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Modeling bifenthrin outdoor uses in residential areas of California, II. Review of the recent modeling studies by USEPA/EFED, PWG, and CDPR/SWPP

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1 Introduction

This study is to summarize and compare the modeling efforts for pyrethroid uses in urban/residential settings recently presented in the following three studies:

- “EFED study” (USEPA, 2016): Preliminary Comparative Environmental Fate and Ecological Risk Assessment for the Registration Review of Eight Synthetic Pyrethroids and the Pyrethrins. U.S. Environmental Protection Agency, Office of Pesticide Programs, Environmental Fate and Effects Division
- “PWG study” (Giddings et al., 2016a): Ecological Risk Assessment of Outdoor Residential Uses of Seven Synthetic Pyrethroids. Compliance Services International and Pyrethroids Working Group
- “SWPP study” (Luo, 2017a): Modeling bifenthrin outdoor uses in residential areas of California. California Department of Pesticide Regulation, Environmental Monitoring Branch, Surface Water Protection Program

The above studies involved different chemicals and geographical regions, but this review only focuses on the chemical of *bifenthrin* and the modeling scenarios for *California* residential areas. Bifenthrin is considered to be the leading cause of pyrethroid-related toxicity in urban areas. Based on the national monitoring data of 1990-2014 (Giddings et al., 2016b), detection frequencies of bifenthrin in urban waterways were 72% in sediment samples and 57% in whole-water samples, much higher than other pyrethroids. In California, the most recent surface water monitoring data by CDPR (July 2015 to June 2016) also showed that bifenthrin was associated with the highest benchmark exceedance frequency in water (75% and 68%, in Northern and Southern California, respectively), and the largest contribution to pyrethroids-related toxicity units in sediment (Budd, 2016; Ensminger, 2016).

To reduce the exposure of aquatic organisms from residential uses of pyrethroids products, a series of mitigation efforts were developed by USEPA, CDPR and registrants. Those include [1] USEPA recommended label statements in 2009 and its 2013 revision (USEPA, 2013) for products intended for occupational and consumer/homeowner uses, [2] “Bifenthrin label memorandum of agreement" (Bifenthrin MOA) between bifenthrin manufacturers and CDPR in 2011 (CDPR, 2011) for selected bifenthrin products for professional uses, and [3] Surface Water Regulations adopted by CDPR in 2012 (CDPR, 2012) for professional applications. The label changes and regulations restrict bifenthrin applications especially on the impervious surface. The new application methods are simulated as current practices of bifenthrin uses in the three modeling studies under review. PWG and SWPP studies also modeled historical application method before the label changes and regulation. EFED study only modeled current practices, but historical practices of bifenthrin applications have been simulated in the previous EFED risk assessment (USEPA, 2012).

This study aims to review the three studies (by EFED, PWG, and SWPP) for their modeling approaches and parameterization, especially the mathematical representations for the historical and current practices of bifenthrin applications in residential areas. Significantly different modeling tools, environmental descriptions, and assumptions were implemented in the three studies. It is very difficult to directly compare the modeling equations and processes for the simulated mechanisms on pesticide runoff generation and transport over residential landscape. It's anticipated that, therefore, by focusing on the model inputs and outputs, this review will capture the main features of each study, and provide a consistent comparison of the modeling approaches for pesticide risk assessment in urban/residential settings. Specifically, the following modeling input/output variables are evaluated here:

(1) Target date and rate for each application;
(2) Area fraction of each surface to be treated (this is the only variable actually differentiate the historical vs. current practices);
(3) Model-predicted EEC's (estimated environmental concentrations) for the historical practices, and comparisons with monitoring data; and
(4) Relative changes of EEC's between the current and historical practices.

This report is organized as follows. Modeling development for pesticide runoff in urban/residential settings during the last decade is summarized in Section 2. Model input parameters are separated as those related to environmental descriptions and pesticide application methods, and discussed in Section 3 and 4, respectively. The historical vs. current application practices are mathematically defined by the surface areas to be treated by bifenthrin (Section 4.2). Modeling results are reviewed in Section 5, followed by discussions and conclusions.

2 Modeling approaches for urban/residential pesticide runoff, 2007-2017

The proper simulation of pesticides from a residential setting requires representations of spatial variability on the urban landscape in terms of permeability, water source, hydrological connectivity, and pesticide application methods. In 2007, the first modeling scenario for residential watershed were developed by EFED and used in the risk assessments for bensulide (USEPA, 2007d), carbaryl (USEPA, 2007c), and malathion (USEPA, 2007b, a). The original purpose of the development is to model unintended pesticide applications on impervious surfaces (e.g., overspray from broadcast applications to lawns). Unlike the uniform landscape in an agricultural modeling scenario, the residential scenario considered two surfaces: pervious surface (50%) and impervious surface (50%). The scenario was implemented in the modeling framework of PRZM (Pesticide Root-Zone Model) and EXAMS (Exposure Analysis Modeling System. Generally, the PRZM-EXAMS modeling was conducted twice (one for the pervious surface and the other for the impervious surface), and then the modeling results were summarized by post processing.

The EFED residential scenario is characterized as 58 quarter-acre house lots in a 10-ha urban watershed, reflecting a nationwide suburban setting. Applications on impervious surfaces are represented by driveways, garage doors, and sidewalks. In 2012, the scenario was used to evaluate risks of bifenthrin use to federally threatened and endangered species in California (USEPA, 2012). Historical bifenthrin labels for residential uses, such as "10-ft perimeter treatment," were modeled and resulted in 21-d EEC up to 36.4 µg/g[OC] in sediment (for the application methods of "*outdoor general surface spray, perimeter treatment, space spray*"). The same scenario was also used in the preliminary ERA for pyrethroids (USEPA, 2016), i.e., the study reviewed here.

Modeling efforts by SWPP for pesticide urban runoff started in 2011, generally in two directions:

(1) Modeling pesticide washoff from impervious surfaces. A semi-mechanistic model (Luo et al., 2013; Luo et al., 2014) was developed and validated with the results of field and laboratory experiments sponsored by CDPR. In addition to commonly reported physicochemical properties, this approach requires additional parameters determined from washoff experiments for each pesticide product (not only the active ingredient).
(2) Model-based registration evaluation of a pesticide for urban/residential uses. The EFED residential scenario was modified according to California field conditions, resulting in SWPP residential scenario with higher impervious surface coverage (ISC, 83%) and higher residential density (20 lots/ha) (Luo, 2014). Paved foundation perimeter was delineated for additional impervious surfaces usually observed in California. The SWPP residential scenario was incorporated into SWPP's Pesticide Registration Evaluation Model (PREM). This model was initially developed for registration evaluation of new pesticide products. It was recently updated and used for post-use risk assessment of residential uses of bifenthrin (Luo, 2017a, b). The modeling approach and results will be reviewed in this study.

Jackson and Winchell (2011) developed a site-specific modeling scenario for the Aliso Viejo neighborhood in Orange County, California, later referred as "PWG regional residential scenario". The scenario was first implemented with the Storm Water Management Model (SWMM) to simulate fipronil uses in the neighborhood. The scenario was improved with the delineation of 8 landscape components (roof, road & sidewalk, foundation perimeter, driveway, patio & walkway, lawn, common area, and pool) and more refined portions (such as the impervious portion of the foundation perimeter receiving irrigation overspray) (Winchell et al., 2013). In later studies, SWMM algorithms for pesticide buildup and washoff were adapted with the semi-mechanistic methods by Luo et al. (2014). A new modeling system was also developed with the modified SWMM (for land-phase simulation) and modified AGRO (combined water quality and food web models, for water-phase simulation), and used to predict pyrethroid residues from their uses in Aliso Viejo neighborhood (Winchell et al., 2014a; Winchell et al., 2014b). Recently, the regional scenario was used in the pyrethroid ERA for 7 regions of the US (California, Northwest, North Central, Northeast, Mid-Atlantic, Southeast, and South Central) (Giddings et al., 2016a; Winchell et al., 2017). The modeling approach and results will be reviewed here.

For better characterizing residential uses of pyrethroids, a number of use/usage surveys were conducted (Wilen, 2001; PWG, 2010; Winchell and Cyr, 2013). Winchell (2013) complied and analyzed the survey results, suggesting the following characteristics to be considered for more realistic representations of pyrethroid applications: (1) fraction of neighborhood households receiving outdoor insecticide treatment; (2) fraction of use sites (residential landscape elements, e.g., driveway) treated during applications; and (3) fraction of applications made with each AI. The fractions were considered in the PWG-sponsored modeling studies. Some of the survey results were also incorporated in the SWPP modeling efforts, specifically, the factor (1) for registration evaluation (Luo, 2017b) and the factors (1) and (3) for risk assessment (Luo, 2017a).

Modeling studies were followed immediately after the regulatory actions on the urban uses of pyrethroids. For example, Williams et al. (2012) assumed no bifenthrin applications on impervious surfaces and pin-stream applications for other pyrethroids under new restrictions. The modeling results suggested an average reduction of 96.7% on the pyrethroid runoff from residential areas in the American River watershed. Jorgenson et al. (2013) estimated 50% and 80% reductions of bifenthrin uses on pervious and impervious surfaces, respectively, according to the Bifenthrin MOA and surface water regulations, resulting in 84% reduction of total toxic unit. Winchell et al. (2013) simulated the current application method of pyrethroids on impervious surfaces as “crack and crevice” applications. The use reduction on impervious surfaces relative to the historical practices was assumed as 95%, and the same reduction was predicted for residual concentrations.

3 General comparison of the three studies

Studies by EFED and SWPP were based on USEPA modeling system with PRZM and VVWM, while PWG study used SWMM and AGRO-2014. USEPA pond scenario was used by all studies as receiving water body. For environmental descriptions, the studies are differentiated mainly by their residential landscape characterizations (Table 1).

Table 1. Model approaches and environmental descriptions in the three studies

	EFED	PWG	SWPP
Weather data	WBAN 23234 (San Francisco), 1961-1990	WBAN 23129 (Long Beach), 1981-1987; and CIMIS 75 (Irvine), 1988-2010	WBAN 23234 (San Francisco), 1961-1990
Land-phase simulation:			
Simulation engine	PRZM	SWMM	PRZM
Washoff algorithm	PRZM	Luo et al. (2014) method	PRZM
Watershed	10-ha nationwide suburban scenario	27-ha the Aliso Viejo neighborhood, California	10-ha California residential scenario
House density	5.8/ha	11.3/ha	20.2/ha
ISC (impervious surface coverage)	50%	58%	83%
Simulated landscape elements for pesticide application	2	15	5
Dry-weather runoff	No	Yes	Yes
Pesticide partitioning	Kd	KOC from LLE	KOC from LLE
Calibration	No	Yes, for bifenthrin	No
Water-phase simulation:			
Simulation engine	VVWM	AGRO2014	VVWM
Receiving water	USEPA pond	USEPA pond, modified for AGRO	USEPA pond
Pesticide partitioning	Kd	KOC from SPME	KOC from LLE

Notes: other (than partitioning coefficients) physiochemical properties of pesticides are slightly different over the three studies, but not shown here. SPME = Solid Phase Micro-Extraction. LLE = Liquid-Liquid Extraction.

4 Modeling scenarios

4.1 Application rate and dates

Label rates of bifenthrin used in the modeling studies were very similar: 0.224 (PWG), 0.247 (USEPA), and 0.254 kg/ha (SWPP). Major differences are observed on the adjustment on label rate for each application and the design of multiple applications (Table 2 and Figure 1). EFED considered only one application per year without any adjustment on the label rate. Both PWG and SWPP incorporated the survey results for residential outdoor uses of insecticides (Winchell, 2013):

- %house (houses using outdoor pest control products) of 75.9% was used in both studies;

- %AI (probability of products containing a certain AI used for treatment) was used, but in different ways. Both studies assumed there were 12 applications (with various AI's) per year for outdoor pest control, but
    - SWPP used the %AI to determine the number of applications with the corresponding AI (here, bifenthrin), and the results suggested that there were 4 applications (out of 12) with bifenthrin treatment at the *label rate*.
    - PWG used the %AI to adjust the rate for each application event. So it's assumed that all 12 applications were associated with the use of bifenthrin, but at a *reduced rate*.

Finally, the three studies are compared in terms of the cumulative application rate, i.e., annual total applied mass per unit of treated surface. The cumulative rate in SWPP study is calculated as [4 applications per year]*[%house, 75.9%] = 3.0X of the label rate. For PWG modeling, no sufficient data were provided in the study report, so the rate is roughly estimated as [AI%, 57.9%]/2*[12 applications per year]*[%house, 75.9%] = 2.6X of the label rate. The %AI was evenly distributed to two sets of applications (with 6-week and 12-week intervals), as suggested in Table 42 of the PWG study report.

Table 2. Application rates and target application dates

	EFED	PWG	SWPP
Label rate (kg/ha)	0.247	0.224	0.254
Rate adjustment, %house	-	75.9%	75.9%
Rate adjustment, %AI	-	57.9% (1)	- (2)
Number of appl.	1	12	4
Application. interval	-	6-week (for 8 applications) and 12-week (for 4 applications)	4-week
Target application dates (mm/dd)	06/01	01/01 (2 applications) 02/15 04/01 (2 applications) 05/15 07/01 (2 applications) 08/15 10/01 (2 applications) 11/15	01/01 (3) 02/01 03/01 04/01
Cumulative application rate per year	1X	~2.6X[label rate]	3.0X

Notes:

(1) The value for foundation perimeters as an example. Other surfaces have similar values (Tables 4~7 of the PWG study report). Also, page 139 of the report, "*to generate EECs for risk assessment, bifenthrin use (and all other actives) was assumed equivalent to all of the pyrethroids combined…*"

(2) The adjustment factor %AI was used by SWPP in determining application frequency (Luo, 2017a).

(3) In SWPP study, 4 monthly applications were simulated with the date of the first application varying from 01/01 (shown as an example in the table) to 12/01.

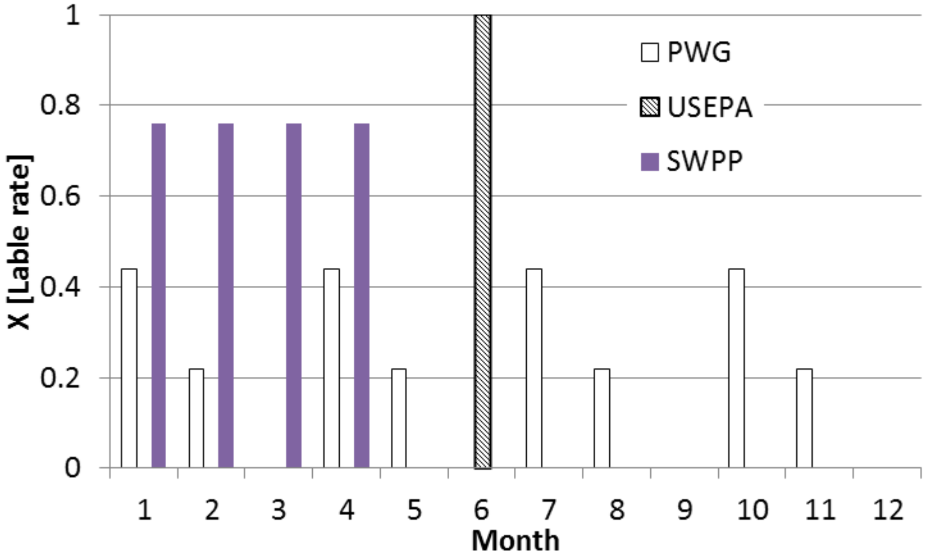


Figure 1. Bifenthrin applications, by dates and rates, simulated in the modeling studies by EFED, PWG, and SWPP. SWPP actually tested the date of the first application from Jan 1st (showing here as an example) to Dec 1st.

4.2 Treated surface fractions

Multiple landscape elements (or surfaces) are considered in the modeling scenarios for urban pesticide uses. This review focuses on the following three surfaces which are associated with high potentials of pesticide runoff (Figure 2 and Table 3):

- Surface I, driveway, including its portions in the foundation perimeter and sidewalk;
- Surface II, other horizontal impervious surfaces that directly routed to storm drain, such as the sidewalk in the front of a building; and
- Surface III, vertical surfaces connected to the surfaces I and II. This includes the garage door and adjacent house walls.

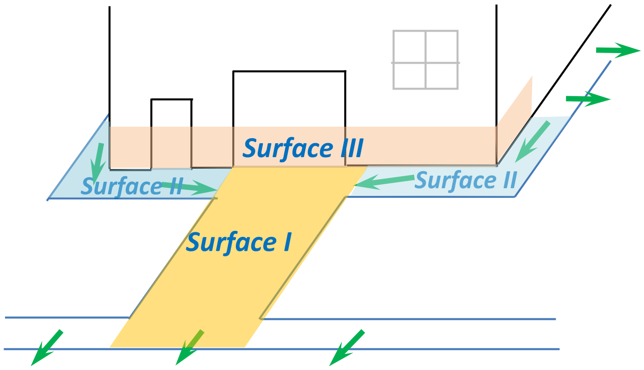


Figure 2. Demonstration of the surfaces with high potentials for pesticide runoff. Adapted from Luo (2017b)

Table 3. Surface areas per house (ft^2) and fractions over the modeled residential watershed (in the parentheses)

	EFED	PWG	SWPP
Surface I	546 (2.9%)	360 (3.8%) (1)	546 (10%)
Surface II	0	38 (0.4%) (2)	149.2 (2.8%)
Surface III (linear ft)	15	18	58.7

Notes:

(1) This value is estimated based on the conceptual diagram of the driveway and garage door (Figure 26 of the PWG study report). The observed driveway size is bigger (7.1% of the Aliso Viejo neighborhood) according to the landscape element characteristics (Table 66 of the PWG study report).

(2) This value is estimated based on the reported total area of impervious footprint perimeter (FP_I) and the corresponding "*fraction routed to stormwater system*" (Table 66 of the PWG study report).

In the modeling parameterization for the *historical application methods*, the total treated fraction by SWPP (8.1% of the watershed) is higher than that by PWG (1.6%) (Table 4). Thereafter, the "total treated fraction" in this document refers to the sum of the individual treated fractions on the three abovementioned surfaces I, II, and III. SWPP assumed a perimeter treatment of 10-ft total band ("7-ft out, 3-ft up"), compared to a 7-ft band ("5-ft out, 2-ft up") by PWG. The 10-ft perimeter treatment was also used by EFED (USEPA, 2012) and UCD (Jorgenson et al., 2013) in their modeling efforts for historical practices of bifenthrin applications. In addition, SWPP considered the potential contributions from the surface II (horizontal impervious surfaces in the front of a house other than drive way) and thus the connected house walls (Figure 2). In a field experiment sponsored by CDPR, significant amount of pesticide runoff was detected from a house without applications to the driveway (Greenberg et al., 2016). During a heavy rain, pesticides from surfaces other than driveway could reach the driveway and then storm drains if there is a continuous impermeable surface in between. Actually, in the PWG modeling scenario, the "FP_I" with 4% area is conceptually equivalent to the surface II, but it's further adjusted by two factors: the "*fraction routed to stormwater system*" of 0.1 (Table 66 in the submitted report) and the "percent of surface are treated" of 0.1 (Table 43), resulting in a very small treated area fraction of 0.04% (Table 4).

Table 4. Treated areas and fractions over the modeled residential watershed (in the parentheses), historical application methods (EFED study did not simulate historical application methods)

	PWG	SWPP
Description	[foundation perimeter: 5-ft out, 2-ft up] + 10%*[lower driveway]	[foundation perimeter: 7-ft out, 3-ft up]
Surface I	117 (1.2%)	105 (2.0%)
Surface II	3.8 (0.04%)	149.2 (2.8%)
Surface III	36 (0.38%)	176.1 (3.3%)
Total	156.8 (1.6%)	430.3 (8.1%)

A reference value for evaluating the total treated fraction is 2.5%, i.e., the recommended treated fraction on impervious surfaces in modeling crack-and-crevice treatment (USEPA, 2012). The PWG settings for the historical practices mathematically represented a crack-and-crevice treatment of bifenthrin, with a total treated fraction of 1.6%, between 2.5% (for a house lot) and 1.25% (estimated by SWPP for the front of a house, Table 5).

For the *current application methods*, the three studies proposed different interpretations on the same set of regulatory actions, including label changes and regulations. Generally, spot and crack-and-crevice treatments are allowed on impervious surfaces by all regulations, while pin-stream treatment is allowed by the USEPA label change and CDPR surface water regulations (but not by the bifenthrin MOA). Therefore, SWPP modeled the current practices of bifenthrin application as crack-and-crevice treatment, with the EFED recommended treatment fraction (2.5% on impervious surfaces, which is divided by 2 for the treatment on the front of a house, or surfaces I and II). Both EFED and PWG simulated narrow-band perimeter treatment (2-in band by PWG and 1-in by PWG). In addition, PWG also considered applications to the lower driveway and house walls adjacent to the garage door.

Table 5. Treated areas and fractions over the modeled residential watershed (in the parentheses), current application methods

	EFED	PWG	SWPP
Description	[upper driveway: pin stream (1 inch)]	[upper driveway: 2-in]+ 1.4%*[lower driveway]+ [walls adjacent to the garage door: 4ft^2]	[driveway and sidewalk: crack and crevice]
Surface I	0.007%	6.8 (0.07%)	(1.25%)
Surface II	0	~0	
Surface III	0	4 (0.04%)	0
Total	0.007%	0.11%	1.25%

Note: For current practices, SWPP study also considered homeowner application methods which are not allowed for professional uses, e.g., applications on vertical walls connected to an impervious surface that could result in runoff into storm drain. To be consistent to other studies, those application methods are not considered in this review.

Relative to absolute values, it's more important to compare relative changes between the current and historical practices. The treated fraction (thus the applied mass) on the surfaces I~III would be reduced by 93% (1-0.11/1.6) in the PWG study, consistent with that proposed in their previous study, 95% (Winchell et al., 2013). The total treated fraction reduced by 84% (1-1.25/8.1) in the SWPP study. For comparison, a previous study had estimated use reductions of 80% on impervious surfaces according to bifenthrin MOA and surface water regulations (Jorgenson et al., 2013).

5 Modeling results and discussion

5.1 Comparison with monitoring data

The 21-d EEC of sediment concentrations was reported in the three studies and selected as the representative output variable for model review (Table 6). The three modeling studies used different partition coefficients in the water-phase simulations (Table 1), specifically, Kd by EFED, KOC from SPME (Solid Phase Micro-Extraction) by PWG, and KOC from LLE (Liquid-Liquid Extraction) by SWPP (Table 1). However, EFED tested the effects of partitioning coefficient on the VVWM modeling results, and concluded that the EEC of pore-water concentrations were very sensitive to the values of partitioning coefficient, but the EEC of sediment concentrations were generally invariant (USEPA, 2016).

Table 6. Summary of model inputs (application rates and methods) and outputs (1-in-10-year 21-d average concentration in sediment)

	Max application rate	Annual total rate	Scenario	Treated area fraction	21-d EEC, µg/g[OC]
EFED	1X [Label rate]	1X	Current	0.007%	0.02 (1)
PWG	0.44X	~2.6X	Historical	1.6%	2.64 (2)
			Current	0.11%	0.22 (2)
SWPP	0.76X	3X	Historical	8.1%	20.2 (3)
			Current	1.25%	3.1 (4)

Notes:

(1) Reported as 1.01 µg/kg[dw] (Table 37 of the EFED study report), converted to the unit of µg/g[OC] with the organic carbon content of 4% in the USEPA pond.

(2) Table 50 of the PWG study report.

(3) Calculated for this review. The original SWPP study only reported the peak EEC (22.2 µg/g[OC], Section 4.1 of the SWPP study report).

(4) Calculated for this review. The original SWPP study included homeowner uses in the current scenarios, resulting in a higher 21-d EEC of 4.0 µg/g[OC] (Table 11 of the SWPP study report).

Monitoring data for pyrethroids were compiled by PWG in 2013 and updated in 2016 (Giddings et al., 2016b) for both urban receiving water and storm drain outfalls in the United States. The statistics as the 90th, 95th, and 99th percentiles, and maximum values were reported, but results in the database report (Giddings et al., 2016b) are slightly different to those in the modeling report (Giddings et al., 2016a). Values in the modeling report (i.e., PWG study reviewed here) are shown in Figure 3 (labelled as "PWG" data). Since California modeling scenarios are reviewed here, the statistics with monitoring data collected by CDPR are considered ("CDPR" data in Figure 3). The same data set has been submitted with the CDPR's comments to the EFED study (CDPR, 2017).

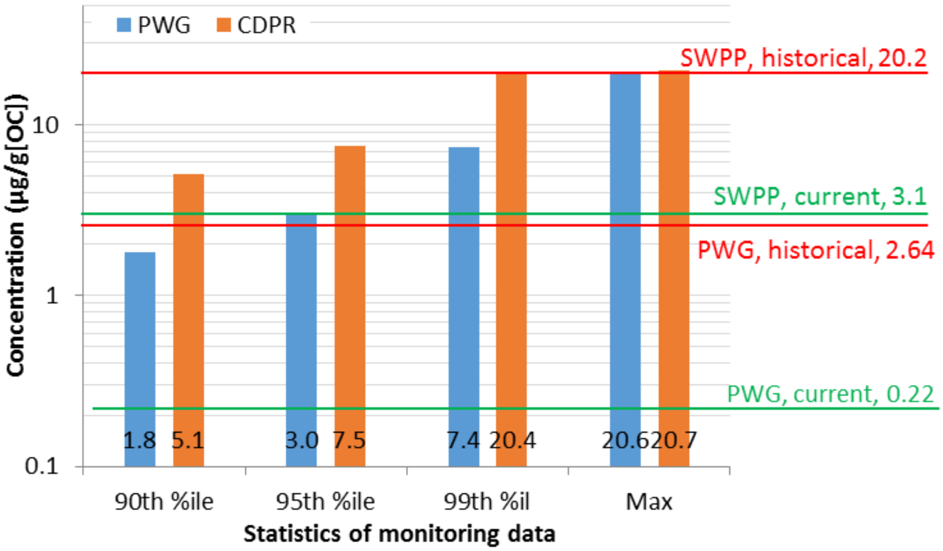


Figure 3. Model predictions (Table 6) vs. monitoring data. Columns are the statistics of monitoring data for concentrations of bifenthrin in sediment. Horizontal lines are modeling results as 21-d EEC's in sediment. EFED's EEC of 0.02 µg/g[OC] is not displayed.

For the historical application methods, the PWC's EEC is between the 90th and 95th percentile, barely meeting the expectation of the modeling efforts: "*systematic over-predictions in the modeled EECs at the high (90th and 95th) percentiles*" (page 158 in the PWG study report). The EEC predicted in SWPP study was originally validated by the representative concentrations in sediment, defined as the 90th percentile of annual maximum concentrations observed in urban receiving water of California. The comparison resulted in a ratio (observation/prediction, or P/O) of 1.6X for all measurements (Luo, 2017a), or about 3X for the measurements with organic carbon content (calculated for this review for the consistency with PWG compiled data for sediment concentration). Generally, this EEC met the SWPP validation criteria of 1~10X of the representative observation value.

EFED also presented their criteria for evaluating modeling results: the EEC and the 90th percentile monitored concentration should be "*within one order of magnitude difference of each other*" (USEPA, 2016). Based on the 90th percentile in California of 5.1 µg/g[OC], both the EEC's from PWG and SWPP studies for historical practices meet the EFED criteria. Note that PWG's EEC (2.64 µg/g[OC]) underestimated the 90th percentile, while SWPP's EEC (20.2 µg/g[OC]) overestimated it.

5.2 Cross-model comparisons

Within a model, a generally linear relationship is observed between the total treated fraction (on the surfaces I~III) and the EEC. From the historical to current practices in PWG study, for example, the total treated fractions were reduced by 14.5X (from 1.6% to 0.11%), while the EEC's were reduced by 12X (from 2.64 to 0.22 µg/g[OC], Table 6). Similar reductions (11~13X) were also observed for all other pyrethroids (cyfluthrin, lambda-cyhalothrin, cypermethrin, deltamethrin, esfenvalerate, and permethrin) based on PWG modeling results (Table 50 of the PWG study report). In SWPP study, the treated fractions were reduced by 6.5X from the historical to current practices, the same as the corresponding EEC reduction of 6.5X. There are no sufficient data to evaluate the linearity within the EFED model which only simulated the current practices.

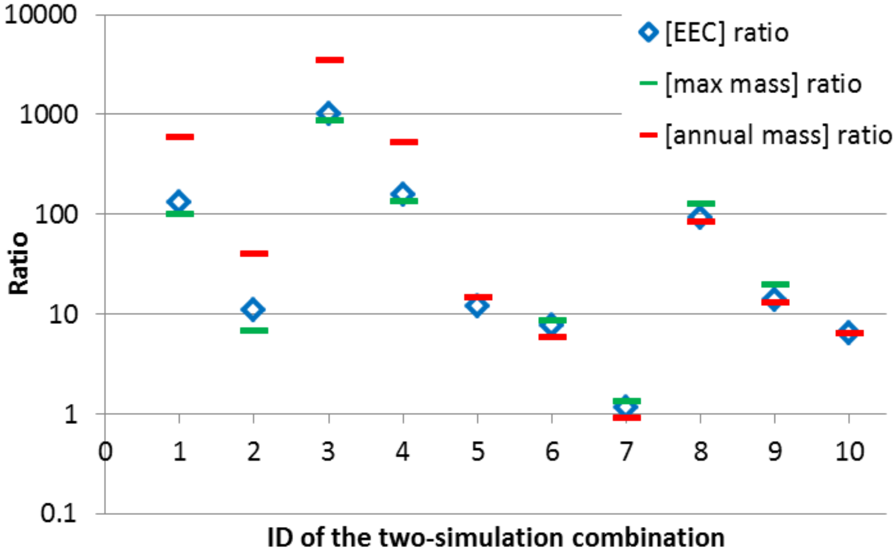
For cross-model comparison, both the treated fractions and application rates should be considered. For each model simulation, applied mass is estimated as two values based on the terminology in Table 6: [max mass] or the maximum mass applied in a single application, and [annual mass] or the cumulative mass applied per year,

$$\begin{aligned}&[\text{max mass}] = [\text{max rate}] * [\text{treated fraction}]\\&[\text{annual mass}] = [\text{annual rate}] * [\text{treated fraction}]\end{aligned} \qquad (1)$$

Among models, a general linear relationship was observed between the applied mass (on the surfaces I~III) and the EEC. Specifically, the ratio of EEC is generally bracketed by the ratios of [max mass] and [annual mass]:

$$\frac{EEC(i)}{EEC(j)} \in \left(\frac{[\text{max mass}](i)}{[\text{max mass}](j)}, \frac{[\text{annual mass}](i)}{[\text{annual mass}](j)}\right) \tag{2}$$

where i and j are any two of the 5 simulations under review (Table 6), and there are 10 combinations in total (Figure 4). Note that, for any two selected simulations, the one with higher EEC will be placed in the numerator, so that the resulting EEC ratio will be always ≥1. This is just for the convenience of result illustration. Taking the first combination in Figure 4 (the current practice by EFED and the historical practices by PWG) as an example, the EEC ratio is 132 (=2.64/0.02, Table 6), between the [max mass] ratio of 100.6 (=[0.44*1.6]/[1*0.007]) and the [annual mass] ratio of 594.3 (=[2.6*1.6]/[1*0.007]). There are two combinations for simulations with the same model, i.e., the historical and current practices by PWG (ID#5 in Figure 4) and the historical and current practices by SWPP (ID#10 in Figure 4). For these two combinations, the ratios for [max mass] and [annual mass] are the same and generally consistent to the EEC ratios, as already discussed above as the within-model linearity.



Notes: ID for each unique combination of any two from the five simulations in Table 6: ID#1=EFED and PWG_historical, 2=EFED and PWG_current, 3=EFED and SWPP_historical, 4=EFED and SWPP_current, 5=PWG_historical and PWG_current, 6= PWG_historical and SWPP_historical, 7= PWG_historical and SWPP_current, 8= PWG_current and SWPP_historical, 9= PWG_current and SWPP_current, and 10=SWPP_historical and SWPP_current

Figure 4. Ratios of EEC, [max mass], and [annual max] between any two simulations

It's also observed that the EEC ratios (blue diamonds in Figure 4) are more consistent to the [max mass] ratios (green bars) compared to the [annual mass] ratios (red bars). This suggests that the model-predicted EEC for bifenthrin in sediment is strongly related to the application event with the maximum rate. Repeated applications would certainly increase the EEC, but in a proportional way. For example, two applications are unlikely to double the EEC that predicted from one application.

The observed linearity in Eq. (2) suggests a simple, linear relationship between the predicted EEC and two dependent variables [max mass] and [annual mass]. This relationship is parameterized by regression with the data in Table 6,

$$EEC = 0.0091 + 2.3518 \times [\text{max mass}] + 0.235 \times [\text{annual mass}]\text{, } R^2=100\% \qquad (3)$$

Note that this equation is only for summarizing the model simulations reviewed here, not for predicting EEC. For example, it doesn’t mean that a EEC of 0.0091 μg/g[OC] should be related to no applications, [max mass]=[annual mass]=0. The applied masses are not random, independent, and continuous values from 0 to infinity, but carefully parameterized by interpreting application methods as documented in the study reports. Also, the relationship in Eq. (3) should not be simply extrapolated to other chemicals or other modeling settings. Finally, note that both [max mass] and [annual mass] are derived from the data values in Table 6. For example, the [max mass] in the EFED study is calculated as 1×0.007, where “1” denote 1X of the label rate and “0.007” is the treated fraction in percentage. The watershed area is not considered here.

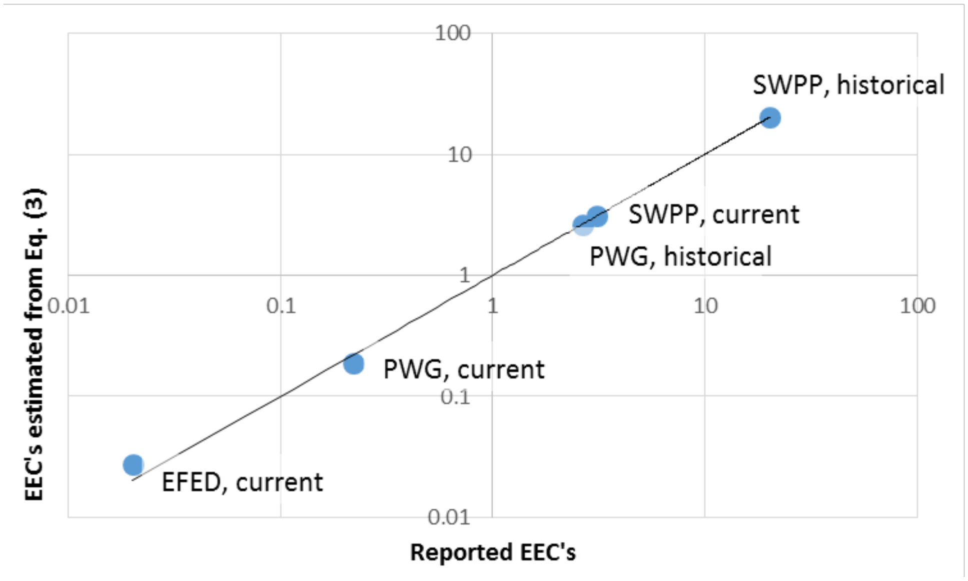


Figure 5. Model similarity with the linear relationship expressed in Eq. (3)

The simple linear relationship in Eq. (3) explained all the five simulations in the three modeling systems (Figure 5). In addition, the SWPP simulation with pinstream treatment of bifenthrin (treated fraction =0.0916%) (Luo, 2017a), not reviewed in this study, also generally follows the same relationship. As summarized in Eq. (3), for the reported simulation sets, the EEC is mainly determined by the pesticide mass applied, but less relevant to the model used. This finding suggests that there might be inherent similarity among the modeling studies presented by EFED, PWG, and SWPP for bifenthrin uses in California residential settings. Obviously, the observed similarity is more applicable where the pesticide runoff from a residential lot is predominated by the contribution from paved areas. If the treated fraction on impervious surfaces is extremely low, such as that in the EFED study (0.007%, Table 6), the linear relationship will underestimate the EEC (Figure 5). In this case, contributions from other surfaces could be significant to EEC’s, but not considered by the linear relationship.

The SWPP modeling study was only conducted for bifenthrin, so there are no sufficient data for a complete comparison for other pyrethroids. EFED and SWPP collaborated for a simple model comparison, with deltamethrin and esfenvalerate as test agents. The results were provided in Section 7.2.6 “Alternative exposure model (CDPR’s SWPP Model)” of the EFED study (USEPA, 2016) and summarized in Table 7. Except for the simulations with very low f_{IMP} (see discussions above), consistent ratios of EEC/f_{IMP} are observed for each chemical: 0.053~0.068 for deltamethrin and 0.105~0.108 for esfenvalerate.

Table 7. Model comparison for pyrethroids other than bifenthrin

	Chemical	f_{other} (%)	f_{IMP} (%)	21-d EEC (μg/L)	EEC/f_{IMP}
EFED	deltamethrin	25.05	0.007	1.16E-05	0.172
EFED	deltamethrin	15.12	1.81	9.60E-04	0.053
SWPP	deltamethrin	12	0.682	4.58E-04	0.067
SWPP	deltamethrin	7.36	3.474	2.35E-03	0.068
EFED	esfenvalerate	25.05	0.007	1.87E-04	2.774
EFED	esfenvalerate	15.12	1.81	1.96E-03	0.108
SWPP	esfenvalerate	12	0.682	7.18E-04	0.105
SWPP	esfenvalerate	7.36	3.474	3.75E-03	0.108

Notes: f_{IMP} = treated fraction on the surfaces I, II, and III (Figure 2), and f_{other} = treated fraction on other surfaces. All EEC’s are taken from tables 131 and 132 of the EFED study (USEPA, 2016). F values for EFED study are taken from table 130, while for SWPP study f’s are calculated during the review.

6 Conclusions

- EFED, PWG, and SWPP recently presented their modeling efforts for bifenthrin uses in residential areas of California. The modeling approaches are different in terms of simulation engines, urban/residential scenarios, environmental descriptions, and chemical properties (Table 1).
- However, the similarity in the three models is observed in spite of the differences. The linear relationship in Eq. (3) links the model inputs and outputs in the five reported simulations. In summary, the model output (the 21-d EEC in sediment) is mainly determined by the pesticide mass applied, but less relevant to the model used.
- In another words, the different EEC’s predicted in the studies by EFED, PWG, and SWPP are mainly attributed to the different pesticide mass applied, or more specifically, the application rates and treated area fractions. Inconsistence interpretations are observed in the modeling studies. For example, the application fractions range from 0.007% to 1.25% (i.e., a 178X difference) for the current practices of bifenthrin application (Table 6).
- Therefore, more efforts are suggested for the appropriate interpretation and mathematical representation of the application methods according to the labels (and label changes) and regulations. A series of studies have been initiated by CDPR for this purpose, including study #303 (source identification for urban pyrethroid use) (Ensminger and Johnson, 2016) and pyrethroid use survey at watershed scale (Budd et al., 2017). Those will be

helpful for more consistent pesticide risk assessment, and also for future development of labels and regulations.

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