than the values in the PWG ERA, *i.e.*, 0.0197 for aerial and 0.0005 for ground application.

4.2 Baseline simulations

Baseline simulations are conducted with the maximum application rates and frequencies permitted in the product labels of pyrethroids (Table 2) and the assumption of no mitigation practices. Note that spray buffer zone and other requirements have been presented in some products before 2008. In the Reregistration processes, however, USEPA determined that the previous spray drift language was not sufficient, and thus needed to be updated in order to be in compliance with FIFRA (USEPA, 2008a). Therefore, the baseline simulation here assumes no spray drift requirements, mathematically implemented with the default drift fractions (Table 7). The results are to establish the upper bound of environmental concentrations of pyrethroids as the worst-case conditions before 2008.

For each pyrethroid, all crop scenarios in Table 2 are modeled and the one with the highest peak EEC is reported (Table 8). Crop scenarios with the highest EEC are generally associated with aerial applications and higher application rates than other scenarios. Compared with monitoring data summarized as the 90th and 95th percentiles during 2001–2011, the ratios between prediction and observation (P/O) are generally within the proposed range of 1–10X as the criterion for model validation.

Table 8. Predicted vs. observed concentrations of pyrethroids for historical application methods

Chemical	Crop scenario for the highest EEC	Peak EEC, KOC (LLE)	P/O		Peak EEC, KOC (SPME)
			90^{th} %ile	95^{th}	
bifenthrin	Lettuce	15128	4.3	1.9	20026
cyfluthrin	Lettuce	1199	1.7	1.0	1218
lambda-cyhalothrin	Cole crops	7676	5.8	3.8	7788
cypermethrin	Lettuce	2594	6.0	2.3	2629
esfenvalerate	Cole crops	7322	10.7	5.1	7514
permethrin	Grapes	17192	5.4	2.9	17800

Except for bifenthrin, modeling results with KOCs from SPME are very similar to those with KOCs from LLE (Table 8). This finding is consistent with that by USEPA, where KOC values from SPME and LLE were tested for deltamethrin and esfenvalerate (USEPA, 2016). For bifenthrin, predictions with KOC (SPME) are higher (1.3X) than KOC (LLE) based results. But this difference is considered relatively small, compared to the modeling results for dissolved concentrations: pore-water peak EEC of bifenthrin is predicted as 63.9 ng/L with KOC (LLE), 13X of the result with KOC (SPME): 4.74 ng/L.

4.3 Effects of spray drift requirements

The spray buffer in the updated spray drift language (USEPA, 2008a) is modeled with the calculated drift fractions in Table 7. Results for the same crop scenarios as in the baseline simulations (Table 8) are reported, so that the corresponding EEC reductions can be calculated for characterizing the effectiveness of the spray drift requirements (Table 9a). As mentioned previously, those crop scenarios are associated with aerial applications of pyrethroids, for which the drift fraction (and the mass loading by spray drift to the receiving water body) is reduced by 70% (from 0.125 to 0.037, Table 8) by introducing the spray drift requirements. Modeled EEC reductions range from 29% to 64%, suggesting significant variations on the effectiveness of spray buffer by chemicals and by environmental settings.

Table 9. Effects of the required spray buffer on EEC reductions
(a) by chemicals

Chemical	Crop	Peak EEC (μg/g[OC])	EEC reduction
bifenthrin	Lettuce	9091	40%
cyfluthrin	Lettuce	594	50%
lambda-cyhalothrin	Cole crops	3890	49%
cypermethrin	Lettuce	1744	33%
esfenvalerate	Cole crops	5202	29%
permethrin	Grapes	6148	64%

(b) for bifenthrin, by crops

Crop	Baseline simulations		With updated spray drift requirements		
	Peak EEC (μg/g[OC])	off-site movement by spray drift	Peak EEC (μg/g[OC])	EEC reduction	off-site movement by spray drift
Almond	3693	67%	2143	42%	42%
Cole crops	13684	61%	8334	39%	32%
Grapes	7481	94%	2581	66%	82%
Lettuce	15128	60%	9091	40%	31%
Corn	7031	52%	4617	33%	26%
Cotton	4711	87%	1752	63%	68%

Notes: Peak EECs are reported for LLE-based KOC. EEC reductions are calculated relative to the baseline simulation results.

Further investigations on the effectiveness of spray buffer over crop scenarios are demonstrated with bifenthrin as an example. With the required spray buffers, EEC reductions for bifenthrin are predicted from 32% to 65% among the modeled crop scenarios (Table 9b). In addition to the decreased drift fractions (Table 7), EEC reduction is mainly determined by the relative contribution of drift to the total off-site movement in the baseline simulation, which varies over crop scenarios according to their soil and crop parameters. For example, the relatively high contribution for the "cotton" scenario is attributed to their low values of the Universal Soil Loss Equation (USLE) crop or "C" factors, while for grapes its low runoff curve number limits both overland flow generation and soil erosion from treated fields. Therefore, larger EEC reductions are predicted for cotton and grapes scenarios (68% and 82%, respectively, Table 9b). See section 4.4 for more detailed data analysis on the hydrological simulations by the crop scenarios.

4.4 Effects of vegetative filter strip

According to the label changes with updated spray drift language for all pyrethroid products used on agricultural crops (USEPA, 2008a), pyrethroid products can be applied onto fields only where a maintained VFS of at least 10 feet between the field and down gradient aquatic habitat. USEPA referred to a USDA publication for information on constructing and maintaining VFS (USDA, 2000). However, there is no specific requirement for the area ratio between the VFS and the field to be treated, so great uncertainty is expected for the implementation and effectiveness of VFS on pyrethroid runoff reduction. For estimating the theoretical *maximum* effectiveness of the 10-ft VFS as required in the product labels, this study assumes that a VFS is installed for each 10-ha agricultural field. The VFS has the same length as the 10-ha field, *i.e.*, 316 m (square root of 10 ha) or 1037 ft. This reflects an area ratio of about 1:100 (VFS:Field). Again, the modeling results only represent the upper bound of the mitigation effects by introducing a 10-ft VFS, while the statewide actual effects cannot be estimated unless the area ratio is further defined by field surveys or additional regulatory actions.

VFS is simulated by adjusting pesticide mass (or flux) from the treated field by runoff and erosion before entering the receiving water body (Figure 4). Continuous simulations of VFSMOD for the 30-year period (1961–1990) are conducted for the overall mass reduction, *i.e.*, pesticide removal efficiency by the VFS (Table 10). In addition, the reduction on EEC in the receiving water body is also evaluated, by comparing the modeling results before and after the VFS installation. The same set of input parameters as in the PREM for baseline simulations are used in VFS, including chemical properties, weather data, and soil properties. Additional parameters, such as Manning's roughness coefficient for VFS, are set as default values recommended by VFSMOD.

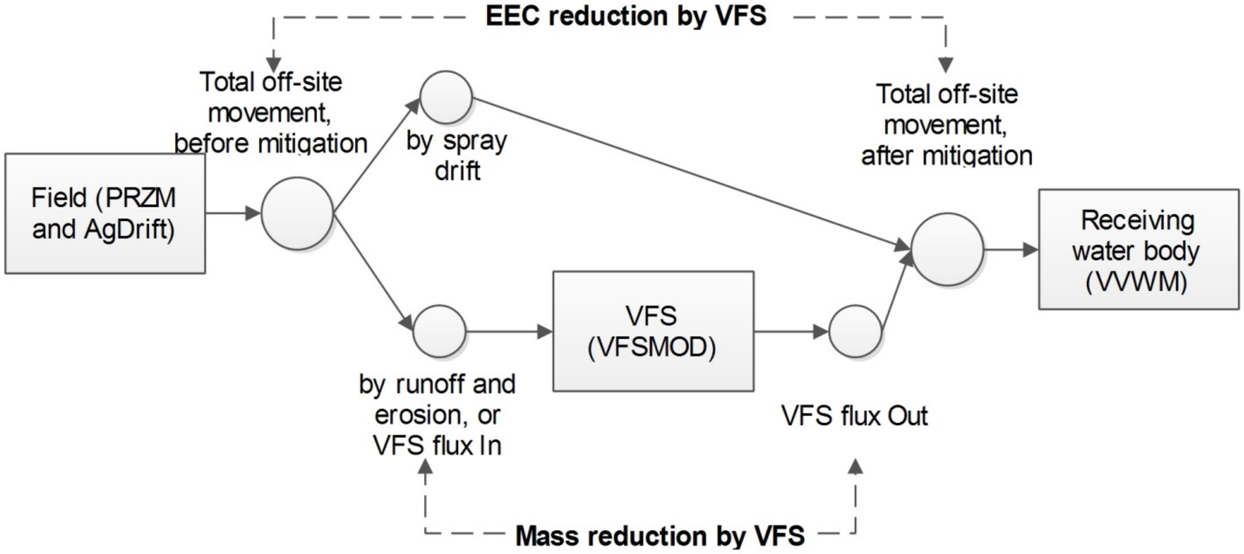


Figure 4. Diagram of the mitigation effects by vegetative buffer strip (VFS) in terms of mass reduction and EEC reduction

4.4.1 Overall mass reduction

The overall mass reduction by a VFS is defined as the relative change between the total influent and total effluent masses of pesticides (Figure 4) during the 30-year simulation period of 1961–1990. *Overall* (rather than *event-based*) values are used in this study since peak concentrations of pesticides (used in the ecological risk assessment) are usually related to large runoff events, while small runoff events are more frequently observed and associated with higher VFS effectiveness. Therefore, the use of event-based statistics may overestimate VFS effectiveness especially for long-term evaluation under the FIFRA modeling framework.

The overall mass reductions (ΔP) of bifenthrin in the demonstrated case studies range from 60% ("cotton") to 97% ("almond" and "grapes") (Table 10). For hydrophobic pesticides like bifenthrin, sedimentation of suspended solid in the coming flow is the primary mechanism for pesticide trapping through a VFS. The effects of infiltration on the dissolved pesticide are secondary, but still contribute to the total removal especially during high flow event. So the optimal conditions for VFS implementation would be: [1] high efficiency of sediment trapping (ΔE, where E is incoming sediment), [2] high fraction of incoming pesticide in sediment-bound phase (indicated by E/Q, or by the VFSMOD output variable 1/Fph=E*Kd/Q, where Q is incoming flow and Kd is soil adsorption coefficient), and [3] high infiltration rate (ΔQ).

Table 10. Effects of the required 10-ft VFS on EEC reductions
(a) by chemicals

Chemical	Crop	Peak EEC (μg/g[OC])	ΔEEC
bifenthrin	Lettuce	9967	34%
cyfluthrin	Lettuce	921	23%
lambda-cyhalothrin	Cole crops	5719	25%
cypermethrin	Lettuce	1616	38%
esfenvalerate	Cole crops	4015	45%
permethrin	Grapes	16425	4%

(b) for bifenthrin, by crops

	Q (mm)	ΔP	ΔEEC	ΔQ	ΔE	Fph
Lettuce	4.5	86%	34%	29%	80%	0.55
Almond	2.2	97%	32%	70%	99%	4.4
Cole crops	4.8	94%	40%	6.70%	93%	1
Cotton	1.6	60%	6%	13%	99%	17.3
Grapes	0.2	97%	6%	53%	99%	2.9
Corn	4.3	82%	41%	22%	74%	2

Notes: ΔP = overall mass reduction, ΔEEC = EEC reduction, Q = incoming flow (presented as the mean value over runoff events, mm over the 10-ha treated field), ΔQ = infiltration (normalized by incoming flow), ΔE = sediment trapping, and Fph = phase distribution factor. Peak EECs are reported for LLE-based KOC. EEC reductions are calculated relative to the baseline simulation results.

Previous field and modeling studies suggest that VFS is generally effective in removing sediment from runoff (*i.e.*, high ΔE). In this study, the predicted ΔE ranges from 74% to 99% (Table 10b), with an average of 80% weighted by incoming sediment loadings. For reference, an median efficiency of 91.3% for sediment trapping was summarized from 181 experimental events reported in 16 studies (Chen et al., 2016) with a median VFS width of 10 m (compared to 10-ft VFS required for pyrethroid applications and simulated in this study).

With consistently high ΔE for most of the runoff events, the variation of pesticide trapping efficiency is more related to 1/Fph and ΔQ. Both of them are related to soil properties. This study assumes the VFS with the same soil properties as in the corresponding PRZM modeling scenarios. For example, the smaller overall mass reduction (ΔP) predicted for the "cotton" scenario is associated with its lower 1/Fph and lower ΔQ compared to other scenarios (Table 10). The "cotton" scenario is assumed with clay soil, compared to other scenarios with sandy loam ("lettuce", "almond") or loam ("grapes", "corn") soils. Clay soils are associated with lower saturated hydraulic conductivity, higher runoff potential, and lower soil erodibility.

4.4.2 EEC reduction

The EEC reductions in the receiving water are predicted as <10% for "cotton" and "grapes" scenarios, and 20–40% for others (Table 10). In addition to physiochemical properties of the modeled pyrethroids, the differences in EEC reduction are related to pesticide spray drift to the receiving water, which is the source not mitigated by a VFS. Smaller EEC reduction is observed for the scenarios with more relative contribution by drift. For example, the baseline simulation results suggest that spray drift explains 87% of total pesticide input to the receiving water for the "cotton" scenario, and 94% for "grapes" (Table 9b). For the two scenarios, the EECs are mainly contributed by spray drift, and thus less dependent on the mass reductions by a VFS. Other scenarios with smaller relative contributions by spray drift, such as the "almonds" (67%), "cole crops" (61%), and "corn" (54%), are predicted with higher EEC reductions by a VFS. A linear relationship is observed as $\Delta EEC=(1-\%Drift)*\Delta P$, where ΔEEC and ΔP are VFSMOD-predicted EEC reduction and mass reduction with VFS implementation (Table 10b), and %Drift is the relative contribution of total pesticide input by spray drift in the baseline simulation (Table 9b).

In summary, modeling results suggest that a well-maintained VFS is very efficient in trapping sediment and associated pesticides. The removal efficiency for pyrethroids (bifenthrin as a test agent here) is dependent on the soil properties. Relatively low efficiency is observed for clay soils with high runoff potential (the "cotton" scenario as an example). In addition, high removal efficiency by VFS does not guaranty significant reduction on EECs in receiving water for risk characterization and exposure analysis. For scenarios where the mass inputs to the receiving water are dominated by spray drift (*e.g.*, the "cotton" and "grapes" scenarios demonstrated in this study), the installation of a 10-ft VFS only slightly reduces the EEC even the VFS substantially removes pesticide masses carried by runoff and soil erosion. Therefore, soil survey and baseline simulation are suggested for supporting the development and implementation of a VFS in field conditions.

4.4.3 Known issues and future direction

VFS modeling demonstrated in this study may have overestimated effectiveness of VFS in field conditions. The known issues and potential solutions are summarized in Table 11 for future development.

Table 11. Assumptions/limitations in the case studies which may overestimate VFS effectiveness

Assumptions/limitations	Potential solutions
Not consider pesticide deposition to the VFS. Since a VFS is installed adjacent to a field, it may receive significant pesticide mass by deposition during application. To simplify the case studies and focus on the VFS effectiveness, this is not considered in the above simulations.	Estimation of pesticide deposition to a VFS based on the AgDrift-predicted drift fraction, *e.g.*, 0.07 for a 10-ft VFS (Tier I Aerial as an example).
Assume uniform distribution of hydrography. The case studies assumed a well-maintained VFS with shallow overland of the same intensity across the entire VFS width (*i.e.*, only one section in the vegetation treatment system, Figure 1). However, field observations suggest different regions in a VFS with lower runoff intensity, higher intensity, and even concentrated flow. Regions with high intensity flow or concentrated flow would reduce the overall effectiveness of a VFS.	Separate VFSMOD runs for the observed hydrograph regions during each runoff event. For example, field experiments showed that 10% of the VFS area received between 25% and 75% of the total field runoff, and the average value of 50% was suggested for modeling (White and Arnold, 2009; Neitsch et al., 2011).
Not consider resuspension of sediment and associated pesticides in a VFS.	This is related to the core algorithm of VFSMOD, and cannot be addressed without significant changes on the model itself.

4.5 Integrated effects of label-required conservation practices

By assuming appropriate implementation of both spray drift buffer and VFS, modeling results reflect the expected mitigation effects (Table 12). The predicted peak EECs are similar to the monitoring data summarized as the 95th percentile for 2012 and later (Table 4).

Table 12. Effects of the required spray buffer and VFS on EEC reductions

Chemical	Crop	Peak EEC (μg/g[OC])	EEC reduction
bifenthrin	Lettuce	3906	74%
cyfluthrin	Lettuce	313	74%
lambda-cyhalothrin	Cole crops	1782	77%
cypermethrin	Lettuce	754	71%
esfenvalerate	Cole crops	1434	80%
permethrin	Grapes	4958	71%

Notes: Peak EECs are reported for LLE-based KOC. EEC reductions are calculated relative to the baseline simulation results.

For comparison with the PWG ERA, model simulations with SPME KOC are also conducted and results are reported as 21-d EEC. For example, the highest 21-d EEC for bifenthrin over the modeled crop scenarios is 5116 μg/kg[OC], 1.7X of that reported in the PWG ERA, 2980 μg/kg[OC]. This is consistent with the difference in drift fractions used in the two studies. For aerial applications, the drift fraction of 0.0373 is used in this study (Table 7), about 1.9X higher than that in the PWG study: 0.0197. This suggests that the modeling approaches in the two studies are comparable although different models are used for pesticide fate simulations in receiving water body (VVWM in this study vs. AGRO-2014 in the PWG study). Different modeling results could be mainly related to the values of input parameters, such as drift fraction in this case.

4.6 Model representations for current conditions (bifenthrin as an example)

The current practices of bifenthrin applications are defined by reduced uses (actual application rate and frequency) and required mitigations (spray buffer and VFS). As mentioned before, effects of VFS are associated with great uncertainty due to insufficient information in the label for field implementation. Only a range of its mitigation effectiveness can be provided: from zero to the maximum values estimated in Section 4.4. Therefore, the current practices are simulated in two sets of model runs (Table 13): [1] spray buffer + reduced use, as the lower bound, and [2] all required and observed conservation practices (drift buffer + VFS + reduced use), as the upper bound. Modeling results for bifenthrin are shown here as an example for the integrated effects of required and observed mitigation practices (Table 13).

Table 13. Modeling results for current application methods (bifenthrin as an example)

	Current condition 1 (spray buffer + reduced use)		Current condition 2 (spray buffer + VFS + reduced use)	
	Peak EEC (µg/kg[OC])	EEC reduction	Peak EEC (µg/kg[OC])	EEC reduction
Almond	1854	53%	784	79%
Cole crops	5966	56%	1840	87%
Grapes	552	93%	419	94%
Lettuce	10133	33%	3528	77%
Corn	5374	24%	2171	69%
Cotton	1463	69%	959	80%

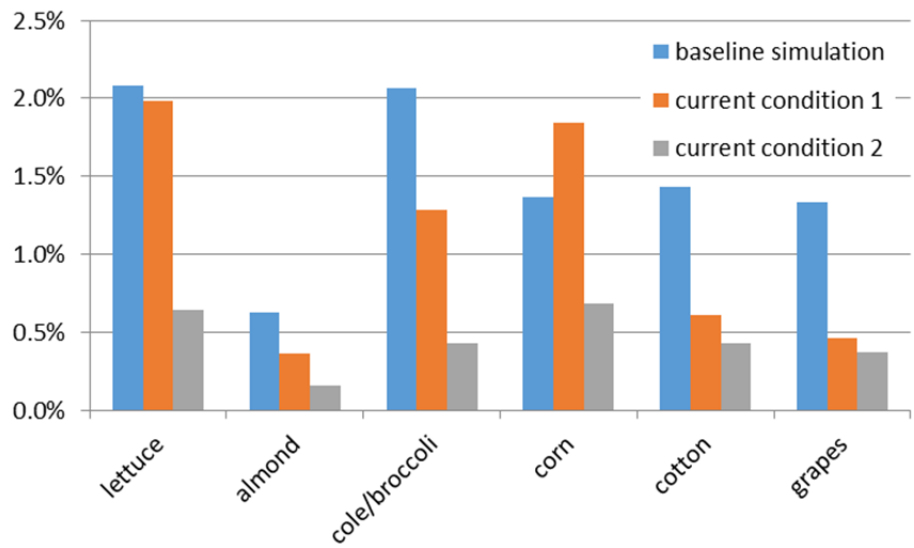
Note: Peak EECs are reported for LLE-based KOC. EEC reductions are calculated relative to the baseline simulation results.

The average value of all predicted EECs in Table 13 is 2920 µg/kg[OC]), comparable to the representative concentration from monitoring data in recent years (2152 and 2961 µg/kg[OC] as the 90th and 95th percentiles, respectively, for bifenthrin, Table 4). If the highest EECs are considered (*i.e.*, 3528–10133 µg/kg[OC] predicted for the "lettuce" scenario), the modeling results overestimate the observation by 1.2–4.7X, which is in the proposed range of 1–10X as the criterion for model validation. The predicted environmental concentrations for bifenthrin with current practices still exceed water quality criteria (Table 5).

Effectiveness of spray buffer and VFS has been discussed in the previous sections. For reduced uses, the corresponding reduction on EEC is generally proportional to that on the annual cumulative application rates by aerial or airblast applications. The effect of reduced uses could be moderated by the extended application window compared to that assumed in the baseline simulation. For example, the baseline simulation for the "corn" scenario schedules pyrethroid applications by following the assumed date of crop emergence on April 1. In reality, aerial applications of bifenthrin to lettuce have been reported throughout the year (Table 3), and higher EECs are predicted for applications during winter, rain season of California. This explains the increased off-site movement for the "corn" scenario with reduced uses and drift reduction (Figure 5a).

Generally, significant reductions are predicted for application rates (as annual total, Table 3), EECs (Table 13), and off-site movement (Figure 5a) in the comparison between the baseline simulation and current conditions. Modeling results for the current conditions actually established the "new" baseline conditions for further efforts in mitigating pyrethroids in agricultural areas. It's observed that, with all required and observed mitigation practices appropriately implementation, the majority of off-site movement will be contributed by spray drift (Figure 5b).

(a)



(b)

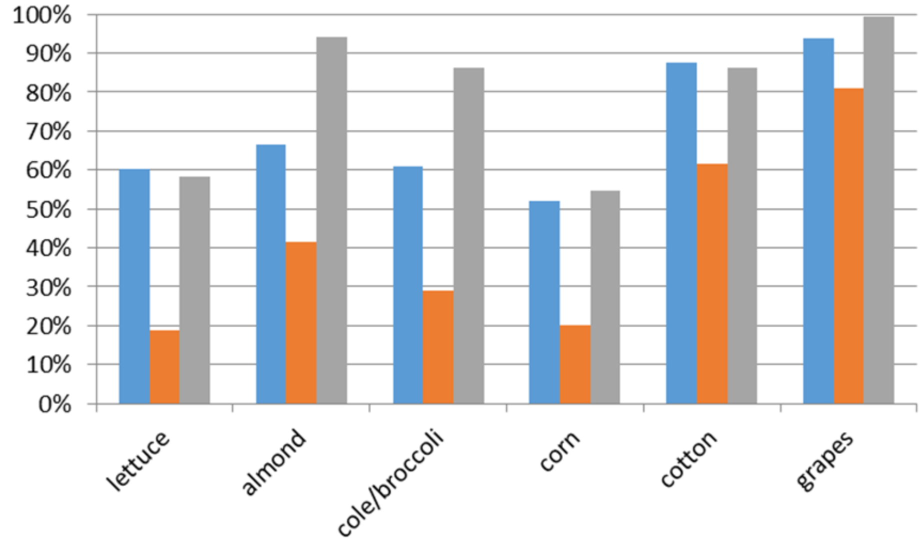


Figure 5. Predicted off-site movement over crop scenarios, predicted as (a) off-site movement normalized by total applied mass, and (b) relative contribution of spray drift to off-site movement. Current conditions are defined in Table 13.

5 Discussion and conclusion

This study evaluates both the historical and current practices of pyrethroid products used in agricultural areas of California. Based on PREM, an integrated modeling system is developed for mathematical representations of conservative practices, including in-field practices, spray drift management, and tailwater treatments. New modeling capabilities are taken from AgDrift and VFSMOD, and dynamically integrated into PREM for continuous daily simulations for the same 30-year period of 1961–1990. The resulting modeling system is tested with required (spray buffer zone and VFS) and observed (reduced uses) practices as scenario analysis.

Modeling results, as estimated environmental concentrations of pyrethroids in sediment, are validated by comparing with monitoring data (before 2012 for historical practices and 2012–2016 for current practices). Even with appropriate implementations of all required and observed conservation practices, observed and predicted environmental concentrations (Table 13) still exceed water quality criteria. The validated configurations for the current practices established a new baseline for additional mitigation options.

Compared to the label-permitted maximum amounts per year, reduced uses of pyrethroids (bifenthrin as an example) are observed in California. Less frequent applications according to the PUR data are simulated as a modeling scenario for a better representation of the current conditions. However, they are not considered as permanent conservation practices since the uses of pyrethroid products could be increased up to the label-permitted rate and frequency. To maintain the predicted EEC reductions, further label changes or regulatory actions are needed to maintain the observed less-frequent applications of pyrethroid products in California. Applications are observed throughout the year (Table 3). Modeling results suggested that pyrethroid uses during the winter rain season of California could generate higher environmental concentrations and undermine the effectiveness of other BMPs (Figure 5).

The required spray buffer zone significantly reduced off-site movement by spray drift (Table 9). In the modeling simulations for the current practices, however, spray drift still contributes more than half of the total off-site movement (Figure 5). For some crop scenarios, spray drift as the sole source could generate environmental concentrations above water quality criteria. Therefore, development and implementation of drift reduction technology (DRT) could significantly contribute to the mitigation of pyrethroids in agricultural areas. Note that model simulations are mainly for selected crop scenarios with aerial applications (Table 2) which result in higher EECs. Spray methods (ground applications, chemigation) and other field conditions should be considered for determining the field-specific drift contributions and associated mitigation practices.

Actual mitigation effects by VFS are also related to spray drift. The required 10-ft VFS is very efficient (60–97%) in terms of trapping pesticide loadings from runoff and soil erosion, but its effects on EEC (6–41%) are moderated due to contributions from spray drift (which are not mitigated by VFS) (Table 10). This confirms the need for integrated modeling with PREM, AgDrift, and VFSMOD in order to simulate the dynamic interactions between conservation practices and off-site movement from various pathways. Based on the modeling results, more informative guidelines for field installation and maintenance of VFS (especially on the soil properties and the VFS:field area ratio) are recommended to secure and enhance the mitigation effects. This study also suggests future research directions to improve mathematical modeling of VFS (Table 11).

In addition to spray buffer zone and VFS already required in the label changes, there are other BMPs to mitigate pyrethroid loadings from treated agricultural fields. Some of them, including cover cropping, sediment basin/wetland, and vegetated drainage ditch, have been tested in California field conditions with small-scale field experiments (Table 14). These practices are currently not required with consistent specifications in California, and thus not modeled in this study, but could be considered for further mitigation as needed to meet water quality criteria.

Table 14. BMP experiments for pyrethroids in agricultural area of California

Year	Reference	BMP	Chemical
2003	DPR study 215	Cover cropping	esfenvalerate
2005	(Moore et al., 2008)	VDD	various pyrethroids
2007	DPR study 242	VDD	lambda-cyhalothrin
2007	(Markle, 2008)	Sediment basin	lambda-cyhalothrin
2007	(Budd, 2011)	Constructed wetland	various pyrethroids
2007	(Moore et al., 2011)	VDD	permethrin
2008	(Anderson et al., 2011)	VDD	various pyrethroids
2009	(Markle et al., 2011)	Sediment basin	lambda-cyhalothrin

Acknowledgments

The author would like to acknowledge Xuyang Zhang, Kean S. Goh, Xin Deng, and Yina Xie for valuable discussions and critical reviews in the initialization and development of this study.

References

Amweg, E.L., Weston, D.P., Ureda, N.M., 2005. Use and toxicity of pyrethroid pesticides in the Central Valley, California, USA. Environmental Toxicology and Chemistry 24, 966-972.

Amweg, E.L., Weston, D.P., You, J., Lydy, M.J., 2006. Pyrethroid Insecticides and Sediment Toxicity in Urban Creeks from California and Tennessee. Environmental Science & Technology 40, 1700-1706.

Anderson, B., Phillips, B., Hunt, J., Largay, B., Shihadeh, R., Tjeerdema, R., 2011. Pesticide and toxicity reduction using an integrated vegetated treatment system. Environmental Toxicology and Chemistry 30, 1036-1043.

Budd, R., 2011. Use of Constructed Wetlands as Best Management Practice To Reduce Pesticide Loads, Pesticide Mitigation Strategies for Surface Water Quality. American Chemical Society, pp. 39-50.

Budd, R., Luo, Y. (2016). Fipronil monitoring and model scenarios (http://cdpr.ca.gov/docs/emon/pubs/ehapreps/analysis_memos/budd_luo_2016_fipronil_monitoring_modelling_combined.pdf). Califonia Department of Pesticide Regulation, Sacramento, CA.

CCWQP (2006). Northern Area Ag-Waiver Monitoring (R3_CMPnorth) data, listed as references #2592 and #2593 in the 2010 and 2012 303(d) report by State Water Resources Control Board. Central Coast Water Quality Preservation Inc, Watsonville, CA.

CDPR (2017). CDPR's comments on USEPA ecological risk assessment for pyrethroids and pyrethrins (http://cdpr.ca.gov/docs/emon/surfwtr/review/pyrethroid_epa-hq-opp-2010-0384.pdf). California Department of Pesticide Regulation, Sacramento, CA.

CEDEN (2017). California Environmental Data Exchange Network (www.ceden.org/). State Water Resources Control Board, Sacramento, CA.

Chen, H., Grieneisen, M.L., Zhang, M., 2016. Predicting pesticide removal efficacy of vegetated filter strips: A meta-regression analysis. Science of The Total Environment 548, 122-130.

Chickering, C. (2014). Determination of partition coefficients for synthetic pyrethroids in natural and artificial sediments using both liquid-liquid extraction (LLE) and solid phase microextraction (SPME) quantification techniques (PWG-ERA-04d). ABC Laboratories Inc. Columbia, MO.

CVRWQCB (2015). Central Valley Pesticide TMDL and Basin Plan Amendment - Water Quality Criteria Method Development, 2015 Pyrethroids Water Quality Criteria Reports (http://www.swrcb.ca.gov/rwqcb5/water_issues/tmdl/central_valley_projects/central_valley_pesticides/criteria_method/). Central Valley Regional Water Quality Control Board, California Environmental Protection Agency.

CVRWQCB (2017). 2017 Proposed Amendments to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for the Control of Pyrethroid Pesticides Discharges (http://www.swrcb.ca.gov/rwqcb5/water_issues/tmdl/central_valley_projects/central_valley_pesticides/pyrethroid_tmdl_bpa/index.shtml). Central Valley Regional Water Quality Control Board, California Environmental Protection Agency.

Deng, X. (2017a). Study 304 Protocol: Surface Water Monitoring for Pesticides in Agricultural Areas in Central Coast and Southern California, 2017 (http://cdpr.ca.gov/docs/emon/pubs/protocol/study304_deng_march_2017.pdf). California Department of Pesticide Regulation, Sacramento, CA.

Deng, X. (2017b). Study 304 Report: Surface Water Monitoring for Pesticides in Agricultural Areas in Central Coast and Southern California, 2016 (http://cdpr.ca.gov/docs/emon/pubs/ehapref/deng_report_304.pdf). California Department of Pesticide Regulation, Sacramento, CA.

Giddings, J., Hendley, P., Holmes, C., Ritter, A., Desmarteau, D., Winchell, M., Wirtz, J. (2015). Ecological risk assessment of agricultural uses of nine synthetic pyrethroids (PWG-ERA-18). Compliance Services International, Lakewood, WA. Pyrethroid Working Group, Valdosta, GA.

Giddings, J.M., Wirtz, J.R., Campana, D. (2016). Updated analysis of monitoring data for synthetic pyrethroids in surface waters and sediments of the United States (PWG-ERA-05A). Compliance Services International, Lakewood, WA; Pyrethroid Working Group, Valdosta, GA.

Liu, Y., Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., Chaubey, I., 2017. A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. Science of The Total Environment 601, 580-593.

Luo, Y. (2017a). Modeling bifenthrin outdoor uses in residential areas of California, II. Review of the recent modeling studies by USEPA/EFED, PWG, and CDPR/SWPP (http://cdpr.ca.gov/docs/emon/pubs/ehapreps/analysis_memos/luo_bifenthrin_urban_modeling2_v3.pdf). California Department of Pesticide Regulation, Sacramento, CA.

Luo, Y. (2017b). Methodology for Evaluating Pesticides for Surface Water Protection: PREM Version 5 Updates (http://cdpr.ca.gov/docs/emon/surfwtr/sw_models.htm). California Department of Pesticide Regulation (CDPR), Sacramento, CA.

Luo, Y. (2017c). Modeling bifenthrin outdoor uses in residential areas of California (http://cdpr.ca.gov/docs/emon/pubs/ehapreps/analysis_memos/bifenthrin_urban_modeling.pdf). California Department of Pesticide Regulation, Sacramento, CA.

Markle, J.C. (2008). The use of agricultural sediment basins and pam as best management practices in irrigated tomatoes (http://www.curesworks.org/bmp/sedimentBasinStudy.pdf). Coalition for Urban/Rural Environmental Stewardship (CURES), Dinuba, CA.

Markle, J.C., Watson, T.E., Prichard, T.L., Klassen, P., 2011. Efficacy of Sediment Basins for Reducing Sediment and Pyrethroid Transport in Almond Orchards, Pesticide Mitigation Strategies for Surface Water Quality. American Chemical Society, pp. 51-63.

Moore, M.T., Denton, D.L., Cooper, C.M., Wrysinski, J., Miller, J.L., Reece, K., Crane, D., Robins, P., 2008. Mitigation Assessment of Vegetated Drainage Ditches for Collecting Irrigation Runoff in California All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Journal of Environmental Quality 37.

Moore, M.T., Denton, D.L., Cooper, C.M., Wrysinski, J., Miller, J.L., Werner, I., Horner, G., Crane, D., Holcomb, D.B., Huddleston, G.M., 2011. Use of vegetated agricultural drainage ditches to decrease pesticide transport from tomato and alfalfa fields in California, USA. Environmental Toxicology and Chemistry 30, 1044-1049.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R. (2011). Soil and Water Assessment Tool, theotetical documentation, verison 2009. Texas Water Resources Institute Technical Report No. 406. Texas A&M University System. College Station, TX.

Phillips, B.M., Anderson, B.S., Cahn, M., Rego, J.L., Voorhees, J.P., Siegler, K., Zhang, X., Budd, R., Goh, K., Tjeerdema, R.S., 2017. An integrated vegetated ditch system reduces chlorpyrifos loading in agricultural runoff. Integrated Environmental Assessment and Management 13, 423-430.

Sabbagh, G.J., Fox, G.A., Muñoz-Carpena, R., Lenz, M.F., 2010. Revised Framework for Pesticide Aquatic Environmental Exposure Assessment that Accounts for Vegetative Filter Strips. Environmental Science & Technology 44, 3839-3845.

Starner, K., White, J., Spurlock, F., Kelley, K. (2006). Pyrethroid Insecticides in California Surface Waters and Bed Sediments: Concentrations and Estimated Toxicities (http://www.cdpr.ca.gov/docs/emon/surfwtr/swposters/starner_pyreth06.pdf). California Department of Pesticide Regulation, Sacramento, CA.

SWRCB (2006). California's 2006 Clean Water Act Section 303(d) List of Water Quality Limited Segments (http://www.waterboards.ca.gov/water_issues/programs/tmdl/303d_lists2006_epa.shtml). State Water Resources Control Board, Sacramento, CA.

USDA (2000). Conservation buffers to reduce pesticide losses. United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), Fort Worth, TX.

USEPA (2007). Data requirements for pesticide registration (http://www2.epa.gov/pesticide-registration/data-requirements, accessed 07/2014). U.S. Environmental Protection Agency, Washington, DC.

USEPA (2008a). Updated spray drift language for pyrethroid agricultural use products (https://www.epa.gov/sites/production/files/2015-08/documents/epapyrethroidletter.pdf). U.S. Environmental Protection Agency, Washington, DC.

USEPA (2008b). Handbook for Developing Watershed Plans to Restore and Protect Our Waters, EPA 841-B-08-002. U.S. Environmental Protection Agency. Washington, DC.

USEPA (2009). Guidance for selecting input parameters in modeling the environmental fate and transport of pesticides, version 2.1 (https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/guidance-selecting-input-parameters-modeling). U.S. Environmental Protection Agency, Office of Pesticide Programs, Washington, DC.

USEPA (2012). Effects Determination for Bifenthrin and the Bay Checkerspot Butterfly, Valley Elderberry Longhorn Beetle, California Tiger Salamander, Delta Smelt, California Clapper Rail, California Freshwater Shrimp, San Francisco Garter Snake, and Tidewater Goby (http://www.epa.gov/espp/litstatus/effects/redleg-frog/2012/bifenthrin/analysis.pdf). U.S. Environmental Protection Agency, Washington, DC.

USEPA (2013a). Guidance on modeling offsite deposition of pesticides via spray drift for ecological and drinking water assessments (EPA-HQ-OPP-2013-0676-0002). U.S. Environmental Protection Agency.

USEPA (2013b). Endangered Species Effects Determinations and Consultations and Biological Opinions (http://www.epa.gov/oppfead1/endanger/litstatus/effects/). U.S. Environmental Protection Agency, Office of Pesticide Programs. Washington, DC.

USEPA (2016). Preliminary Comparative Environmental Fate and Ecological Risk Assessment for the Registration Review of Eight Synthetic Pyrethroids and the Pyrethrins

(https://www.regulations.gov/document?D=EPA-HQ-OPP-2010-0384-0045). U.S. Environmental Protection Agency, Washington, DC.
USEPA (2017a). Office of Pesticide Program aquatic life benchmark database (https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/aquatic-life-benchmarks-pesticide-registration). Office of Pesticide Programs, U.S. Environmental Protection Agency, Arlington, VA.
USEPA (2017b). Models for Pesticide Risk Assessment (https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/models-pesticide-risk-assessment). U.S. Environmental Protection Agency, Washington, DC.
White, M.J., Arnold, J.G., 2009. Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. Hydrological Processes 23, 1602-1616.
Winchell, M.F., Padilla, L., Hendley, P. (2017). Relevance of the PWG regional residential pyrethroid exposure modeling scenarios for national risk assessment. PWG Number: PWG-PRAresp-01; Doc. No. 378-1253; Study ID 299865. Stone Environmental, Inc., Montpelier, VT., Pyrethroid Working Group, Valdosta, GA.
Young, D.F., 2012. Development and Evaluation of a Regulatory Model for Pesticides in Flooded Applications. Environmental Modeling & Assessment 17, 515-525.