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Projected Hg Dietary Exposure of 3 Bird Species Nesting on a Contaminated Floodplain (South River, Virginia, USA)

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ABSTRACT

Dietary Hg exposure was modeled for Carolina wren (*Thryothorus ludovicianus*), Eastern song sparrow (*Melospiza melodia*), and Eastern screech owl (*Otus asio*) nesting on the contaminated South River floodplain (Virginia, USA). Parameterization of Monte-Carlo models required formal expert elicitation to define bird body weight and feeding ecology characteristics because specific information was either unavailable in the published literature or too difficult to collect reliably by field survey. Mercury concentrations and weights for candidate food items were obtained directly by field survey. Simulations predicted the probability that an adult bird during breeding season would ingest specific amounts of Hg during daily foraging and the probability that the average Hg ingestion rate for the breeding season of an adult bird would exceed published rates reported to cause harm to other birds ($>$100 ng total Hg/g body weight per day). Despite the extensive floodplain contamination, the probabilities that these species' average ingestion rates exceeded the threshold value were all $<$0.01. Sensitivity analysis indicated that overall food ingestion rate was the most important factor determining projected Hg ingestion rates. Expert elicitation was useful in providing sufficiently reliable information for Monte-Carlo simulation. Integr Environ Assess Manag 2013;9:285–293. © 2012 SETAC

Keywords: Bird   Expert elicitation   Exposure   Food   Mercury   Monte-Carlo simulation

INTRODUCTION

Mercury from anthropogenic sources can elevate Hg concentrations in ecosystems to harmful levels (Bergeron et al. 2007; Flanders et al. 2010; Bundschuh et al. 2011). Top predators are especially susceptible because Hg body burden in these species might be elevated to levels that cause adverse effect due to Hg biomagnification (Wren and MacCrimmon 1983; Newman et al. 2011). Many birds occupy relatively high trophic positions in terrestrial communities, and, consequently, are often used to biomonitor available Hg in contaminated habitats (Evers et al. 2005). Determinations of bird exposure to Hg can provide the insight required for decision making about the overall state of a terrestrial community.

Birds are exposed primarily through food items that vary in Hg concentration (Wren and MacCrimmon 1983; Morel et al. 1998; Rumbold 2005). It follows that, with enough understanding of an avian species' feeding ecology, one could identify potential food items, their consumption frequencies, and associated Hg concentrations. Probabilistic models also incorporating bird body weight information could then be used to define possible Hg exposure distributions. Such models were built to assess Hg exposure to several piscivorous birds (Moore et al. 1999; Sample and Suter 1999; MacIntosh et al. 1994; Rumbold 2005). Probabilistic models have also been used to assess potential risk associated with other chemicals or species (Moore et al. 1997; Wayland et al. 2007).

The South River (Virginia, USA) was contaminated (1929 to 1950) with Hg from a former DuPont Facility at Waynesboro where it was used as a catalyst during acetate fiber manufacture (Carter 1977). After discharge ended, many descriptive studies and assessments were done to define the Hg contamination and potential impacts in related habitats. Currently, Hg concentrations remain elevated in different components of South River watershed.

Three avian species were selected based on a previous study (Newman et al. 2011) and dialog with river risk managers to address 2 crucial issues in this study. The first issue was description and determination of current Hg exposure to adults of 3 avian species during nesting on the South River floodplain. Results were to be expressed as cumulative probability distributions of (average) daily Hg ingestion rates. The distributions were then to be compared among these potentially at-risk species. The second issue was to judge the risk of harmful Hg exposure to these species by comparing the distributions of average daily Hg ingestion rates to published toxicity test results. A formal expert elicitation involving a modified Delphi framework was conducted to collect specific information that was either unavailable from the published literature or too difficult to collect reliably by field survey.

MATERIALS AND METHODS

Study species

Carolina wren, *Thryothorus ludovicianus*, maintains territories and pair bonds year-round (Haggerty and Morton 1995). It is a ground-foraging insectivore feeding mostly on

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insects and spiders, and also small amounts of plant material (Haggerty and Morton, 1995; Kurpinski and Kirschbaum 2011).The Eastern song sparrow, *Melospiza melodia*, also defends territories and maintains pair bonds year-round (Arcese et al. 2002). It often eats large amounts of plant material such as fruit and grain, but during breeding period, shifts its diet to include more insects. The Eastern screech owl, *Otus asio*, maintains its territories in winter and summer (Gehlbach 1995). It feeds mainly on invertebrates (insects, crayfish, and earthworms) and some vertebrates (songbirds and rodents) (Gehlbach 1995).

The daily Hg ingestion rates of adult birds during breeding periods were modeled in this study. Sexual differences were not included for 2 reasons. Body weight, which influences Hg ingestion rate, is only slightly different between sexes (Gehlbach 1995; Haggerty and Morton 1995; Arcese et al. 2002) relative to differences among individual birds within a sex. Any such differences were regarded as included in the range of body weights among individual birds. Also, although there were published studies suggesting that female birds eliminate Hg by deposition in eggs, Brasso et al. (2010) found that there was no decline in Hg concentrations with laying sequence in eggs of tree swallows nesting on the South River floodplain. This study suggested that daily ingestion of Hg on the South River might compensate for any Hg loss, as suggested by Evers et al. (2005). Finally, as a result of morphological, food selection, and metabolic rate differences, juvenile birds might experience quite different Hg exposure from adult birds (Rumbold 2005) and require different methods for assessing risk from Hg exposure. Therefore, the scope of this study was confined to adult birds only. Furthermore, during breeding seasons, diets of birds might shift to comprise more animal matter that could result in higher exposure. Because the 3 species maintain territories in the contaminated area during breeding, foraging range and strategy during breeding seasons could result in these birds having higher Hg exposure than at any other time during a year.

Sampling and chemical analysis

The studied reach extended downriver approximately 22 miles from the historical Waynesboro source. Samples of different potential bird food items were taken at Augusta Forestry Center (river miles below the historical site = 11.8 RM) and Grottoes Town Park (RM 22.4) in May 2009, and North Park (RM 2.0) and Grand Cavern (RM 22.0) in May 2010. Supplementary samples were taken at Grand Cavern in September 2010 to ensure there was enough food information for modeling exposure. General sampling locations could be found in Brasso and Cristol (2008). Additional details about the field sampling procedure could be found in Newman et al. (2011) and Wang et al. (in press). Samples, taken together with those from other trophic transfer studies (Newman et al. 2011; Wang et al. in press), included plants (seed of smooth hydrangea, *Hydrangea arborescens*; grain of Virginia wild rye, *Elymus virginicus*; grain of Johnson grass, *Sorghum halepense*; grain of crabgrass, *Digitaria sp.*; fruit of pokeberry, *Phytolacca americana*; fruit of twistedstalk, *Streptopus lanceolatus*; fruit of winter grape, *Vitis* sp.; fruit of spice bush, *Lindera benzoin* and fruit of poison ivy, *Toxicodendron radicans*), whole detritivores (earthworms, *Lumbricus rubellus*; slugs, *Prophysaon dubium*; isopods, *Microcerberidae*), whole insects (eastern tent caterpillar, *Malacosoma americanum*; ladybug, *Harmonia axyridis*), whole spiders (wolf spider, *Lycosidae*), emergent aquatic insects (mayfly, *Ephemeroptera*; caddisfly, *Trichoptera*; midge, *Diptera*), small mammal (deer mouse, *Peromyscus maniculatus*), aquatic invertebrate (crayfish, *Astacoidea*), and small birds (Northern cardinal, *Cardinalis cardinalis*; Eastern tufted titmouse, *Baeolophus bicolor*; Eastern song sparrow, *Melospiza melodia*; Carolina wren, *Thryothorus ludovicianus*; Gray catbird, *Dumetella carolinensis*; Red eyed vireo, *Vireo olivaceus*).

Sample preparation and analytical procedures can be obtained from Tom et al. (2010) and Wang et al. (in press). Triplicate samples were collected for each species in supplemental sampling and were analyzed using a direct Hg analyzer (DMA-80; Milestone, Shelton, CT) for total Hg following EPA Method 7473(SW-846) (USEPA 1998).

The accuracy and precision of Hg analyses from CEBAM Analytical Laboratory (Bothell, WA), where the samples were analyzed, were gauged with laboratory sample splits, laboratory spiked samples and certified reference materials (BCR-580, Dorm-2, IAEA350, IAEA142). The mean differences between sample splits were 1.2% (SD = 0.8%, $n = 36$) for total Hg. The mean recoveries for spiked analysis and reference materials analysis were 100.1% (SD = 7.9%, $n = 28$) and 100.6% (SD = 2.9%, $n = 9$) for total Hg, respectively. Quality of analysis of samples in our laboratory was also gauged with sample splits and certified reference materials (Tort-2). The mean differences between sample splits were 0.8% (SD = 11.2%, $n = 6$). The mean recoveries for reference materials analysis were 104.2% (SD = 1.4%, $n = 24$). All results from the above procedures documented analytical accuracy and precision adequate for the intended modeling.

Effect characterization

The most abundant organic Hg compound, methylmercury, readily penetrates the blood-brain barrier in birds, producing brain lesions, spinal cord degeneration, and central nervous system dysfunction (Wolfe et al. 1998). Most effects information comes from acute toxicity tests under controlled laboratory conditions. However, at most contaminated sites, bird exposure is chronic and involves low levels of dietary Hg (Wren and MacCrimmon 1983). Spalding et al. (1994) found that mortality of great white heron (*Ardea herodias occidentalis*) due to chronic disease was associated with high kidney Hg concentrations greater than 6 μg/g total Hg (wet weight, w/w). On the South River floodplain, a statistically significant decrease of reproductive success was reported for tree swallows with mean blood total Hg concentrations of 3.56 μg/g (w/w) (Brasso and Cristol 2008).

Mercury ingestion and consequent effects information for adult Carolina wren, Eastern song sparrow, or Eastern screech owl are unavailable but those for other species might provide useful information for inferring possible effects. Barr (1986) reported reduction in egg laying and territorial fidelity of common loons (*Gavia immer*) associated with prey Hg concentration of 0.3 to 0.4 μg/g fresh weight. Heinz (1979) dosed 3 generations of Mallard ducks (*Anas platyrhynchos*) with methylmercury dicyandiamide at 0.5 mg/kg food in dry weight every day, starting from the first generation growing to adults or from the 9th-day posthatch for the 2nd and 3rd generation ducks. Based on the food ingestion rate provided by Heinz (1979) (156 g/kg of duck body weight for the dosing group), methylmercury daily ingestion rate was calculated to be 0.078 mg/kg of duck body weight. No acute toxicity effects were observed; however, different reproduction effects such as egg laying outside the nestbox, fewer sound eggs and ducklings, and behavioral effects were observed in the dosed group. Another study by Spalding et al. (2000) on Great egret (*Ardea albus*) with daily dosing rates from 0.048 mg/kg body weight to 0.135 mg/kg of methylmercury chloride noted sublethal effects to dosed egrets.

The present study used total Hg in prey items to characterize Hg exposure. Considering the dosing rate from the Heinz (1979) and Spalding et al. (2000) studies and the percentage of methylmercury of the total Hg in samples, 0.1 mg total Hg/kg bird body weight daily (100 ng/g-day) was chosen as the toxicity reference value (TRV) to judge the risk of Hg exposure for the 3 species.

Exposure analysis

Model for Hg dietary exposure. Daily Hg ingestion rate (DMIR, ng total Hg/g bird body weight) was modeled by incorporating bird body weight and feeding ecology (food ingestion rate and diet item choice) in Equation 1:

$$\text{Daily Hg Ingestion Rate}\left({}^{ng}\!/_{g}\right) = \textstyle\sum_i BW_{p(i)} \times C_i \Big/ BW_b, \quad \text{and} \sum_i BW_{p(i)} \le BW_b \times FIR \tag{1}$$

where BW_b = the body weight of selected bird, FIR = food ingestion rate, $BW_{p(i)}$ = the body weight of prey item *i*, and C_i = Hg concentration of prey item *i*.

Daily Hg ingestion rate was expressed as the amount of total Hg that an adult bird might ingest relative to its body weight during its daily foraging. Average daily Hg ingestion rate (ADMIR) was generated by calculating an arithmetic mean of the DMIR of each day of the breeding periods. It reflected the average amount an adult bird might ingest relative to its body weight each day.

Input variables for Monte-Carlo models. Monte-Carlo simulation generated a cumulative probability distribution for DMIR for each species. To build this model, estimated distributions were needed for the following variables: 1) bird body weight (BW_b), 2) *FIR* defined as grams of food (wet) per gram of bird body weight consumed daily, 3) body weight (wet) of prey items in the bird's diet ($BW_{p(i)}$), and 4) the Hg concentrations in different food items (C_i). South River floodplain birds select food items based on species-specific foraging strategies. Consequently, information was needed about the relative proportions of various food items in a species' diet (PP_i), which was treated as the probability of a bird picking a certain item during foraging. Because it was impractical to sample all possible prey items, the prey items used in this study were those most abundant at the sample locations. They were assumed to be representative of groups of prey with similar trophic position. According to Hg biomagnification research by Newman et al. (2011), Hg concentration of a South River floodplain organism was related closely with trophic position as quantified by $\delta^{15}N$. Prey of similar trophic position had similar Hg concentrations. Therefore, using representative prey species instead of all prey species was justifiable.

Body weights ($BW_{p(i)}$, w/w) and the Hg concentrations (C_i, w/w basis) of different prey items were obtained by field survey and laboratory analysis. Because many biological qualities follow log-normal distributions, especially those expressed as small and non-negative variables (Limpert et al. 2001) such as the size of fruit and flowers (Groth 1914), initial assumptions of this study were that total Hg concentration and the body weight of individual prey items conformed to log-normal distributions defined with 2 estimated parameters for each item. To avoid unrealistic values being used during simulation such as negative body weight or unrealistically high Hg concentration, a lower limit of 0 and a higher limit of 3 standard deviations (SD) from the mean were set for each distribution limit except for the small birds. Because an owl generally will not take prey larger than 40 g (Gehlbach 1995), we set the upper limit of owl prey items to be the smaller of 40 g or 3 SD from the mean. All parameters were generated based on samples of whole body except for plants, mice, and small birds. Edible seeds and berries were selected for plants and the resulting data were pooled to produce one distribution for plant food items. Mice and small birds are prey for Eastern screech owl. We assumed the concentrations in mouse and bird tissue eaten by owls were similar to those measured in muscle tissue. Because of our nonlethal sampling method for bird tissue, we multiplied bird blood Hg concentrations by 2 to estimate muscle concentrations based on the ratio published by Evers et al. (2005).

Limited information was available for bird body weight (BW_b), food ingestion rate (*FIR*), and the relative proportions of food items (PP_i) taken by the 3 species. As a result, a formal expert elicitation was conducted under the general Delphi method framework to estimate the associated variable distributions. An expert elicitation is an exchange between an expert and a facilitator aimed at getting quantitative estimates (sometimes probability distributions) from expert opinions about some unknown information (Garthwaite et al. 2005; O'Hagan 2005). This format, suggested by the work of O'Hagan (1998, 2005), allowed us to design questions in a specific sequence and establish rules intended to reduce some common estimation errors in elicitations for distributional information.

Performance feedback and multiple experts can improve calibration (goodness of elicitation) for an expert elicitation (Stone and Opel 2000; O'Hagan et al. 2006). This was achieved with a modified Delphi approach. The Delphi method was developed at the RAND Corporation in the early 1950s (Cook 1991), and was further refined and applied to a wide range of situations thereafter. In the usual Delphi method, a group of separate experts are selected to provide quantitative opinions about some event or situation. Results from separate experts are compiled and the compiled information sent to each expert for possible changes or comments. Experts' feedback are compiled and redistributed until a consensus of expert opinions is achieved. During this process, each expert is isolated from the others except for the review of compiled reports. The Delphi approach was customized to our needs and timeline as described below.

The expert elicitation questionnaire for each bird was organized into 3 sections: bird body weight, diet composition, and overall food ingestion rate (see Supplemental Data S8). The sections for BW_b and *FIR* included similar questions for generating distributional information. The questions were arranged in a particular order and could not be modified after being answered. There were panels in which experts could review their input and provide comments or explanations of any typographical errors or mistakes they might have made. Experts were sequentially asked to provide estimates of lowest value, highest value, and then mode of BW_b and FIR. Based on these 3 single values, experts were then asked to provide estimates of the probabilities that the variable would fall in 3 intervals ($q1$, $q2$, and $q3$) shown in Equations 2 to 4. Estimates for these intervals were asked in this sequence to minimize instances of experts estimating very low probabilities and anchoring (O'Hagan 1998). Four resulting probabilities ($p1$, $p2$, $p3$, and $p4$) were then calculated via Equations 5 to 8 and used to define the distributions of BW_b and FIR:

$$q1 = \Pr\ (lowest \leq X \leq mode) \tag{2}$$

$$q2 = \Pr\ (lowest \leq X \leq (lowest + mode)/2) \tag{3}$$

$$q3 = \Pr\ ((mode + highest)/2 \leq X \leq highest) \tag{4}$$

$$p1 = \Pr\ (lowest \leq X \leq (lowest + mode)/2) = q1 \tag{5}$$

$$p2 = \Pr\ (lowest + mode)/2 \leq X \leq mode) = q1 - q2 \tag{6}$$

$$p3 = \Pr\ (mode \leq X \leq (mode + highest)/2) = 1 - q1 - q3 \tag{7}$$

$$p4 = \Pr\ ((mode + highest)/2 \leq X \leq highest) = q3 \tag{8}$$

It was impractical to ask experts to provide a series of estimates for PP_i for each prey item as done for BW_b and FIR, and instead, experts were asked for a single estimate of the proportion of each food item expected of the total weight of food consumed each day. Using the resulting expert input, a probability distribution for BW_b, a probability distribution for FIR, and a pool of estimates of PP_i could then be generated from each expert.

Two calibration questions were included in each of the 3 sections to accommodate differences in accuracy and precision of expert responses during elicitation. One question was a general knowledge question and the other was a quantitative question. Answers of experts were assigned a score up to 5 for each question and summed to a maximum of 10 for each set of information. Responses in each section that had a score of 8 or above were regarded to be a good response; a score between 5 (inclusive) and 8 was judged as fair and that below 5 was judged to be limited. Composite estimates of BW_b, FIR, and PP_i across experts were generated by combining all experts' information using weightings generated with the above scores.

Monte-Carlo simulation. A Monte-Carlo simulation approach used the distributions of the previously described variables from the field surveys and expert elicitation. Daily Hg ingestion rate could be modeled using Equation 1 for each expert's estimates and also composite estimates.

The simulation began by selecting values of FIR and BW_b randomly from their distributions. A total amount of food that a bird would ingest during a simulated day (M_T) was then calculated as $FIR \times BW_b$. Prey items were then randomly picked according to their PP_i together with a value of $BW_{p(i)}$ and C_i from corresponding distributions until the sum of $BW_{p(i)}$ reached M_T at which point the bird had eaten its maximum for that day. The daily Hg ingestion rate was calculated by dividing the sum of total Hg (M_{Hg}) contained in the selected items by the bird body weight, M_{Hg}/BW_b. This procedure was repeated 1000 or more times until the preset number of iterations had been reached, generating a distribution of daily Hg ingestion rates.

To obtain average daily Hg ingestion rate (ADMIR) during the breeding season, the average was calculated from N (days, equal to the approximate duration of breeding season) of the randomly selected daily Hg ingestion rates from the distribution generated above. After 1000 such averages were generated, the cumulative probability distribution of ADMIR was generated. This distribution was compared to a TRV to make conclusions about the risk of harmful exposure.

Sensitivity analysis

Sensitivity analysis identified the most influential variables on the simulation outcomes. The simulation results could be influenced by either the magnitude of the input variables or the distributions selected for bird body weight and food ingestion rate derived by expert elicitation. Sensitivity of the quantities of an input variable was assessed with a Spearman rank correlation coefficient using the SAS program (Version 9.2.1; SAS Institute, Cary, NC). Coefficients were calculated for the correlation between each input variable and daily Hg ingestion rate. Sensitivity of the distributions selection was assessed by comparing the results of different input distributions.

RESULTS

Prey items information

Prey body weight and Hg concentration were fit to log-normal distributions using the analytical and measured data. The estimated parameters (mean and SD of log-normal distribution) are listed in Supplemental Data S1.

Expert input

Nine experts from an initial pool of 40 candidates expressed their willingness to contribute to the elicitation exercise. Candidate experts were nominated by our collaborator based on their knowledge and regionality. Because of scheduling problems, 6 experts finished the original questionnaire with reliable input and 4 of these experts decided to revise their input after reviewing the compiled report of the panel's initial input. The revised input of the 4 experts and the original input of 2 other experts were used to conduct the Monte-Carlo simulations.

Figure 1 represents expert estimates, in which the upper and lower quartiles were calculated based on the probabilities that experts estimated for the intervals. Panel members A, C, E provided similar estimates of body weight for the 3 birds, respectively. The range of estimates overlapped in most cases. The combined ranges of body weight were 16 to 25 g for Carolina wren, 15 to 35 g for Eastern song sparrow, and 125 to 240 g for Eastern screech owl. These results were consistent with measurements from other sources (Cornell Lab of Ornithology 1999a, 1999b, 1999c).

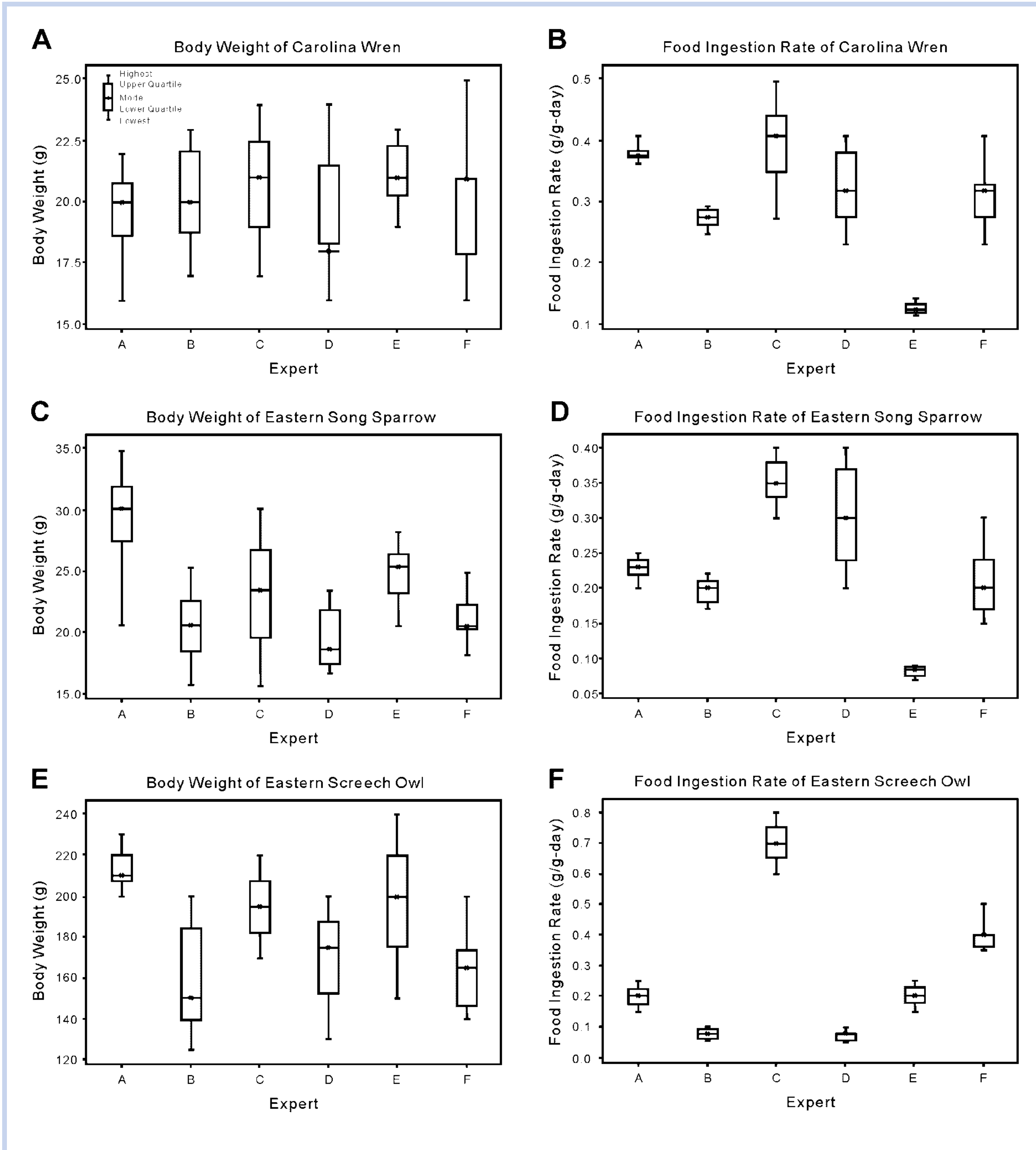

Figure 1. Expert estimates of bird body weight and food ingestion rate. Legends indicate experts' estimates for highest, lowest, mode, upper quartile, and lower quartile of specific quantities.

Estimates of food ingestion rate were less consistent across experts. Five of 6 experts estimated the food ingestion rate to be larger than 0.2 g per g of body weight per day (g/g-day). One expert estimated it to be approximately 0.1 g per g-day. For Eastern song sparrow, 5 of 6 experts estimated the food ingestion rate to be higher than 0.15 g/g-day, and as high as 0.4 g/g-day. The other expert estimated it to be 0.1 g/g-day, declining to modify the estimates during revision. Four experts estimated the food ingestion rate of Eastern screech owl to be lower than 0.3 g/g-day. One expert estimated it to be approximately 0.35 to 0.5 g/g-day and another estimated it to be 0.6 to 0.8 g/g-day. Regardless of differences among experts, the general pattern of expert estimates agreed with previous research that small birds eat more food in proportion to their body weight than larger birds (Lack 1954).

To get distributional information for bird body weight (BW_b) and food ingestion rate (*FIR*), we had anticipated that the expert-generated probabilities could be used directly to build probabilities density functions. However, unexpected difficulties arose when calculating the distributional probabilities ($p1$, $p2$, $p3$, and $p4$) from expert estimates ($q1$, $q2$, and $q3$). Four out of the total 36 expert distributions had gaps in their distributions with $p3$ being zero. Fourteen distributions had unrealistic and slightly concave patterns instead of an expected peaked or flat shape. Because of these unexpected patterns, we used experts' estimates of lowest value, highest value and mode to build a triangular distribution as the input of Monte-Carlo simulation to assess the Hg exposure. Daily Hg ingestion rate from the experts' original distributional estimates (applied as customized distributions), together with uniform distributions based on experts' highest and lowest estimates, were also calculated for comparison during sensitivity analysis.

Experts were required to estimate the relative proportions of the potential prey items in a bird species' diet (PP_i) (see Supplemental Data S5). Experts did reach consensus despite individual differences. Carolina wren were estimated to ingest primarily caterpillars (>15% of their diet) and spiders (>20%), which was consistent with previous stomach content research on Carolina wren (Haggerty and Morton 1995). Experts estimated the Eastern song sparrow ingested a large portion of plant tissue (seeds and fruits, relative to owls and wrens) and many insects and spiders, which also consistent with previous research (Judd 1901; Arcese et al. 2002). For Eastern screech owl, consistent with Van Camp and Henry (1975) and Turner and Dimmick (1981), experts opined that this owl took primarily small birds and mammals such as deer mouse.

Expert weightings

The elicitation gathered 3 sets of answers for each bird (body weight, diet, and food ingestion rate) that were scored and the accuracy of answers used to weight the information from each expert. Table 1 lists the level of responses of expert, where percentage represents the proportion of experts in the indicated level. All experts were capable of providing good or fair responses for the body weight for the 3 species. Some experts gave fair responses for the diet questions and more experts gave limited responses for food ingestion rate questions than for the other 2 sets of questions.

A weighting was assigned to each expert based on the scores that experts got for each section (body weight, food preference, and ingestion rate). Composite distributions were then based on these weightings.

Daily Hg ingestion rate and average daily Hg ingestion rate

For each species, Monte-Carlo simulations were conducted with information from each expert individually and then with the combined information from all experts (plotted in Supplemental Data S6). Distributional statistics for simulations could be found in Supplemental Data S2 to S4. The variation among experts was adjusted with weightings to produce a composite exposure distribution for each bird.

According to the composite estimates (Figure 2), an adult Carolina wren consumed more Hg than Eastern song sparrow during daily foraging, but its consumption was comparable to Eastern screech owl.

When exposure was averaged over breeding season (163 days for Carolina wren [Larner 2008], 131 days for Eastern song sparrow [Larner 2008], and 126 days for Eastern screech owl [Gehlbach 1995]), there was less than 1% chance that any of the 3 species will consume a potentially harmful amount of Hg over a breeding season. The mean ADMIR estimates were 50 ng/g(w/w)-day, 31 ng/g(w/w)-day, and 65 ng/g(w/w)-day for Carolina wren, Eastern song sparrow, and Eastern screech owl, respectively (Figure 3).

Sensitivity analysis

Sensitivity analysis was intended to identify the contribution of input components to the resulting output distribution of a Monte-Carlo simulation. The current study compared the outputs generated from different types of input distributions of BW_b and *FIR*, which were triangular distribution, uniform distribution, and customized distribution (Figure 4). No differences were observed between mean DMIR of the 3 species that would influence the study conclusions. The 75th percentiles of DMIR were also compared. The values estimated from triangular, uniform and customized distribution for Carolina wren were 66, 67, and 65 ng/g(w/w)-day, respectively. For sparrow, the values were 36, 34, and 39 ng/g (w/w)-day. For the owl, the values were 73, 69, and 77 ng/g (w/w)-day, respectively. Again, no material differences were observed.

To analyze the contribution of each input variable, Spearman rank correlation coefficients were calculated between each input variable and the DMIR based on the 1000 Monte-Carlo trails for each bird (see Supplemental Data S7). Ingestion rate of all 3 species played the most important role in bird Hg exposure. The coefficients of *FIR* for all 3 species were more than 0.4. Bird body weight either ranked low, as in the case of Eastern screech owl, or not at all for the other 2 species. Body weight only ranked seventh in sensitivity analysis of Eastern screech owl, and its correlation with owl DMIR was very low (coefficient of 0.04). In addition to food ingestion rate, different food items contributed differently. For Carolina wren, the size of Eastern tent caterpillar ranked as the 2nd most important factor but had a negative coefficient. The Hg concentration of earthworm, the Hg concentration of caterpillar, the weight of earthworm, and the weight of midge ranked from 3rd to 6th with positive coefficients and p values lower than 0.01 among the top 10 factors. For Eastern song sparrow, again the Hg concentration of earthworm ranked high (2nd) with a positive value and the weight of caterpillar ranked 3rd with a negative value.

Table 1. Analysis of expert weighting questions

Section of expert elicitation	Carolina wren			Eastern song sparrow			Eastern screech owl		
	Good (%)	Fair (%)	Limited (%)	Good (%)	Fair (%)	Limited (%)	Good (%)	Fair (%)	Limited (%)
Body weight	100			83	17		83	17	
Diet composition	17	83			33	67	17	67	17
Food ingestion rate	33	50	17	67		17		33	67

Nbr of experts = 6.

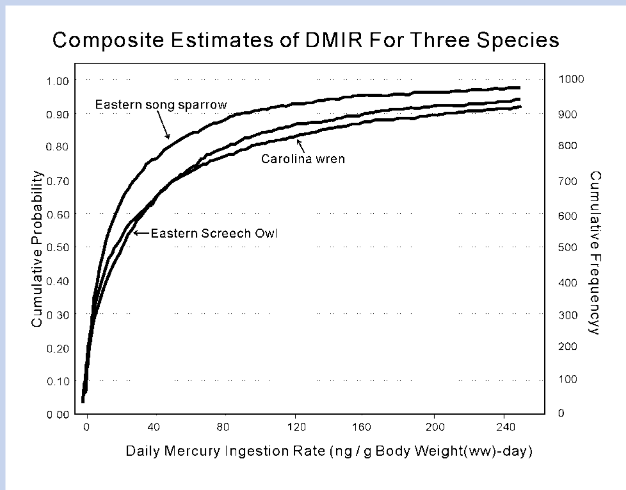

Figure 2. Comparison of daily Hg ingestion rate. Mean DMIR of wren, sparrow, and owl were approximately 68 ng/g(w/w)-day, 41 ng/g(w/w)-day, and 87 ng/g(w/w)-day, respectively

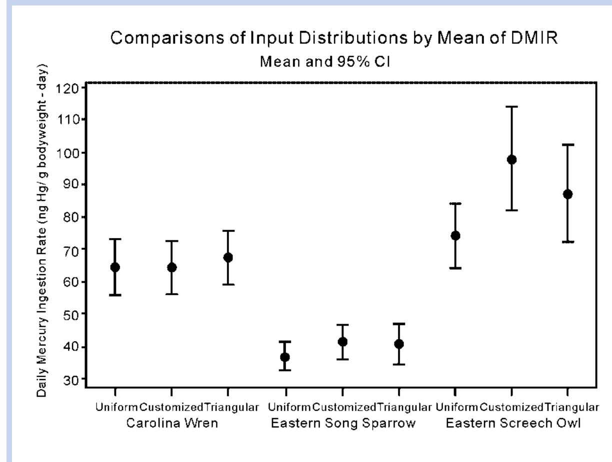

Figure 4. Comparisons of input distributions by means of DMIR for each species.

Another detritivore (slug) also ranked high with a positive value for song sparrow. As indicated previously, song sparrows eat a large portion of vegetation that has relatively low Hg concentration, leading to a high rank with a negative coefficient for fruit. For Eastern screech owl, in addition to food ingestion rate, Hg concentration of small birds, mice, and crayfish ranked high in the sensitivity analysis.

DISCUSSION

Two questions posed at the beginning of this article could be answered. This study used both the daily Hg ingestion rate and average daily Hg ingestion rate during breeding periods to estimate Hg exposure to the adult avian species on South River floodplain. Based on the simulation results, Carolina wren and Eastern screech owl had similar exposures that were higher than that of the Eastern song sparrow. The differences in exposure might be due to several factors. The diet of Carolina wren consisted principally of animals with much higher Hg concentrations than the floodplain plants. Consequently, Carolina wren tended to have higher Hg exposure than the Eastern song sparrow whose diet included mainly of plants. The food consumed by Eastern screech owl and Carolina wren was predominantly animal. The majority of the owl's food, according to our expert elicitation and previous studies, consisted of animals from higher trophic levels such as small birds or mice than those of Carolina wren. These higher trophic level prey had higher Hg concentrations in their tissues (Newman et al. 2011). However, the wren consumed more food (normalized to body weight) than the owl so the wren Hg exposure was comparable to that of the owl.

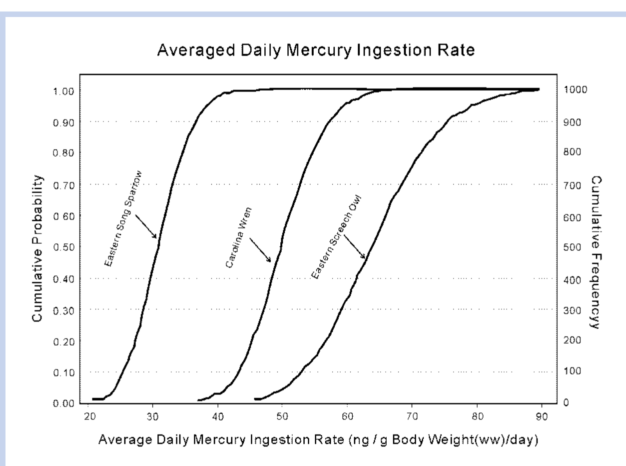

Figure 3. Average daily Hg ingestion rate from Monte-Carlo simulations. Mean ADMIR of wren, sparrow, and owl were approximately 50 ng/g(w/w)-day, 31 ng/g(w/w)-day, and 65 ng/g(w/w)-day, respectively

Daily Hg ingestion rate described exposure for 1 day only, not the average exposure over the entire breeding season. The TRV value used in this study, however, was based on continuous dosing experiments of Mallard ducks and Great egrets, that is, the average of daily Hg dosing. So it is more suitable to compare this TRV value with the average daily Hg ingestion rate simulated in this study. Averaging over breeding period, ingestion rates of 3 species shifted from 68, 41, and 88 ng/g(w/w)-day to 50, 31, and 65 ng/g(w/w)-day for wren, sparrow, and owl, respectively. These average exposures suggested a less than 1% probability that an adult bird of these 3 species might ingest Hg exceeding the TRV value (Figure 3): there was less than 1 out of 100 chance that an adult bird would ingest harmful amounts of Hg on South River floodplain during the breeding season.

This study underscored the advantage of probabilistic risk assessment, which provides risk managers and other relevant groups with distributions of projected exposures and allows them to select the best suitable criteria to gauge risk. More specifically, distributions of daily Hg ingestion rates in this study were scientifically founded and calculated with explicit formulations. Risk decision based on the distributions would involve the discretion of the risk manager, perhaps changing as published TRV estimates are refined. Differences between the current study exposure scenarios and the experimental context from which the TRV was derived exist. Importantly, species differences between waterfowl (ducks and egrets) and the 3 study species exist, contributing to the uncertainty on risk decisions (Rumbold 2005).

Sensitivity analysis provided insight about the influence of different components of Monte-Carlo simulations on the results. The influence of input distribution type was judged not to be critical relative to the goal of this study based on comparisons of means and 75th percentiles from the 3 distributions. Regardless, more realistic input distributions would result in more accurate estimates.

Based on the Spearman rank correlation coefficients, *FIR* was the most important determinant of daily Hg ingestion rate differences for all 3 species. In a similar study by Moore et al. (1999), kingfisher (*Ceryle alcyon*) metabolic rate, a parameter correlated to daily food intake, was the key factor that determined Hg exposure. In contrast to food ingestion rate, bird body weight (BW_b) did not have a substantial influence for these 3 birds. This was expected given the structure of Equation 1, and the magnitude and variation of BW_b. According to Equation 1, daily Hg ingestion rate represents a ratio of Hg ingested (numerator) to BW_b (denominator). The magnitude of BW_b, which was characterized using grams, is much larger than ingested Hg that was expressed as nanograms. BW_b itself had less variation than the other variables. As a result, it was understandable that bird body weight was not a significant factor for daily Hg ingestion rate. In addition to *FIR* and BW_b, interpretation of other factors was not quite as straightforward. Generally, caterpillar and earthworm qualities might influence Hg ingestion rate substantially given that they ranked high in the sensitivity analysis for both Carolina wren and Eastern song sparrow. (Eastern screech owl rarely ate caterpillars and earthworms according to the experts.) The reason that prey got a negative Spearman coefficient similar to caterpillar weight might be because Hg concentration of that item was below the average prey concentration: the larger it was, the more low Hg concentration materials were in a bird's diet on a particular day. Furthermore, the reason that some prey items were ranked high for this bird species but not another might be because the proportion of those items varied among bird species. For example, the proportion of slugs that experts estimated increased from 0.2% in diet of Carolina wren to 2.4% for Eastern song sparrow.

Although experts did not respond ideally in providing distributional information, expert elicitation provided enough reliable information to meet the study goals as judged from the consistency between experts input, and both the published literature and expert calibration results. In addition to the general success of its application, expert elicitation overcomes some shortcomings of field sampling. For example, field sampling often does not generate sufficiently representative samples, and sample size requirements might not be met if the population of target organisms is small. Assigning appropriate uncertainty to sampling data is another challenging task. Expert elicitation could combine knowledge of experts who might have conducted similar studies and the local conditions to provide reasonable representative estimates and assign more plausible uncertainties to them.

Expert elicitation does have disadvantages. In this study, to elicit distributional information from experts' knowledge, specifically determined intervals were presented to experts that required their estimation of the probabilities for these intervals. However, the complex question format lowered the quality of expert responses. The experts did not provide enough correct distributional information. Two changes could be implemented in future to improve expert responses. Training in probability and statistics at the beginning of expert elicitation could improve expert calibration. Visual aids could be introduced to illustrate the intervals that require estimation (O'Hagan et al. 2006).

CONCLUSIONS

Mercury exposure was projected for 3 bird species on the South River floodplain based on expert elicitation and field surveys of Hg concentrations in potential food items. Monte-Carlo simulation was applied to define the distributions of daily Hg ingestion rates of an adult bird during breeding season and the probability that, averaged over the entire breeding season, an adult bird could ingest harmful amounts of Hg. What was a harmful amount was defined using the TRV of 100 ng/g-day derived by Heinz (1979) and Spalding et al. (2000). According to simulation results, Carolina wren and Eastern screech owl were exposed at comparable levels that were higher than the exposure of Eastern song sparrow. If daily ingestion rates are averaged over breeding seasons by Monte-Carlo sampling of each bird's daily ingestion rate distribution, the probability that an individual bird of these species exceeding the TRV was all less than 0.01.

SUPPLEMENTAL DATA

S1 (table): Parameters of log-normal distributions for prey items (Mean and SD based on natural log)

S2 (table): Statistics of daily mercury ingestion rate from Monte Carlo simulations for Carolina wren

S3 (table): Statistics of daily mercury ingestion rate from Monte Carlo simulations for Eastern song sparrow

S4 (table): Statistics of daily mercury ingestion rate from Monte Carlo simulations for Eastern screech owl

S5 (figure): Expert estimations of proportion of prey items

S6 (figure): Daily mercury ingestion rate from Monte Carlo simulations

S7 (table): Spearman rank correlation coefficients between input variables and DMIR

S8 Sample questionnaire

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