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ORIGINAL PAPER

A two-dimensional probabilistic acute human-health risk assessment of insecticide exposure after adult mosquito management

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Abstract Ultra-low-volume (ULV) aerosol applications of insecticides are used to manage high densities of adult mosquitoes. We used two-dimensional probabilistic risk assessment methodologies to evaluate three pyrethroid insecticides (phenothrin, resmethrin, and permethrin), pyrethrins, and two organophosphate insecticides (malathion and naled), applied by truck-mounted ULV sprayer. Piperonyl butoxide, a synergist commonly used in pyrethroid and pyrethrins formulations, was also assessed. The objective of our study was to evaluate probabilistically if a deterministic human-health risk assessment of mosquito insecticides was sufficiently conservative to protect human-health. Toddlers and infants were the highest risk groups while adult males were the lowest risk group assessed in this study. Total acute exposure ranged from 0.00003 to 0.0003 mg/kg day^{-1} for the chemicals and subgroups assessed examining inhalation, dermal, oral, and hand-to-mouth exposure. We used the risk quotient (RQ) method for our risk assessment, which is calculated by dividing the total potential exposure for each subgroup and chemical by its ingestion toxic endpoint value (RfD). Mean RQs ranged from 0.000004 to 0.034 for all subgroups and chemicals, with none exceeding the RQ level of concern. Naled had the highest RQs of any chemical assessed while PBO had the lowest. Sensitivity analysis demonstrated that the exposure from inhalation and deposition contributed the largest variance to the model output. Results support the findings of previous studies that the risks from adult mosquito management are most likely negligible, and that the human-health deterministic risk assessment is most likely sufficiently conservative.

Keywords Pest management · Risk analysis · Ultra-low-volume · Pyrethroid · Organophosphate

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1 Introduction

Ultra-low-volume (ULV) aerosol applications of insecticides are used to manage high densities of adult mosquitoes. ULV is the minimum effective volume of insecticide that is used as a space spray for adult mosquitoes. Small droplets from 5 to 25 μm are the optimum size to impinge on and knock down flying adult mosquitoes (Lofgren et al. 1973; Mount 1998; Weidhaas et al. 1970). Smaller droplets tend to travel farther and not settle out of the air column as quickly as larger droplets, making ULV an effective measure for the control of host seeking adult mosquitoes.

Since West Nile virus was introduced into the United States in 1999, more areas of the country have been experiencing large-scale insecticide applications for mosquito-borne diseases. With the majority of Americans not concerned about contracting West Nile virus (Ho et al.

2007), there has been greater public attention to the human-health and environmental risks associated with ULV insecticide applications (Peterson et al. 2006; Reisen and Brault 2007). In response to concerns about the safety of ULV insecticides, tier I/II (reasonable worst case) risk assessments have been performed to quantify estimates of risk. Peterson et al. (2006) performed a deterministic human-health risk assessment for acute and subchronic exposures to 6 mosquito insecticide active ingredients, and the synergist piperonyl butoxide (PBO), after ground-based ULV applications. They found that acute and subchronic risks to humans from the insecticides would most likely be negligible.

Davis et al. (2007) conducted a deterministic tier I/II ecological risk assessment and examined the same mosquito insecticides and synergist as Peterson et al. (2006) and found that the risks to mammals, birds, and aquatic vertebrates and invertebrates most likely would be negligible after truck-mounted ULV applications. Schleier et al. (2008a) examined deterministically and probabilistically the 6 mosquito insecticides and the synergist as well, and found similar results, demonstrating that the equine risks from truck-mounted ULV would be very low. The probabilistic analysis of Schleier et al. (2008a) demonstrated that the deterministic analysis was sufficiently conservative, with deterministic exposures between the 85th and 95th percentile of exposures.

Macedo et al. (2007) determined that the risks to military personnel exposed to truck-mounted ULV permethrin, resmethrin, phenothrin, or PBO are most likely negligible. Carr et al. (2006) showed that the use of aerially applied ULV resmethrin above agricultural fields as a result of a public health emergency would most likely result in negligible human dietary risk. Biomonitoring and epidemiological studies, reports, and regulatory assessments have concluded that risks to humans and non-target organisms from exposure to mosquito insecticides most likely are negligible (Currier et al. 2005; Karpati et al. 2004; NYCDOH 2005; O'Sullivan et al. 2005; Suffolk-County 2006).

Because of ongoing concerns by the public about the safety of insecticides used for the control of adult mosquitoes, the objective of our study was to evaluate probabilistically the conservatism of the human-health risk assessment of mosquito insecticides performed by Peterson et al. (2006). We also examined which input variables were contributing the largest amount of variability to the model outputs. Even though the deterministic risk assessments conducted to date have not revealed unacceptable exposures, it is important to conduct probabilistic assessments to ensure appropriate conservatism in deterministic assessments and to better quantify uncertainty and variability. An understanding of the variables that are contributing the largest amount of variability to the model outputs will help to direct future research.

2 Materials and methods

2.1 Problem formulation

We performed a probabilistic two-dimensional assessment of acute human exposure after truck-mounted ULV insecticide applications. Few studies have characterized deposition and inhalation of these insecticides, so we used the two-dimensional analysis to separate uncertainty from variability (i.e. body weight, inhalation rate, etc.) (Frey and Rhodes 1996). We used one-dimensional sensitivity analysis to determine the impact of input variables on the overall variation in the output values of the model (Cullen and Frey 1999). Acute exposures were defined in this study as single-day exposures after a single insecticide application.

We examined exposures to several population subgroups to account for age related differences in exposure. Groups included adult males and adult females (18–65 years of age), youth (10–12 years of age), children (5–6 years of age), toddlers (2–3 years of age) and infants (0.5–1.5 years of age).

2.2 Hazard identification

We assessed two classes of chemicals and a synergist commonly used in mosquito management. Malathion and naled are organophosphate insecticides, which are neurotoxins that inhibit acetylcholine esterase in mammals. Permethrin, resmethrin, and phenothrin are pyrethroid insecticides, which are neurotoxins that act on the sodium channels of mammals. Pyrethrins are naturally derived insecticides from Chrysanthemum species and, like pyrethroids, are neurotoxins that target the sodium channels of mammals. The synergist, piperonyl butoxide (PBO), is a P450 monooxygenase inhibitor present in many of the pyrethroid and pyrethrins formulations. All compounds are currently registered by the United States Environmental Protection Agency (USEPA) for use in adult mosquito management in the United States. The maximum application rates for PBO, phenothrin, permethrin, resmethrin, malathion, naled, and pyrethrins are 43.94, 4.48, 7.85, 7.85, 71.62, 22.42, and 10.09 g active ingredient/ha, respectively.

Dose-response information for each compound was reviewed and endpoints were chosen based on acute exposure. The toxicity endpoints used in this assessment were ingestion reference doses (RfD) that are based on the no-observed-adverse-effect-level in mammals with the appropriate safety factors, which are determined by the USEPA. The acute oral RfD for PBO, phenothrin, permethrin, resmethrin, malathion, naled, and pyrethrins are 6.3, 0.7, 0.25, 0.1, 0.14, 0.01, and 0.07 mg/kg day^{-1}, respectively (USEPA 2000b, c, 2002b, 2006a, b, c, d).

2.3 Estimation of environmental concentrations

We used the Kenaga nomogram (Fletcher et al. 1994) to predict environmental deposition of the insecticides on tomatoes. The Kenaga nomogram is a linear model that uses application rate to predict concentrations of the insecticide on different types of food. To provide a conservative exposure value, we used fruits and vegetables as the insecticide recipient. To estimate exposure to each subgroup from the ingestion of tomato products, we used the dietary exposure estimation model (DEEM). We created custom distributions from the percentiles of exposure generated in DEEM for our assessment.

We used AERMOD version 1.0 tier-1 air dispersion model (USEPA 1999) to predict the air concentrations at 7.62 m (25 ft) from the spray source, for the six active ingredients and PBO within 6 h after truck-mounted ULV application (Peterson et al. 2006). The assumptions included: (a) each chemical had a 24-h half-life in the air except for naled, which had a 18-h half-life; (b) the insecticides were applied at the maximum application rate as stated on each label; (c) all of the insecticides were susceptible to the same weather conditions using standardized weather data from Albany, New York, USA from 1988; (d) all spray events occurred at 2100 hours; and (e) each spray release was at 1.5 m.

Receptors were established within the model on a Cartesian grid at 5 intervals of 7.6 m from the edge of the spray source. The receptors were at a height of 1.5 m. At each receptor, the estimated 6 h average air concentrations for each insecticide were determined. Distributions were created from the six receptors at 7.6 m that were not at the edges of the spray zone.

The industrial source complex dispersion model (ISCST3) was used to model particle deposition at 7.62 m from the spray area at the 6-h average (USEPA 1995). ISCST3 is AERMOD's predecessor and was developed first for prediction of deposition and aerial concentrations of industrial pollutants. The same assumptions were used with this program as with AERMOD except that the default meteorological data were from Salem, MA, USA. The following assumptions were made in addition to those from AERMOD: the ULV applications had 3% of the emitted particles greater than the allowable particle size as stated on the label, and the particles were assigned a density in accordance with the specific gravity of each insecticide. A similar Cartesian grid was used for ISCST3 that was used in AERMOD. The receptors were at ground level and accordance with the grid used for AERMOD. The same methods were used to calculate the average deposition at 7.6 m. Table 1 shows the distributions for each chemical for AERMOD and ISCST3.

2.4 Acute exposure

We assumed multi-route exposures immediately after a single-spray event were limited to 24 h. Routes of insecticide exposure to each subgroup were inhalation, dermal, and dietary and non-dietary ingestion. Assumptions of body weight, respiration rate, and frequency of hand-to-mouth activity are presented in Table 2. We assumed that each subgroup would be outside when the spray truck passed and the duration of the exposure was for 6 h. Peterson et al. (2006) contains more information on the exposure modeling assumptions, which are briefly reviewed here. Acute inhalation exposure was estimated by

$$PE_{inhalation} = (EEC \times RR \times D)/BW, \quad (1)$$

where $PE_{inhalation}$ is potential exposure from inhalation (mg/kg BW), EEC is estimated environmental air concentrations as estimated by AERMOD ($\mu g/m^3$), RR is respiratory rate for each subgroup (m^3/h; Table 2), D is duration of exposure (h), and BW is body weight for each subgroup (kg; Table 2).

Acute dermal exposure from spray deposition was estimated by

$$PE_{Dermal} = (ADE \times CF \times AR \times AB \times D)/BW, \quad (2)$$

where PE_{Dermal} is potential exposure from dermal contact (mg/kg BW), ADE is adjusted dermal exposure (mg/lb AI), CF is the dermal conversion factor which is the increase in exposure from the flagger scenario, which we assumed a person would be exposed 10 to 100 times more than the flagger scenario (Macedo et al. 2007; Peterson et al. 2006), we used a uniform distribution to represent this, AR is

Table 1 Input distributions for ground deposition and aerial concentrations for each chemical

Input	Distribution type	Parameter	PBO	Phenothrin	Permethrin	Resmethrin	Malathion	Naled	Pyrethrins	Units
Soil deposition	Gamma (truncated)	Location	3.48	0.36	0.7	0.73	4.62	1.29	0.76	mg/m^2
		Scale	5.94	0.58	1.15	1.2	8.44	2.22	1.25	
		Shape	0.97	1.091	1.043	1.035	0.754	0.961	1.039	
Aerial concentrations	Maximum extreme (truncated)	Mode	0.5286	0.0895	0.1285	0.1285	0.876	0.876	0.1871	$\mu g/m^3$
		Scale	0.1172	0.0198	0.0285	0.0285	0.1842	0.18418	0.0415	

Table 2 Assumptions for body weight, respiration rate, and frequency of hand-to-mouth activity for each subgroup assessed

Input variables	Subgroup	Parameter	Values	Units	Distribution	Source
Body weight	Adult Males	Mean	78.65	kg	Log-normal (truncated)	Portier et al. (2007)
		SD	13.23			
	Adult Females	Mean	65.47	kg		
		SD	13.77			
	Youth	Mean	36.16	kg		
		SD	7.12			
	Children	Mean	19.67	kg		
		SD	2.81			
	Toddlers	Mean	13.27	kg		
		SD	1.62			
	Infants	Mean	9.1	kg		
		SD	1.24			
Respiration rate	Adult Males	Mean	17.53	m^3/day	Log-normal (truncated)	Brochu et al. (2006)
		SD	2.8			
	Adult Females	Mean	13.78	m^3/day		
		SD	2.1			
	Youth	Mean	11.3	m^3/day		
		SD	2.14			
	Children	Mean	7.74	m^3/day		
		SD	1.04			
	Toddlers	Mean	5.03	m^3/day		
		SD	0.94			
	Infants	Mean	3.72	m^3/day		
		SD	0.81			
Hand-to-Mouth frequency	Toddlers	Location	5.3	events/h	Weibull (truncated)	Xue et al. (2007)
		Scale	3.41			
		Shape	0.56			
	Infants	Location	14.5	events/h		
		Scale	15.98			
		Shape	1.39			

SD standard deviation

application rate (lb AI/acre), AB is dermal absorption rate for each chemical, D is duration of exposure (h), and BW is body weight (kg). Surface area for all subgroups was estimated using

$$\mathrm{SA} = 4\mathrm{BW} + 7/\mathrm{BW} + 90, \quad (3)$$

where SA is surface area and BW is body weight (USEPA 1997b, 2002a). To adjust the flagger exposure we used

$$\mathrm{ADE} = \mathrm{FE} \times (\mathrm{SA}_{\mathrm{subgroup}}/\mathrm{SA}_{\mathrm{male}}), \quad (4)$$

where ADE is the adjusted dermal exposure (mg/lbs AI), FE is the flagger exposure, $\mathrm{SA}_{\mathrm{subgroup}}$ is the surface area of each subgroup as estimated by Eq. 3, $\mathrm{SA}_{\mathrm{male}}$ is the surface area of an adult male as estimated by Eq. 3. Because there are few data available on dermal deposition after truck-mounted ULV applications, we used the USEPA Pesticide Handler Exposure Database (USEPA 1998) as a conservative surrogate. We used a flagger exposure scenario in which a person is exposed to an application of a liquid formulation, we assumed a triangular distribution with the maximum being a flagger with no clothing (0.053 mg/lb AI), a minimum being a single layer of clothing with no gloves (0.011 mg/lb AI), and the most likely being a person with their face, arms, legs, hands, and feet exposed (0.0327 mg/lb AI) (USEPA 1997b, 1998). The dermal absorption rates for PBO, phenothrin, permethrin, resmethrin, malathion, naled, and pyrethrins are 2, 70, 15, 2, 10, 100, and 0.22%, respectively (USEPA 2000a, c, 2002b, 2005a, c, 2006b, e).

For infants and toddlers, hand-to-mouth exposure from insecticide settling onto their hand was estimated by

$$\mathrm{PE}_{\mathrm{Hand-to-mouth\,skin}} = [(\mathrm{AMH} \times \mathrm{AR} \times \mathrm{CSA}) \times \mathrm{PC} \times \mathrm{SEF}]/\mathrm{BW}, \quad (5)$$

where $PE_{Hand\text{-}to\text{-}mouth\ skin}$ is potential exposure from hand-to-mouth activity from the insecticide settling on the skin (mg/kg BW), AMH is adjusted male hand dermal exposure (mg/lb AI) and was estimated using Eq. 4 with an FE (flagger exposure) of 0.00272 (mg/lb AI) (USEPA 1998), AR is application rate (lb AI/acre), CSA is child hand surface area (m^2), PC is percent of the hand contacted with the mouth which we assumed to be 50%, SEF is saliva extraction factor of 50% (USEPA 2005b), and BW is body weight (kg). Child hand surface area (CSA) was estimated by

$$CSA = (SA \times PH)/2, \quad (6)$$

where SA is the surface area as calculated by Eq. 3 and PH is the percent surface area of two hands. PH for infants had a triangular distribution with a mean of 5.3% and a minimum value of 5.21% and a maximum value of 5.39% and for toddlers we used a triangular distribution with a mean of 5.68% a minimum of 5.57% and a maximum of 5.78% (USEPA 2002a).

Although not included in Peterson et al. (2006), we examined acute hand-to-mouth exposure from turf dislodgeable residue to toddlers and infants through contact of the hand with insecticide that has settled onto turf. Exposure from hand-to-mouth activity from turf dislodgeable residue was estimated by

$$PE_{Hand-to-mouth\ turf} = [(EEC \times CSA \times DR) \times PC \times AR \times FA \times SEF \times D]/BW, \quad (7)$$

where $PE_{Hand\text{-}to\text{-}mouth\ turf}$ is potential exposure from hand-to-mouth turf dislodgeable residue (mg/kg BW), EEC is estimated environmental ground deposition as estimated by ISCST3 (mg/m^2), CSA is child hand surface area as estimated by Eq. 6 (m^2), DR is the dislodgeable residue, which we assumed to be 20% for all chemicals (USEPA 1997a), PC is percent of the hand contacted with the mouth which we assumed to be 50% per event, FA is frequency of activity (events/hour), SEF is saliva extraction factor of 50% (USEPA 2005b), D is duration of exposure, and BW is body weight (kg).

For acute ingestion exposure from tomatoes, we assumed that all foods containing tomatoes eaten per day were consumed from tomatoes grown in a home garden without being washed, and we assumed there would be no degradation in the preparation process. Acute ingestion was estimated by

$$PE_{Ingestion} = DE/BW, \quad (8)$$

where $PE_{Ingestion}$ is potential exposure from ingestion (mg/kg BW), DE is the estimated ingestion exposure as estimated by DEEM (mg), and BW is body weight (kg).

Total acute exposure to active ingredients for each subgroup was estimated by

$$PE_{Total} = PE_{Inhalation} + PE_{Dermal} + PE_{Hand-to-mouth\ turf} + PE_{Ingestion} \quad (9)$$

2.5 Risk characterization

We used the risk quotient (RQ) method for our risk assessment, which is calculated by dividing the total potential exposure PE_{Total} for each subgroup and chemical by its ingestion toxic endpoint value (RfD). The multiroute exposure in our assessment was compared to the ingestion RfD because it provided a conservative endpoint, which is based on the most sensitive no-observed-adverse-effect-level. Estimated RQs are compared to a RQ level of concern (LOC), which is set by the USEPA or another regulatory agency to determine if regulatory action is needed. The RQ LOC used in our assessment was 1.0. An RQ of >1.0 means that the estimated exposure is greater than the relevant RfD.

2.6 Probabilistic analysis

For the probabilistic risk assessment, we used Monte–Carlo simulation (Crystal Ball® 7.3; Decisioneering, Denver, CO) to evaluate the RQ and input variables used to calculate the RQ. Probabilities of occurrence of RQ values were determined by incorporating sampling from the statistical distribution of each input variable used to calculate the RQs. Each of the input variables was sampled so that each input variable's distribution shape was reproduced. Then, the variability for each input was propagated into the output of the model so that the model output reflected the probability of values that could occur. For soil deposition, air concentrations, body weight, respiratory rate, and hand-to-mouth frequency we used gamma, maximum extreme, log-normal, log-normal, and weibull distributions, respectively. We truncated respiratory rate, body weight, hand-to-mouth frequency, air concentrations, and ground deposition at zero because it is not possible for these quantities to have negative values (Table 2).

Two-dimensional analyses were performed using 10,000 randomizations of variability and 250 randomizations of uncertainty to calculate the mean and 95% confidence interval for our estimate of risk. For the two-dimensional analysis body weight, inhalation rate, percent surface area of two hands, and hand-to-mouth frequency were placed in the variability category. Uncertainty parameters were dermal exposure from direct deposition, dermal conversion factor, ground deposition, air concentrations, and ingestion exposure. Sensitivity analysis was performed using one-dimensional probabilistic analysis using 20,000

randomizations on permethrin, naled, and PBO to examine which of the uncertainty parameters were contributing the most the output of the model for each subgroup and chemicals. We chose these chemical to represent their class of insecticide because the input variables for each class were similar for the chemicals.

3 Results

Our results show that the deterministic risk estimates of Peterson et al. (2006) were 6–100 times greater than our results at the 95th confidence interval of exposure (Table 3). Toddlers and infants were the highest risk groups while adult males were the lowest risk group assessed in this study (Table 3). Total acute exposure ranged from 0.00003 to 0.0003 mg/kg BW day^{-1} for the chemicals and subgroups assessed. Mean RQs ranged from 0.000004 to 0.034 for all subgroups and chemicals with none exceeding the RQ LOC (Table 3). Naled had the highest RQs of any chemical assessed, while PBO had the lowest RQ.

Our results show that mean inhalation exposure contributed about 60% to the overall exposure to adult males and females, youth, and children; however, the mean inhalation exposure only contributed 8% to the overall exposure of toddlers and infants. Exposure from hand-to-mouth turf dislodgeable residue at the mean contributed 60% to the overall exposure of toddlers and infants. Mean ingestion exposure contributed about 30% to the overall exposure of all subgroups.

The sensitivity analysis for permethrin demonstrated that air concentrations contributed the largest amount of variance to the output for adult males and females, youth, and children (Table 4). For toddlers and infants, ground deposition contributed the largest variance to the output (Table 4). The sensitivity analysis for naled demonstrated that the dermal conversion factor contributed the largest variance to the output for all subgroups (Table 4). The sensitivity analysis for PBO showed that the dermal

Table 3 Acute RQ means and 95% confidence intervals for each subgroup and chemical assessed

Chemical	Adult male[b]	Adult female[c]	Youth[d]	Children[e]	Toddlers[f]	Infants[g]
PBO[a]						
Mean	4.02E-06	4.44E-06	5.32E-06	7.16E-06	4.77E-05	8.36E-05
95% C.I.	5.50E-06	6.03E-06	7.75E-06	1.00E-05	1.13E-04	1.36E-04
Phenothrin						
Mean	1.62E-05	2.51E-05	3.11E-05	3.39E-05	7.15E-05	9.42E-05
95% C.I.	2.12E-05	3.16E-05	3.94E-05	4.16E-05	1.44E-04	1.42E-04
Permethrin						
Mean	2.48E-05	2.66E-05	3.26E-05	3.56E-05	2.51E-04	4.38E-04
95% C.I.	3.45E-05	3.79E-05	4.96E-05	5.08E-05	5.94E-04	6.95E-04
Resmethrin						
Mean	7.14E-05	7.20E-05	8.99E-05	9.06E-05	2.98E-02	8.19E-02
95% C.I.	9.98E-05	1.02E-04	1.37E-04	1.34E-04	7.86E-02	1.39E-01
Malathion						
Mean	4.32E-04	3.68E-04	6.07E-04	7.94E-04	3.41E-03	5.29E-03
95% C.I.	5.94E-04	4.99E-04	8.60E-04	1.12E-03	7.75E-03	8.43E-03
Naled						
Mean	1.17E-02	1.52E-02	1.91E-02	1.82E-02	2.68E-02	3.35E-02
95% C.I.	1.44E-02	1.91E-02	2.53E-02	2.33E-02	4.89E-02	4.63E-02
Pyrethrins						
Mean	6.40E-05	5.08E-05	6.93E-05	9.34E-05	5.02E-04	8.77E-04
95% C.I.	9.76E-05	7.45E-05	1.09E-04	1.37E-04	1.12E-03	1.41E-03

[a] Piperonyl Butoxide

[b] 18–65 years of age

[c] 18–65 years of age

[d] 10–12 years of age

[e] 5–6 years of age

[f] 2–3 years of age

[g] 0.5–1.5 years of age

Table 4 Sensitivity analysis (percent contribution of the input variable to the output variance) of uncertain factors for permethrin, naled, and piperonyl butoxide (PBO)

	Adult male	Adult female	Youth	Children	Toddlers	Infants
Permethrin						
Air concentrations	48.9[a]	41.4	32.9	18.1	0.4	0.2
Dermal conversion factor	28.6	32.5	22.2	10.5	0.3	0.1
Ingestion exposure	14.3	16	38.7	68.5	11.6	0.4
Dermal exposure	8.2	10.1	6.2	2.9	0.1	0
Ground deposition	0	0	0	0	87.6	99.4
Naled						
Air concentrations	0.2	0.2	0.3	0.3	0.2	0.2
Dermal conversion factor	79.8	80.2	80.1	79.9	75.9	67.8
Ingestion exposure	0	0	0.1	0.3	0.8	0.1
Dermal exposure	20	19.6	19.5	19.5	18.8	17.5
Ground deposition	0	0	0	0	4	14.4
PBO						
Air concentrations	32.3	26.3	23.2	12.9	0.4	0
Dermal conversion factor	41.6	43.4	29.6	14.6	0.5	0.1
Ingestion exposure	14.8	17.6	39.2	68.2	12.8	0.6
Dermal exposure	11.4	12.7	8	4.3	0.1	0
Ground deposition	0	0	0	0	86.2	99.2

[a] Percent contribution of the input variable to the output variance

conversion factor contributed the largest variance to the output for adult males and females, for youth and children ingestion exposure contributed the largest amount of variance to the output, and for toddlers and infants ground deposition contributed the largest amount of variance to the output (Table 4).

4 Discussion

In our assessment, we estimated the risks from a multi-route exposure after a truck-mounted ULV insecticide application. The USEPA in their reregistration eligibility documents only examined exposure from inhalation after ULV applications (USEPA 2006b, c, d, e). Inhalation contributed 60% to the estimated overall exposure for adult males and females, youth and children, but it only contributed about 8% to the overall exposure of toddlers and infants. Our results demonstrate that when examining the acute risks after ULV application, turf dislodgeable residue should be considered for toddlers and infants even though the estimated risks were well below RQ LOCs.

Sensitivity analysis suggested that permethrin inhalation for adult males and females, youth, and children contributed the most to the output variability while for naled across all subgroups the dermal conversion factor contributed the largest amount to the output variance, which can be explained by the application rate. When larger application rates (i.e. naled) are multiplied with the dermal conversion factor, this generates a larger range of exposures, and thus variance, when compared to a lower application rate (i.e. permethrin).

To predict deposition we used ISCST3, which is an industrial plume model and was not designed to model ULV applications. However, this was the most appropriate model for deposition onto surfaces like the ground. For deposition onto skin, we used a flagger exposure scenario which was designed for agricultural applications of insecticides not ULV applications. Previous studies of truck-mounted ULV applications have found 1 to 22.3% of the insecticide sprayed during application settled onto the ground, with concentrations decreasing substantially over 36 h (Knepper et al. 1996; Moore et al. 1993; Tietze et al. 1994; Tucker et al. 1987). The values predicted by ISCST3 were 1.7–13.5 times more than what was observed in other studies (Knepper et al. 1996; Moore et al. 1993; Tietze et al. 1994). The values that were modeled by ISCST3 are 103- and 205.8-fold more than concentrations measured after aerial application of ULV pyrethrins and PBO (Schleier et al. 2008b).

In addition to deposition onto surfaces our use of the default flagger scenario in the USEPA Pesticide Handler Exposure Database overestimates exposure by about 40% (Driver et al. 2007). Our model is very conservative for deposition when compared to truck-mounted and aerial applications; even though it is conservative with respect to

deposition, there is a substantial data gap in the air concentrations after aerial and truck-mounted ULV applications.

In addition to uncertainties in air concentrations, there are also toxicological uncertainties with respect to PBO. PBO has been shown to increase the toxicity of pyrethroids to aquatic organisms, but there is no indication that PBO acts as a synergist in mammals (Amweg et al. 2006; Paul et al. 2005; USEPA 2006c). If a tenfold uncertainty factor was applied to the RfDs based on the toxicological uncertainties of PBO synergizing with pyrethroids or pyrethrins, no chemical would exceed the RQ LOC.

The present study supports the findings of Peterson et al. (2006) that the risks from WNV most likely are greater than the risks from adult mosquito management. Additionally, our results show that the deterministic risk estimates of Peterson et al. (2006) were very conservative. RQs ranged from 0.000004 to 0.034 for all subgroups and chemicals with none exceeding the RQ LOC. Sensitivity analysis demonstrated that air concentrations contributed 0.1–48.9% while the conversion factor contributed 0.1–79.8% to the output variance for all subgroups and chemicals. For infants and toddlers, ground deposition contributed 4.3–99.4% to the output variance for all chemicals assessed. The present study demonstrated that the air concentrations and surface deposition contribute the largest amount of variability to the model output, and are also highly uncertain. Additional data need to be generated to more accurately characterize risk and reduce uncertainty.

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