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Mercury Exposure Assessment of South River Floodplain Birds

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Mercury Exposure Assessment of South River Floodplain Birds

A Thesis
Presented to

The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Science

by
Jincheng Wang
2011
APPROVAL SHEET

This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Science

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ABSTRACT

The studies involved in this thesis expanded the current project being conducted in Dr. Newman’s laboratory that aimed to define and quantify the impacts of mercury movement in contaminated aquatic and terrestrial food webs in the South River watershed (Virginia, USA). This expansion involved a two phase study, which fulfilled the requirement of a master thesis.

Previous research in our lab documented mercury biomagnification in the river itself and two floodplain locations on the South River watershed. Predictive models were built for mercury concentration in members of these food webs. These studies reached a preliminary conclusion that mercury biomagnification in members of floodplain food webs was faster than that of the aquatic food web. To substantiate this finding and further understand the factors that might produce the differences observed among floodplain locations, two additional floodplain locations were sampled and modeled in 2010. Overall, the models constructed in this study for predicting methylmercury were superior to models for total mercury or the percentage of the mercury present as methylmercury. Including previous models for other sites, four of five attempted methylmercury models based on δ¹⁵N met the criterion for useful prediction. For the floodplain models, thermoregulatory strategy was found to have substantial influence on mercury concentrations of food web members. The food web biomagnification factors for the four floodplain locations were consistently higher than that of the contiguous aquatic food web.

The second phase of this research focused on description and determination of current mercury exposure to adults of three avian species during nesting on the South River floodplain and judgment of the risk of harmful mercury exposure to these species by comparing the mercury exposure distributions to published toxicity test results. This study incorporated a formal expert elicitation involving a modified Delphi framework and a Monte Carlo simulation to accomplish a probabilistic risk assessment. Simulations from this study predicted the probability that an adult bird during breeding season would ingest harmful amounts of mercury during daily foraging and also the probability that the average mercury ingestion rate for the breeding season of an adult bird would exceed published rates found to cause harm to other birds (>100 ng total Hg/g body weight per day). The probabilities that these species’ averaged ingestion rates exceeded the threshold value were all less than 0.01.
Mercury Exposure Assessment of South River Floodplain Birds
CHAPTER I. Introduction

Mercury, as one of the most notorious metal contaminants, remains a great concern due to its high toxicity, potential for biomagnification, and also its widespread release from anthropogenic sources. This persistent pollutant is the subject of much study today although it has been widely studied since the infamous poisoning in Minamata City, Japan (Gavis and Ferguson 1972).

1.1 Mercury Sources

Mercury is found in a variety of chemical forms in rock, soil, water, air, plants, and animals. Elemental (zero valence) mercury can exist as a liquid or gas in the natural environment, but is found primarily combined with other elements in minerals such as cinnabar or metacinnabar (Schierow 2006). Substantial amounts of mercury are released from both natural and anthropogenic sources (U.S. Environmental Protection Agency (EPA) 1997). Also important to consider is re-emission into atmosphere of mercury deposited onto plants, soils and other surfaces (EPA 1997; Schroeder 1998), which confounds efforts to estimate of the amounts of mercury from different sources.

The natural sources of mercury include volcanoes and deep sea vents that release tons of mercury to the atmosphere and oceans annually (Schierow 2006). It is well established that volcanic activities release mercury into natural environment
(Witt et al. 2008; Bagnato et al. 2009). A recent estimate by Bagnato et al. (2011) suggested global volcanic mercury emission rates of approximately 95 tons/year. It was not until recently that deep sea hydrothermal activities were found to release mercury into the submarine environment. Stoffers et al. (1999) were the first to document cinnabar (HgS) and liquid elemental mercury released from sea-floor hot springs. Lamborg et al. (2006), however, suggested that the fluids in these submarine hydrothermal systems contained monomethylmercury that was demethylated and deposited around the sources as cinnabar or other minerals.

Some of the unique physical (e.g., density, liquid states at environmental temperatures and volatility) and chemical (e.g., ease of reduction) properties that make mercury a useful industrial reagent also contribute to its propensity for accidental leakage and release into the environment. An EPA (1997) estimate of annual mercury emission due to human activities suggested that anthropogenic sources accounted for about 50% to 75% of mercury emissions from all sources. Such releases from anthropogenic sources are more variable than those from natural sources. This makes it difficult to rank the relative contributions of different anthropogenic sources (Shroeder and Munthe 1998). Prior to the 1970s, chlor-alkali plants were the dominant sources in many industrialized countries (Shroeder and Munthe 1998). Nowadays, most mercury is released through mining and smelting, fossil fuel burning, industrial processes, and burning of municipal and medical wastes (Schierow 2006).
1.2 Mercury Speciation

Understanding mercury speciation in environmental compartments is important because different species exhibit different transport characteristics, and therefore, might have different influence to any related ecosystem (Lindberg and Stratton 1998). Mercury released from natural and anthropogenic sources into the atmosphere environment is predominantly in the form of gaseous elemental mercury (Hg\(^0\)), reactive gaseous mercury (RGM, mostly divalent inorganic mercury, Hg\(^{2+}\)) and particulate mercury (Hg\(_p\)) (Shroeder and Munthe 1998). Hg\(^0\) is most abundant species (more than 95%) in the atmosphere (Swartzendruber et al. 2006; Fang et al. 2011). But mercury species can be transformed to other forms due to atmospheric chemistry. After emission, Hg\(^0\) can be oxidized by ozone (O\(_3\)), hydroxyl radical (\(\cdot\)OH), or hydrogen peroxide (H\(_2\)O\(_2\)) (Lindberg and Stratton 1998) or bromine atoms (Holmes et al. 2009). Oxidized mercury could combine with other anions (such as those of halogens and hydroxide) to form RGM, or attach to particles in the air to form Hg\(_p\) (Swartzendruber et al. 2006) that is readily transferred to the lithosphere and hydrosphere via wet and dry precipitation (Keeler 1995, Lindberg 1998). In addition to the three major forms, minute amounts of organic mercury also exist in the air (Brosset and Lord 1995), suggesting degassing from air-water exchange as another source (Shroeder and Munthe 1998). Elemental mercury that exists as a gas in ambient air is relatively inert chemically and sparingly soluble in water. This results in an atmospheric resident time of approximately one year (Slemr et al. 1985) and associated potential for long distance transport. Although resident times of the
other forms remain ill defined, it was commonly believed that RGM and Hg_p are easily scavenged by dry and wet deposition at regional and local scales.

In addition to direct input from natural and anthropogenic sources, mercury initially released into the atmosphere is also deposited into the hydrosphere. The speciation of mercury in hydrosphere is more complex than that in the atmosphere, and is influenced strongly by pH of waters and redox conditions (Boszke et al. 2002). Also critical are the concentrations of other ions and complexation with functional groups of dissolved and particulate-associated organic matter (Gavis and Ferguson 1972). Soluble mercury species such as HgCl_2^0 and CH_3Hg^+ dominate in low pH waters; but, as pH increases, Hg^0 and (CH_3)_2Hg^0 dominate. In oxic waters, the dominant compounds are HgCl_4^{2-} and HgOH^+; whereas in reduced conditions, CH_3HgS^- and HgS_2^- dominate (Boszke et al. 2002). Among these species, mercury often exists in organic forms that can be either organomercurials or complexes of Hg^{2+} with organic ligands (Gill and Bruland 1990).

Similar as in hydrosphere, mercury speciation in lithosphere is much more complex than in the atmosphere. In the lithosphere, including the pedosphere, mercury speciation is determined by redox conditions and also the presence of complexing compounds (Schuster 1991; Gabriel and Williamson 2004). Under reduced conditions, the major species exist in the form of HgSH^+, HgOHSH and HgClSH; but, the major species are Hg(OH)_2, HgCl_2, HgOH^+, HgS and Hg^0 under oxidizing conditions (Gabriel and Williamson 2004). In addition to these, an important characteristic that makes soil and sediments environments different from
water system is the tendency to serve as important sources of mercury. Soil can sequester a great amount of atmospheric mercury due to its large size and ligand-rich environment (Gabriel and Williamson 2004). Eventually, mercury deposited by soil can enter into surface water during erosion, run-off, (Gabriel and Williamson 2004) and flooding (Cooper and Gillespie 2001). Moreover, oxidized mercury could be reduced and volatized as Hg\(^0\) in soil (Gabriel and Williamson 2004), providing another path way by which mercury can enter surface water and the atmosphere.

Mercury precipitated in aquatic sediments has long been recognized as a source of mercury to riverine systems. For example, Telmer et al. (2006) revealed that, although gold mining operations provided the original mercury input in Tapajos River (Para, Brazilian Amazon), it was the mercury-enriched sediments that provided long-lasting mercury input into the river. Also, other studies suggested (Cristol et al. 2008; Newman et al. 2011) or recognized (Heaven et al. 2000) that mercury from river sediments could be deposited onto contiguous floodplain during seasonal flooding.

1.3 Mercury Methylation

Another important role of soil and sediments in mercury cycling involves mercury biomethylation. Biomethylation was first reported by Jensen and Jernelov (1969) who detected mono- and dimethylmercury generation after adding HgCl\(_2\) to aquatic sediments and decomposing fish. Compeau and Bartha (1985) later noted that it was sulfate reducing bacteria that methylated inorganic mercury in an anoxic aquatic environment. These same authors pointed out that sulfate reducing bacteria
could effectively methylate inorganic mercury only under low sulfate relative to organic substrate conditions, and suggested methylcobalamin is the likely methyl donor (Robinson and Tuovinen 1984). Other studies have found that low redox, salinity (Campeau and Bartha 1984), and pH (Miskimmin et al. 1992) favor mercury biomethylation.

Mercury could also be methylated via abiotic processes. Akagi and Takabatake (1973) reported mercuric chloride was converted to methylmercuric chloride by irradiation with light in the presence of propionic acid. Nagase et al. (1984) noted humic substances in river sediment and leaf litter could produce methylmercury. This methylation was favored by high temperature, high concentrations of mercury and humic substance concentrations, and extreme pH conditions. Mercury methylation was also reported under aerobic conditions at a lower rate than that noted under anaerobic conditions (Robinson and Tuovinen 1984). Although the above abiotic processes were observed, none of them contributed as substantially to methylmercury production in natural world as biomethylation (Campeau and Bartha 1985).

1.4 Mercury Detoxification

Compared to work on mercury toxicity, fewer studies have been conducted on the detoxification of mercury. Different features of detoxification are reported using terms such as mercury detoxification, mercury demethylation, mercury depuration, and mercury resistance.
Mercury resistant bacteria were first isolated from mercury contaminated soil in Japan (Tanaka et al. 1983). Later researchers contributed to understanding the mechanisms of microbial resistance. The major mechanism proposed was that mercury resistant bacteria transform mercuric ions and organomercurials to volatile forms that then can move readily out of the growth media (Robinson and Tuovinen 1984). The volatized form was shown to be metallic mercury by later research.

Summers (1972) analyzed toluene extracts of mercury resistant bacteria cultures exposed to $^{203}\text{HgCl}_2$ for 7 min at 37°C by coupled gas-liquid chromatography-mass spectroscopy that showed a single peak containing mercury in the chromatographs. This single peak had the same retention time as metallic mercury. Nelson et al. (1973) isolated sediment bacteria that had the catalytic capability to produce Hg° and benzene from phenylmercuric acetate (PMA), a key component of pesticides used in many countries.

Plants also have some capacity to detoxify mercury. Direct mercury uptake of volatized metallic or methylated mercury could take place via plant stomata (Shroeder and Munthe 1998; Patra et al. 2004) but direct absorption of mercury via the roots from soil was low unless mercury was in water soluble state such as that in some pesticides and fungicides (Patra et al. 2004). Mechanisms proposed for plant detoxification of mercury include mercury sequestration by compounds such as phytochelatins. Phytochelatins (PCs) are oligomers of the thiol-containing amino acid, glutathione, that complexes mercury ions with consequent toxicity reduction. Maitani (1996) used a root culture of *Rubia tinctorum* to show that mercury induced
phytochelatin synthesis. Howden (1992) compared the dose-response effect of a PC-deficient mutant of a mercury resistance plant *Arabidopsis* with its wild type, showing that seedling wet weight (toxicity endpoint) of the mutant type was significantly lower than that of the wild type with the increase of mercury doses. This suggested that PCs function to reduce mercury toxicity. It is worth noticing that Vatamaniuk (2001) found that the Ce-pcs-1 gene of the nematode, *Caenorhabditis elegans*, encoded for a functional PC synthase (Vatamaniuk 2001), suggesting that PCs might be a common detoxifying mechanism in other taxonomic Kingdoms.

Birds have several mechanisms to mitigate mercury intoxication. Birds could transport mercury to feather tissues during the nestling and adult molting stages. The mechanism involved in this pathway was that methylmercury has a high affinity for the abundant free thiol groups in feather keratin (Furness et al. 1986). The growing feather was connected with the avian body by a blood vessel through which mercury could be transported. During feather growth, mercury can be transferred from blood to feather where it is bound to keratin. When feather growth stops, the mercury could not be remineralized to enter the blood. Consequently mercury in feathers can be considered sequestered away from sites of potential harmful action. In addition to sequestration in feathers, female birds can eliminate mercury by deposition in eggs. Kennamer et al. (2009) studied box-nesting wood ducks (*Aix sponsa*) in a mercury contaminated reservoir in South Carolina and found elevated mercury concentrations in egg tissues (albumen, yolk and shell). Also, mercury concentrations in these tissues
were influenced by egg laying sequence, suggesting that hens were moving accumulated mercury from their tissues into eggs.

Mercury accumulated by mammals through diet is assumed to be predominately methylmercury. Many studies (e.g. Westoo (1968)), however, have pointed out that methylmercury comprised no more than 15% of the total mercury in kidney tissues of some mammals. Potential mechanisms were proposed that included mercury demethylated in mammals with consequent storage in kidney tissues. For example, Rowland (1984) demonstrated that mouse gut flora can demethylate methylmercury. Suda et al. (1992) later found that phagocytic cells of some animal species had the ability to degrade methylmercury and ethylmercury to inorganic mercury. In addition to directly demethylation of organic mercury, mercury in some mammals could be sequestered in tissues to form mercury-selenium granules. Koeman et al. (1973) showed that there was a significant correlation between mercury and selenium, and these elements were present at a molar ratio of 1:1. Gailer et al. (2000) further explained that mercuric ions (mercuric complex) could also react with selenide anions to form a Hg-Se-S species, resulting in an association of mercury with cellular proteins also.

Surprisingly little research has been published about human detoxification mechanisms of mercury. But it is generally accepted that mercury species undergo enterohepatic recirculation, leading to its reabsorption and uptake into the red blood cells where they can be metabolized to form inorganic salts (Chapman and Chan 2000). The majority of dosed inorganic mercury accumulates either in the liver,
where it can be excreted in the bile, or in the kidney, where it is excreted in a complexed form in the urine (Chapman and Chan 2000).

1.5 Mercury Analysis

Methods of determining mercury concentration vary according to speciation. In most methods, different mercury species are ultimately converted to elemental mercury and detected by atomic fluorescence spectrometry (AFS) or atomic absorption spectrometry (AAS) at a wavelength of 253.7 nm. Aqueous samples for total mercury and methylmercury (specifically mono-methylmercury) commonly are determined by EPA Method 1631 (EPA 2002) and EPA Method 1630 (EPA 2001), respectively.

Liang et al. (1994) modified these two EPA methods and developed a more efficient procedure to simultaneously determine methylmercury and Hg (II). Total mercury concentration could then be calculated by adding the methylmercury and Hg (II) concentrations. They also proved total mercury concentrations obtained via this method for different tissues were quantitatively equivalent to total mercury determined from EPA Method 1631. Most of our samples were analyzed via this modified method. Consequently a brief description of it is presented here.

Biota tissues (not soil samples) were digested with a KOH methanolic solution in an oven at 75°C for 3h. After being diluted with methanol, the digests were added to reaction vessels containing 50-100 ml distilled, deionized water
(DDW) and 200 μl of 2 mol/L acetate buffer. Ethylation of mercury species then took place after adding NaBEt₄ to the reaction vessels. Methylmercury and Hg (II) in the original digests were converted to methylethylmercury and diethylmercury respectively, which were collected on a trapping column. These columns were then heated in a separate unit to release the volatile ethyl derivatives. These were then carried by an inert gas stream onto a packed isothermal gas chromatography (GC) column, where the two derivatives were separated due to different affinities to the stationary phase. Separated mercury ethyl derivatives were then decomposed thermally into elemental mercury and detected by a cold vapor AFS unit (CVAFS).

Soil samples were digested using a 3:1 HNO₃/HCl solution for total mercury and 3 N HNO₃ for methylmercury. The digests were analyzed following either Method 1631 for total mercury or Method 1630 for methylmercury.

In addition to above methods, some samples were analyzed in our lab using a direct mercury analyzer (DMA-80, Milestone Systems Inc., Beaverton, OR, USA) following EPA method 7473 (EPA 2002). Solid samples were weighed and placed into clean nickel boats. These were then sent to a combustion unit, where samples were dried and decomposed at a temperature of 800 °C. The decomposition products were then carried by a flow of oxygen into a catalyst furnace, where the mercury was trapped and all species reduced to elemental mercury for spectrophotometric detection. Reduced mercury was further carried into a gold amalgamator, trapped, until the oxygen flow removed any residual gas and decomposition products in the
system. The mercury-gold amalgamation was then heated to release elemental mercury and purged into a CVAAS unit, where mercury concentration was determined. All processes were carried out automatically.

1.6 Mercury Exposure in South River

During the period of 1929 to 1950, the South River (Figure 1.1) was contaminated with mercury discharged from a former DuPont Facility at Waynesboro where it had been used as a catalyst in acetate fiber manufacture (Carter 1977). Twenty-seven years after cessation of manufacturing (1977), the contamination of mercury in the South River drew much attention when visible globules of mercury were discovered during the routine repair of a leaking water pipe of the Waynesboro old chemical buildings. Since then, many descriptive studies and assessments have been done to define the mercury exposure and to determine any adverse impacts to related ecosystems.

Figure 1.1 Location of the South River watershed in Virginia, USA
According to Carter (1977), mercury concentrations reported in 1976 for several South River sediments samples exceeded 240 µg/g, much higher than those from an upriver reference location with concentrations of approximately 1 µg/g. Some measured concentrations (0.86-1 µg/g) for fish exceeded the Food and Drug Administration’s action level at that time. In the following years, Bolgiano (1981) examined the mercury contamination of the South River floodplain soil. The soil mean mercury concentration was 10.7 µg/g in the first 40 km downriver from the historical source with soil from the highest site containing 34.5 µg/g of mercury. He also concluded that the deposition of mercury on floodplain soil was most likely a consequence of contaminated sediment movement onto the land during periodic flooding. Nicoletto and Hendrick (1988) showed that filets of adult redbreast sunfish had an average mercury concentration of 0.7 µg/g wet weight and rock bass had an average mercury concentration of 0.84 µg/g wet weight 17 km downriver (Crimora) of the historical source. Bidwell and Health (1993) reported 1.37 µg/g of mercury in muscle tissue of rock bass and 2.86 µg/g of mercury in liver. Another study in 1996 and 1997 reported mercury concentrations in water samples from Crimora to be 97 ng/l of total mercury and 2.7 ng/l of methylmercury (Turner 1999). Sixty years after the cessation of industrial use of mercury at Waynesboro, elevated mercury concentrations were still observed in different compartments of South River ecosystem, such as water and sediments (Flanders 2010), floodplain soil (Newman 2011), and biota (Brasso 2008, Kyle 2010, Newman 2011).
1.7 Project overview

My thesis work expanded the current project being conducted in Dr. Newman’s laboratory that aimed to define and quantify the impacts of mercury contamination to the South River (northwestern Virginia) biota. Specifically, research in our laboratory is focused on mercury movement in contaminated aquatic and terrestrial food webs. During this process, several avian species in the South River floodplain were documented to occupy high trophic positions in the food webs and to have high mercury concentrations (blood and feather tissue) relative to other sampled organisms. This established them as potentially at-risk species for the adverse mercury effects. My thesis focused on the mercury exposure assessment of at-risk South River floodplain birds.

To achieve the goal of my master degree, I conducted a two phase study to assess mercury exposure of South River floodplain birds.

In phase I, mercury trophic biomagnification models were built based on mercury and light isotope analyses of samples taken in May of 2009 and May of 2010 at four floodplain sites (Figure 1.2), and defining the potential food items of birds. This study phase included field sampling, mercury and stable isotope analyses, and biomagnification modeling. Results of studies in this phase are reported in Chapter 2 of this thesis.

In phase II, measured mercury concentration data and dietary information of potential prey for avian species from field surveys, and bird morphological and feeding information from expert elicitation were incorporated in a Monte Carlo
simulation model to generate a probabilistic distribution of bird daily mercury ingestion rates. These ingestion rates were used to define mercury exposure of at-risk birds by simultaneously modeling both natural variability in the data and variability due to other sources such as error. Results of studies in this phase are reported in Chapter 3 of this thesis.

Figure 1.2 Sampling locations along the contaminated reach of the South River. Locations illustrated by dots with green edges were sampled in 2009 and locations illustrated by dots with red edges were sampled in 2010. Blue symbols indicate the location of aquatic sites sampled by Tom et al. (2010).
CHAPTER II. Methylmercury Biomagnification on South River Floodplain

2.1 Introduction

Mercury, especially methylmercury, can be elevated in some species due to biomagnification. Consequently, an ecosystem with modestly elevated mercury concentrations in soils or sediments might still have high body burdens of mercury in apex predators (dos Santos et al. 2006; Macedo-Sousa et al. 2009). Consequently, effective natural resource management and decision making requires tools for predicting mercury concentrations in apex predators via biomagnification (Tom et al. 2010).

Mercury biomagnification is influenced by community structure (Chasar et al. 2009), food source (Gorski et al. 2003; Chetelat et al. 2011), food chain length (Cabana et al. 1994), trophic position (Newman et al. 2011) and other factors; however, trophic position is the most widely studied factor. Trophic position is commonly characterized with stable nitrogen isotope quotients ($\delta^{15}$N). Models to estimate mercury biomagnification based on $\delta^{15}$N have been published for diverse aquatic food webs (Campbell et al. 2008; Chasar et al. 2009; Tom et al. 2010). Less work has been done for terrestrial food webs (Gaines et al. 2002; Choy et al. 2010; Newman et al. 2011) despite suggestions from several studies that members of
terrestrial food webs might experience similar or even higher mercury exposure (Cristol et al. 2008).

This study phase extends previous trophic transfer studies of a mercury-contaminated reach of the South River (Virginia USA). In a 2008 sampling of aquatic organisms at six locations along a river reach extending downstream 23 miles from the historic site of release, Tom et al. (2010) found that a δ^{15}N based trophic transfer model could predict methylmercury concentrations in members of aquatic food webs. The methylmercury food web biomagnification factor (FWMF) calculated from that model was 4.6 fold increase per trophic level (TL) (95% CI of 3.6-5.8) assuming that δ^{15}N increased 3.4‰ per TL. Because several studies (Brasso and Cristol 2008; Cristol et al. 2008) suggested that wildlife on the South River floodplain might experience harmful mercury exposure, two terrestrial sites on the South River floodplain, Augusta Forestry Center (AFC, Crimora, VA, river mile below historic point of input = 11.8 RM) and Grottoes Town Park (GTP, Grottoes, VA, RM = 22.4), were studied in 2009 (Newman et al. 2011). The 2009 floodplain study built models for each site, reinforcing the results of the previous aquatic study that a δ^{15}N based model had better predictive capability for methylmercury concentrations than total mercury, and that the FWMF from these floodplain sites (9.3, 95% CI of 5.4-16.2 and 25.1, 95% CI of 12.6-50.1 for AFC and GTP respectively) were higher than that of the contiguous aquatic food webs. Models for additional floodplain sites were deemed necessary due to the large difference between floodplain and aquatic food webs, and the wide variation between the two modeled floodplain sites. In May 2010, two more
floodplain sites were studied (1) to assess whether the floodplain food webs had consistently higher FWMF than the adjacent aquatic food webs; and (2) to explore factors that might produce the differences observed among floodplain locations.

2.2 Materials & Methods

2.2.1 Sampling

Two locations (AFC and GTP) were sampled during the summer of 2009 and another two were sampled in the same 23 mile river reach (North Park (NP, RM=2.0) and Grand Cavern (GC, RM=20.0)) during the first two weeks of May 2010. Details about the sampling procedure could be found in Newman et al. (2011). Briefly, three sites were randomly picked in each location and samples gathered at each site were used as one replicate for each species. Biota from the aquatic habitat that could enter the terrestrial food web included whole crayfish (Astacoidea) and emergent insects (mayfly, Ephemeroptera; caddisfly, Trichoptera; midge, Diptera) which were collected using a specifically designed aspirator kit (BioQuip Product, Rancho Dominguez, CA, USA). Samples from the floodplain included green tissues of plants (violet, viola striata; honey suckle, Lonicera japonica; grass, Festuca elatior), whole detritivores (earthworms, Lumbricus rubellus; slugs, Prophysoon dubium; isopods, Microcerberidae), whole insects (Eastern tent caterpillar, Malacosoma americanum; common black ground beetle, Pterostichus melanarius; Asiatic garden beetle, Maladera castanea; ladybug, Harmonia axyridis), whole spiders (wolf spider, Lycosidae), muscle and liver tissue of mammal (deer mouse, Peromyscus
maniculatus, pine vole, Microtus pinetorum), blood and feathers of birds (American
goldfinch, Spinus tristis; American robin, Turdus migratorius; Carolina wren,
Thryothorus ludovicianus; Downy woodpecker, Picoides pubescens; Eastern
bluebird, Sialia sialis; Eastern phoebe, Sayornis phoebe; Eastern screech owl, Otus
asio; Eastern song sparrow, Melospiza melodia; Eastern tufted titmouse, Baeolophus
bicolor; Eastern wood pewee, Contopus virens; Gray catbird, Dumetella
carolinensis; Great crested flycatcher, Myiarchus crinitus; Mourning dove, Zenaida
macroura; Northern dardinal, Cardinalis cardinalis; Red eyed vireo, Vireo olivaceus;
Rufous-sided towhee, Pipilo erythrophthalmus; Scarlet tanager, Piranga olivacea;
White breasted nuthatch, Sitta carolinensis; Wood thrush, Hylocichla mustelina) and
abiotic samples of soil and decayed leaf litter samples. Abiotic samples and plant
tissues were directly collected and stored in Ziploc bags. Insects, spiders were
collected either by pitfall traps or sweep net. Mice and voles were captured by baited
snap trap. Birds were captured with mist nets.

2.2.2 Sample Analysis

All results were reported in a dry weight basis unless otherwise indicated.
Freeze dried samples were weighed, homogenized, and one portion of each sample
was sent to the commercial analytical laboratory, CEBAM Inc. (Bothell, WA, USA)
for total mercury (THg) and methylmercury (MeHg) analyses. Another portion was
sent to the Stable Isotope Facility at the University of California-Davis (Davis, CA,
USA) for $\delta^{15}$N and $\delta^{13}$C analysis. The mercury analytical quality at CEBAM was
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=5.8%, n=36) for THg and -0.1% (SD=4.7%, n=36) for MeHg. The mean recoveries for spiked analysis were 100.1% (SD=7.9%, n=28) for THg and 101.6% (SD=5.5%, n=24) for MeHg. The mean recoveries for CRMs analysis were 100.6% (SD=2.9%, n=9) for THg and 98.0% (SD=3.4%, n=9) for MeHg. Analytical quality analysis for stable isotope at UC Davis was assessed using replicate analyses for five standard materials, G-11 Nylon, G-12 Glutamic Acid-Enriched, G-13 Bovine Liver, G-7 Peach leaves, and G-9 Glutamic acid. The mean recoveries of \( \delta^{13}C \) for G-11, G-12, G-13, G-7 and G-9 were 100.0% (SD=0.1%, n=52), 100.1% (SD=0.4%, n=11), 100.0% (SD=0.2%, n=5), 100.2% (SD=0.1%, n=4) and 100.1% (SD=0.2%, n=13), respectively. The mean recoveries of \( \delta^{15}N \) for G-11, G-12, G-13, G-7 and G-9 were 100.0% (SD=1.0%, n=50), 100.1% (SD=0.4%, n=8), 100.0% (SD=3.0%, n=5), 103.5% (SD=15.7%, n=4) and 93.6% (SD=6.6%, n=11), respectively. All results from the above procedures indicated excellent analytical accuracy and precision that was adequate for the intended modeling.

2.2.3 Model Construction and Selection

The procedure of model construction was reported previously (Newman et al. 2011). Briefly, a predictive model was constructed,

\[ Y_i = a + bX_{1i} + cX_{2i} + dX_{3i} + \cdots + \varepsilon \]  \hspace{1cm} (2.1)

where \( Y \) = the response variable. Estimated model parameters were \( a \) (intercept), and \( b,c,d \) (estimated regression coefficients for factors, \( X_{1i}, X_{2i}, X_{3i}, \ldots \)). The \( X_i \) were the
values of different factors associated with the sampled organisms and \( \epsilon \) was the unexplained error associated with the response.

Previous research on two floodplain sites revealed that mercury concentration could be predicted using \( \delta^{15}N \), organism thermoregulatory strategy (denoted as \( \text{Therm} \)) that, given the sampling methods, could also include a confounding influence of tissue type (Newman et al. 2011). Adding data from two more sites allowed further exploration of factors that might have a material influence on biomagnification and potentially improve model predictive capability. The candidate response variables \( (Y) \) included \( \text{THg} \) concentration, \( \text{MeHg} \) concentration, and percentage of total mercury that was methylmercury (pMeHg). Predictors \( (X_i) \) included \( \delta^{15}N \), \( \delta^{13}C \), site and \( \text{Therm} \). Site was treated in initial modeling as a categorical variable with four categories (NP, AFC, GC and GTP) and \( \text{Therm} \) was also treated as a categorical variable with two categories (poikilotherm = 0 and homeotherm = 1).

Best models were selected based on PROC GLMSELECT of the SAS\textsuperscript{®} package (SAS Institute Inc., Cary, NC, USA) with forward selection and Akaike’s Information Criterion (AIC) as the stopping criterion. A cross validation coefficient \( (r^2_{\text{prediction}}) \) was used to gauge model predictive capability. An \textit{a priori} criterion for useful prediction was set to an \( r^2_{\text{prediction}} \) of approximately 0.80 (Tom et al. 2010, Newman et al. 2011). The SAS\textsuperscript{®} PROC GLM was used to explore the general influence of explanatory variables on model response variables and interlocation differences. Akaike’s Information Criterion (AIC) was calculated in SAS program using following equation,
\[ AIC = n \times \ln(MSE) + 2k \]  

(2.2)

where \( n \) is the number of total non-missing observations, \( MSE \) is model mean squared error, and \( k \) is the number of explanatory variables. The applied minimum AIC estimation (MAICE) method favors model with the fewest explanatory variables (lowest \( k \)) and best goodness-of-fit (lowest \( MSE \)).

After the best model was selected, that model was refit using trophic level (TL) instead of \( \delta^{15}N \). This was done by converting \( \delta^{15}N \) to TL using the following equation, assuming there was a consistent increase of \( \delta^{15}N \) per TL (typically 3.4\% per TL, Newman et al. 2011; Chasar et al. 2009),

\[ TL = (\delta^{15}N_i - \delta^{15}N_{pp})/3.4\% + 1 \]  

(2.3)

where \( \delta^{15}N_i \) and \( \delta^{15}N_{pp} = \delta^{15}N \) of sample \( i \) and primary producer.

2.3 Results

Stable isotope analysis was used to estimate relative trophic positions of members of a food web (\( \delta^{15}N \)) or to suggest food sources of organisms (\( \delta^{15}N \) and \( \delta^{13}C \)). Previous study of the AFC and GTP sites (Newman et al. 2011) indicated that members of South River floodplain food webs could generally fall in three groups: terrestrial species that were detritivory-based (earthworm, slug and isopod), aquatic species that were also primarily detritivory-based (emergent insects), and terrestrial species that were primarily herbivory-based (all other species). Stable isotope data in this study were consistent with this categorization as shown in Figure 2.1. At both sites, \( \delta^{15}N \) of herbivory-based species steadily increased with increasing trophic status.
as gauged from their feeding habitats. Emergent insects from the river (mayfly, caddisfly and midge) clustered below the general trend. Crayfish, an aquatic prey item of the Eastern screech owl, was also below the general trend. Terrestrial detritivores (earthworm, slug and isopod) were not obviously different from the general trend but tended to have similar $\delta^{15}$N (interpreted as occupying similar trophic status) and $\delta^{13}$C (interpreted as having similar food source). Because these aquatic species and terrestrial detritivores had feeding pathways distinct from the herbivory-based species, they were omitted from biomagnification modeling.
Figure 2.1 Isotopic patterns from North Park (RM=2.0) and Grand Cavern (RM=20.0) based on averages for each sample type. The dotted lines defined the samples coming from trophic pathways other than that of herbivory, i.e., terrestrial and aquatic detritivory-dominated paths. Soil and leaf litter were included for reference.

Using $\delta^{15}$N to quantify trophic position, the relationship was explored between mercury concentration of terrestrial herbivory-based species and trophic positions. Clear trends were observed between $\log_{10}$THg concentration or $\log_{10}$MeHg concentration and trophic status at both locations. Many previous studies suggested that pMeHg would increase with organism trophic position (e.g., Hill et al. 1996, Tom et al. 2010), but our results only showed such a clear relationship for the North Park food web (Figure 2.2). Generally, plant tissues and herbivorous insects contained less than 10% of their mercury body burden as MeHg; bird tissues (blood and feather) contained consistently higher percentages of MeHg. If data for all birds were pooled, pMeHg of blood samples was 93.5% (95% CI = 92.1%-94.9%), slightly higher than that of the feather samples (88.5%, 95% CI= 85.8%-91.2%).
Use of feather mercury as an indicator of mercury exposure has been criticized by many researchers (e.g., Bond and Diamond 2008), mainly because “individual variation in physiological response to Hg, as well as the broad differences in inter-species pharmacokinetics” make it difficult to interpret according to Evers et al. (2005). These new data, as well as that of previous research (Newman et al. 2011) were characterized by substantial variation among feathers, so feather mercury results were omitted during model construction.

After pooling data from all four terrestrial sites and omitting terrestrial detritivores, members from aquatic food webs and bird feathers, PROC GLMSELECT was applied to examine the models that used $\log_{10}(\text{THg})$, $\log_{10}(\text{MeHg})$, or pMeHg as response variables. Forward selection picked $\delta^{15}\text{N}$ first and then Therm as predictive variables for all three response variables. The model with MeHg also included $\delta^{13}\text{C}$ as a predictor and the model with pMeHg included both $\delta^{13}\text{C}$ and site as well. Previous research (Newman et al. 2011) discussed the differences that might exist among different sites and the model with pMeHg did identify an influence of site. As a result, it was deemed necessary to model the four sites separately to get better estimates of factors influencing biomagnification and to better predict mercury concentrations in food web members. Fitting full models (including $\delta^{15}\text{N}$, $\delta^{13}\text{C}$ and Therm) to the three response variables for the individual sites showed that $\delta^{15}\text{N}$ was significant in all models, whereas Therm was significant in most models except for models of THg and MeHg for NP, models of THg for GTP and models of pMeHg for AFC. The value of $\delta^{13}\text{C}$ was not selected in most models.
Figure 2.2 Examination of the relationship between percentage of total mercury that was methylmercury (pMeHg) with $\delta^{15}$N for North Park (RM=2.0), Augusta Forestry Center (RM=11.8), Grand Cavern (RM=20.0) and Grottoes Town Park (RM=22.4). Only terrestrial herbivory-based food web members were included.
except that for MeHg for NP, pMeHg for GC and THg for GTP. Consequently, and consistent with Newman et al. (2011), $\delta^{15}$N and Therm were selected to model mercury concentrations for individual sites (equation (2.4)). Model results with $\delta^{15}$N and calculated TL were given in Table 2.1. Previously reported models for AFC and GTP were included for comparison.

$$\log_{10}(\text{Total Mercury}) / \log_{10}(\text{Methylmercury}) / \text{PMHg} = a + b \delta^{15}N + c(\text{Metabolic Status}) + \epsilon$$

(2.4)

Given the current results, models with MeHg, but not THg and pMeHg, had sufficient predictive capabilities (Figure 2.3) that met the a priori criterion. Consequently, models with THg and pMeHg were not analyzed further. The only exception was the MeHg model for GC which failed to meet the a priori criteria for adequate prediction. Overall, the biomagnification models based on $\delta^{15}$N effectively predicted MeHg on most sites (three of floodplain sites and one aquatic site). Models based on calculated TL were built for the four sites (Table 2.1). Prediction of mercury concentration could be made by back transforming to the arithmetic scale with a proper correction (Newman 1993; Newman 2011).

The MeHg food web biomagnification factor (FWMF, fold increase per TL) was calculated using the estimated model parameter $b$, i.e., $(10^b)$ (Figure 2.4). The FWMF for North Park and Grand Cavern were 17.4 (95% CI of 9.5 - 31.6) and 6.2 (95% CI of 3.5 -11.0), respectively. Overall MeHg FWMF values of terrestrial food webs were higher than those of the contiguous river food web, reinforcing previous findings of Newman et al. (2011).
Table 2.1 Summery of model parameters for four sites

<table>
<thead>
<tr>
<th></th>
<th>$r^2$</th>
<th>$a$ (95% CL)</th>
<th>$b$ (95% CL)</th>
<th>$c$ (95% CL)</th>
<th>MSE</th>
<th>$r^2_{\text{prediction}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Mercury (THg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP</td>
<td>0.47</td>
<td>-1.23 (-1.59, -0.88)</td>
<td>0.20 (0.12, 0.28)</td>
<td>-0.07 (-0.52, 0.39)</td>
<td>0.329</td>
<td>0.41</td>
</tr>
<tr>
<td>AFC</td>
<td>0.71</td>
<td>-1.47 (-1.76, -1.18)</td>
<td>0.20 (0.14, 0.27)</td>
<td>0.37 (-0.04, 0.78)</td>
<td>0.274</td>
<td>0.67</td>
</tr>
<tr>
<td>GC</td>
<td>0.39</td>
<td>-1.14 (-1.43, -0.85)</td>
<td>0.12 (0.06, 0.17)</td>
<td>0.36 (0.06, 0.66)</td>
<td>0.296</td>
<td>0.33</td>
</tr>
<tr>
<td>GTP</td>
<td>0.75</td>
<td>-1.83 (-2.11, -1.54)</td>
<td>0.29 (0.21, 0.37)</td>
<td>0.14 (-0.31, 0.58)</td>
<td>0.241</td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Methylmercury (MeHg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta^{15}N$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP</td>
<td>0.81</td>
<td>-2.70 (-3.02, -2.37)</td>
<td>0.36 (0.29, 0.44)</td>
<td>0.16 (-0.26, 0.58)</td>
<td>0.279</td>
<td>0.79</td>
</tr>
<tr>
<td>AFC</td>
<td>0.83</td>
<td>-2.66 (-2.99, -2.34)</td>
<td>0.29 (0.21, 0.36)</td>
<td>0.89 (0.43, 1.35)</td>
<td>0.343</td>
<td>0.80</td>
</tr>
<tr>
<td>GC</td>
<td>0.63</td>
<td>-2.55 (-2.94, -2.15)</td>
<td>0.23 (0.16, 0.31)</td>
<td>0.99 (0.58, 1.40)</td>
<td>0.549</td>
<td>0.59</td>
</tr>
<tr>
<td>GTP</td>
<td>0.87</td>
<td>-3.12 (-3.42, -2.82)</td>
<td>0.41 (0.32, 0.50)</td>
<td>0.55 (0.08, 1.03)</td>
<td>0.273</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>TL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP</td>
<td>0.81</td>
<td>-3.71 (-4.21, -3.21)</td>
<td>1.24 (0.98, 1.50)</td>
<td>0.16 (-0.26, 0.58)</td>
<td>0.279</td>
<td>0.79</td>
</tr>
<tr>
<td>AFC</td>
<td>0.83</td>
<td>-3.45 (-3.91, -3.00)</td>
<td>0.97 (0.73, 1.21)</td>
<td>0.89 (0.43, 1.35)</td>
<td>0.343</td>
<td>0.80</td>
</tr>
<tr>
<td>GC</td>
<td>0.63</td>
<td>-3.19 (-3.75, -2.63)</td>
<td>0.79 (0.54, 1.04)</td>
<td>0.99 (0.58, 1.40)</td>
<td>0.549</td>
<td>0.59</td>
</tr>
<tr>
<td>GTP</td>
<td>0.87</td>
<td>-4.26 (-4.74, -3.78)</td>
<td>1.40 (1.10, 1.70)</td>
<td>0.55 (0.08, 1.03)</td>
<td>0.273</td>
<td>0.85</td>
</tr>
<tr>
<td><strong>Percentage of Methylmercury in Total mercury (pMeHg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NP</td>
<td>0.81</td>
<td>-8.32 (-19.22, 2.58)</td>
<td>11.08 (8.51, 13.64)</td>
<td>14.27 (0.16, 28.39)</td>
<td>313.336</td>
<td>0.79</td>
</tr>
<tr>
<td>AFC</td>
<td>0.57</td>
<td>14.56 (0.51, 28.62)</td>
<td>5.26 (2.22, 8.29)</td>
<td>28.65 (8.77, 48.52)</td>
<td>640.073</td>
<td>0.49</td>
</tr>
<tr>
<td>GC</td>
<td>0.70</td>
<td>7.13 (-4.28, 18.54)</td>
<td>6.25 (4.13, 8.36)</td>
<td>42.93 (31.16, 54.71)</td>
<td>456.481</td>
<td>0.67</td>
</tr>
<tr>
<td>GTP</td>
<td>0.70</td>
<td>6.47 (-4.66, 17.60)</td>
<td>6.26 (3.00, 9.53)</td>
<td>29.16 (11.66, 46.65)</td>
<td>375.512</td>
<td>0.66</td>
</tr>
</tbody>
</table>

\(^{a}\) The number of observations for North Park (NP), Augusta Forestry Center (AFC), Grand Cavern (GC) and Grottoes Town Park (GTP) were 49, 43, 63 and 40 respectively.

\(^{b}\) Models based on trophic level (TL) for THg and pMeHg were not constructed. Parameters were from models based on $\delta^{15}N$ unless otherwise indicated.
2.4 Discussion

These mercury trophic transfer studies were prompted by river manager concerns about potentially harmful mercury exposure of apex species inhabiting this contaminated reach of the South River. Results from this study were consistent with those of previous studies (Tom et al. 2010; Newman et al. 2011) that MeHg was more amenable to biomagnification modeling than THg, and that pMeHg generally increased with trophic level. This was the case for both aquatic and floodplain food webs. All models but one (GC) presented good predictive capability for MeHg. After further examining GC data, two bird species (American goldfinch and Mourning dove) and a replicate of Eastern tent caterpillar deviated substantially from the general trend.
These two bird species had relatively low MeHg concentrations compared to those of the other birds. An explanation might be that they were nonresident birds caught while passing through the site. The Eastern tent caterpillar had a very high $\delta^{15}N$ value but no plausible explanation could be found to explain it. If omitting the two opportunistic birds, the model $r^2$ increased to 0.70 and the $r^2_{\text{prediction}}$ increased to 0.66, but the FWMF didn’t change substantially. A possible explanation for the poor fit of the GC model was that this location had the most topographical heterogeneity of all locations, suggesting more exchange of birds with nearby less-contaminated habitats and also more small scale variability in soil mercury concentrations. These factors could have contributed the unexplained variability that limited accurate predictions for the Grand Caverns food web.
Regardless, FMWF factors calculated in this study were consistent with Newman et al. (2011). MeHg concentration increased more rapidly in the floodplain food webs than in the contiguous aquatic food web of the South River. The mercury biomagnification in the South River floodplain food webs were also more rapid than that noted for the aquatic food web of a similar Virginia river, the Holston River (Tom et al. 2010). Although many studies explored factors that might influence mercury biomagnification, no clear general conclusion was been reached to date. Wong et al. (1997) studied two aquatic communities with similar physical and chemical qualities, finding that food web structure might have influenced mercury biomagnification. Although this research was based on aquatic systems, they might provide some insight about the differences between floodplain and aquatic food webs in this study. The aquatic community in this study was composed of poikilotherms only but many of the floodplain community members were homeotherms that must consume more mercury-contaminated food than pokilotherms to meet their metabolic requirements. Also, compared to the adjacent river, samples from the terrestrial floodplain included more omnivores such as beetles, small mammals, and small birds that increased the complexity of the terrestrial food web structure. A more complex food web might lead to higher biomagnification rates (Vander Zanden and Rasmussen 1996). Finally, the mercury assimilation efficiency of the terrestrial species might be higher than of their aquatic counterparts, resulting in higher biomagnification rates (Morel et al. 1998).
Figure 2.4 Comparison of methylmercury FWMF for the four floodplain sites: Augusta Forestry Center (RM=11.8) and Grottoes Town Park (RM=22.4) from Newman et al. (2011), and North Park (RM=2.0) and Grand Cavern (RM=20.0) from the current study. River FWMF were calculated from six pooled sites within the contaminated 23 mile reach of the South River contaminated (Tom et al. 2010). (Error bars indicate 95% confidence intervals).

Although biomagnification rates in the terrestrial food webs were consistently higher than the studied aquatic food webs, variation among terrestrial sites was substantial. Including more locations allowed a further examination of differences among floodplain food webs. Because of the lipophilicity of MeHg, it moves more readily through trophic webs than inorganic mercury. Therefore, pMeHg would increase consistently with increasing trophic positions for a food web with an uncomplicated structure, e.g., driven by a progressive movement from primary producer, to primary consumer, to secondary consumer, etc. However, only North Park in the current study showed a clear and consistent relationship between pMeHg and δ15N that was comparable to the aquatic food web (Tom et al. 2010). Grottoes
Town Park had an obvious relationship but it was not as clear as that of North Park. Augusta Forestry Center and Grand Cavern showed the least clear relationships. The differences between locations might be a result of different habitat conditions. North Park is relatively small and has relative uniform topography compared to Augusta Forestry Center and Grand Cavern. More habitat heterogeneity might obscure the relationship between pMeHg and trophic position. The Augusta Forestry Center and Grand Cavern also had relatively low FWMF (9.3 and 6.2 for AFC and GC respectively) compared to the other two locations. Given the above analysis, it might be more suitable to compare FWMF between North Park (17.4) as the best of the floodplain food webs and the contiguous river food web (4.6) with comparable mercury trophic transfer potentials, in which case floodplain food web was still approximately 3.8 times higher than that of the river food web.

Avian species were the apex predators on the South River floodplain. The present study documented increased mercury concentrations with increasing trophic position, and produced models to predict the mercury concentrations. Previous South River studies suggested adverse effects due to mercury exposure of tree swallow (Brasso and Cristol 2008) and Eastern bluebird (Condon and Cristol 2009). Combining our 2009 and 2010 data, blood mercury concentrations of 82 birds and feather mercury concentrations of 81 birds were available to compare with the avian biomonitoring literature. Unfortunately, minimal information about toxicity thresholds could be found based on avian blood and feather concentration. Evers et al. (2008) suggested that captive loons with blood mercury concentrations (ww, THg)
over 3 μg/g were at high risk of adverse effects. Their corresponding threshold based on feathers was 40 μg/g (ww, THg). Ignoring uncertainties associated with variation in sensitivity between loon and the avian species in this study, only two out of eight-two blood samples (2.4%) were greater than 3 μg/g and one out of eight-one feather samples (1.2%) was greater than 40 μg/g in this study. Using the mercury concentrations at which adverse effects were noted for tree swallows (Brasso and Cristol 2008) (3.56 ppm ww, THg for blood and 13.55 ppm ww, THg) for feather, two blood samples (2.4%) and seven feather samples (8.5%) from this study were above the corresponding values. Contrary to our initial assumption, the evidence suggested that the avian species populations sampled in this study might not be exposed to harmful mercury levels.

2.5 Conclusions

Extending the previous mercury trophic transfer study of the mercury-contaminated South River watershed, the current study assessed models for making useful predictions of mercury concentration in members of the floodplain food webs at two additional sites (North Park and Grand Cavern). Acceptable prediction from each model was gauged with an a priori established prediction \( r^2 \) of approximately 0.80. Overall the models predicting methylmercury were superior to models for total mercury or the percentage of the mercury present as methylmercury. Including previous models for other river sites, four of five attempted methylmercury models based on \( \delta^{15}N \) met the criterion for useful prediction. For floodplain models,
thermoregulatory strategy was included in the models. The only location failing to produce a good model, Grand Caverns, had the most topographical heterogeneity of all locations, suggesting more exchange of birds with adjacent less-contaminated habitats and more small scale differences in soil mercury concentrations. The food web biomagnification factor of North Park and Grand Cavern were 17.4 (95% CI of 9.5 - 31.6) and 6.2 (95% CI of 3.5 - 11.0) respectively, supporting previous findings that the South River floodplain food webs had higher biomagnification rates than the adjacent aquatic food web.
3.1 Introduction

Mercury from anthropogenic sources can elevate mercury concentrations in ecosystems to harmful levels (Bergeron et al. 2007; Flanders et al. 2010; Bundschuh et al. 2011). Top predators are especially susceptible because methylmercury is subject to 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 mercury in contaminated habitats (Evers et al. 2005). Determinations of bird exposure to mercury 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 mercury concentration (Morel et al. 1998; Rumbold 2005). Based on information about feeding ecology of an avian species, potential food items, their frequencies of consumption, and associated mercury concentrations, general distributions for these qualities can be defined. With such information, probabilistic models incorporating information about bird potential food items, general feeding ecology, and body weights can then be used to define mercury exposure. Such models were built to
assess mercury 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 other potential risk from chemicals such as hexachlorobenzene and selenium to avian species (Moore et al. 1997; Wayland et al. 2007) and mercury exposure to human community (Holloman and Newman forthcoming).

Three avian species were selected based on a previous trophic transfer study (Newman et al. 2011) and dialog with river risk managers to address two crucial issues. The first was description and determination of current mercury exposure to adults of three avian species during nesting on the South River floodplain. Results were to be expressed as cumulative probability distributions of (averaged) daily mercury ingestion rates. The distributions were then to be compared for these potentially at-risk species. The second issue was to judge the risk of harmful mercury exposure to these species by comparing the mercury exposure distributions 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 hard to collect reliably by field survey.

3.2 Materials & Methods

3.2.1 Sampling and Chemical Analysis

The studied river 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. Additional details about the field sampling
procedure of 2009 sites could be found in Newman et al. (2011). Supplementary
samples were taken at Grand Cavern in September 2010 to ensure there was enough
food information for modeling exposure. Samples, taken together with those from
another trophic transfer study (Newman et al. 2011), included plants (seed of smooth
hydrangea, *Hydrangea arborescens*; grain of Virginia wild eye, *Elymus virginicus*;
grain of Johnson grass, *Sorghum halepense*; grain of crabgrass, *Digitaria sp.*; fruit of
pokeberry, *Phytolacca americana*; fruit of twisterdstalk, *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* and 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*).

All samples except those of plants, mice and birds were processed as whole
body. Fruits and grains were collected for plants and muscle tissue was collected for
deer mice. Non-lethal methods were used to collect bird tissue. Birds were released
after sampling of a few tail feathers and small volume of blood. All samples were weighed, homogenized, freeze-dried in preparation for mercury analysis.

Total mercury and methylmercury analysis of most samples was conducted at a commercial analytical lab, CEBAM Analytical Inc. (Bothell, WA, USA). Supplemental samples were analyzed in our own lab using a direct mercury analyzer (DMA-80; Milestone, Shelton, CT, USA) for total mercury. Both analyses provided excellent results as detailed below.

3.2.2 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 insects and spiders, and also small amounts of plant material (Kurpinski and Kirschbaum 2001; Haggerty and Morton, 1995). The Eastern song sparrow, *Melospiza melodia*, also defend territories and maintain pair bonds year-round (Arcese et al. 2002). They often eat large amounts of plant material such as fruit and grain, but during breeding period, shift their diets to include more insects. The Eastern screech owl, *Otus asio*, maintain their territories in winter and summer (Gehlbach 1995). They feed mainly on invertebrates (insects, crayfish and earthworms) and some vertebrates (songbirds and rodents) (Gehlbach 1995).

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

3.2.3 Effect Characterization

The most abundant organic mercury 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). Inorganic mercury in bird kidneys can produce kidney lesions and dysfunction. Most effects information came from acute toxicity tests under controlled laboratory conditions. At
most contaminated sites, birds are exposed to low levels of mercury via the diet (Wren and Macrimmon 1983) and can suffer chronic effects. Spalding (1994) recognized that mortality of great white herons caused from chronic disease was associated with kidney mercury concentration greater than 6 μg/g total mercury (wet weight, ww). On the South River floodplain, a statistically significant decrease of reproductive success was observed for tree swallows with mean blood total mercury of 3.56 μg/g (ww) (Brasso et al. 2008).

Mercury ingestion and 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 associated with prey mercury concentration of 0.3 to 0.4 μg/g fresh weight. Heinz (1979) dosed three generations of Mallard ducks 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 ninth day post hatch for the second and third generation ducks. Based on the food ingestion rate provided by Heinz (156 g/kg of duck body weight for the dosing group), methylmercury was calculated to be ingested at a rate of 0.078 mg / kg of duck body weight daily. 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 dosing group. Another study by Spalding (2000) on Great egret with daily dosing rates from 0.048 mg/kg bird
body weight to 0.135 mg/kg of methylmercury chloride noted sub-lethal effects to dosed egrets.

This study used total mercury in prey items to characterize mercury exposure. Considering the dosing rate from Heinz and Spalding’s studies and the percentage of methylmercury in total mercury in our samples, we decided to use 0.1 mg total mercury/kg bird body weight daily (100 ng/g-day) as the toxicity reference value (TRV) to assess the risk of mercury exposure to the three species.

3.2.4 Exposure analysis

3.2.4.1 Model for mercury dietary exposure

Daily mercury ingestion rate (DMIR) was modeled by incorporating bird morphological data (body weight) and feeding ecology (food ingestion rate and diet item choice), using equation (3.1):

\[
\text{Mercury Daily Ingestion Rate (ng/g)} = \sum_{i} BW_{p(i)} \cdot C_{i} / BW_{b},
\]

\[
\text{and } \sum_{i} BW_{p(i)} \leq BW_{b} \times FIR
\]

where \( BW_{b} \) = the body weight of selected bird, \( FIR \) = food ingestion rate, \( BW_{p(i)} \) = the body weight of prey item \( i \), and \( C_{i} \) = mercury concentration of prey item \( i \).

Daily mercury ingestion rate (DMIR) modeled in this study was expressed as the amount of mercury that an adult bird might ingest relative to its body weight during its daily foraging. Average daily mercury 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.

3.2.4.2 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) food ingestion rate ($FIR$),
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 mercury
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 food items in a species diet ($PP_i$), which was
treated as the probability of a bird picking a certain food item during foraging.
Because it would have been 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 status. According
to mercury biomagnification research by Newman et al. (2011), mercury
concentration of a South River floodplain organism is related closely with its trophic
status as characterized by $\delta^{15}N$. Prey of similar trophic status have similar mercury
concentrations so using representative prey species instead of all prey species was
justifiable.
Body weights ($BW_{p(i)}$, wet weight) and the mercury concentrations ($C_i$, wet weight 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 was that total mercury concentration and the body weight of individual prey items conformed to log-normal distributions defined with two estimated parameters for each item. To avoid unrealistic values being used during simulation such as negative body weight or unrealistically high mercury concentration, a lower limit of 0 and a higher limit of three standard deviations 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 grams (Galbach 1995), we set the upper limit of owl prey items to the smaller of 40 grams or three standard deviations 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 material food items. Mice and small birds are prey for Eastern screech owl. We assumed the concentrations in mouse tissue eaten by owls were similar to those measured in muscle tissue. Because of our non-lethal sampling method for bird tissue, we multiplied bird blood mercury concentrations by two 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 three species. As a result, a formal expert elicitation was conducted under the general framework of the Delphi method 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 (O’Hagan 2005; Garthwaite et al. 2005). The exchange in this study involved an electronic questionnaire (see Appendix) provided to experts by email or an ftp site. This format, suggested by the work of O’Hagan (1998, 2005), allowed us to design questions in a specific sequence and establish some 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 (O’Hagan et al. 2006; Stone and Opel 2000). This was achieved with a modified Delphi method. The Delphi method was developed at the RAND Corporation in the early 1950s for a military project (Cook 1991) and was further developed and widely applied to diverse situations thereafter. In the usual Delphi method, a group of separate experts are selected by researchers to provide quantitative opinions about some event or situation. Results from separate experts are complied and the compiled information sent to each expert for possible change or comment. Their feedback is complied and distributed 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.

The expert elicitation questionnaire for each bird was organized into three sections: bird body weight, diet composition, and overall food ingestion rate. 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 three single values, experts were then asked to provide estimates of the probabilities that the variable would fall in three intervals \((q_1, q_2 \text{ and } q_3)\) shown in equations (3.2) to (3.4). These intervals were picked and opinion asked in this sequence to minimize instances of experts estimating very small probabilities and anchoring (O’Hagan 1998). Four resulting probabilities \((p_1, p_2, p_3 \text{ and } p_4)\) were then calculated via equation (3.5) to (3.8) and used to structure the distributions of \( BW_b \) and \( FIR \).

\[
q_1 = \Pr (\text{lowest} \leq X \leq \text{mode}) \tag{3.2}
\]

\[
q_2 = \Pr (\text{lowest} \leq X \leq (\text{lowest} + \text{mode})/2) \tag{3.3}
\]

\[
q_3 = \Pr ((\text{mode} + \text{highest})/2 \leq X \leq \text{highest}) \tag{3.4}
\]

\[
p_1 = \Pr (\text{lowest} \leq X \leq (\text{lowest} + \text{mode})/2) = q_1 \tag{3.5}
\]

\[
p_2 = \Pr ((\text{lowest} + \text{mode})/2 \leq X \leq \text{mode}) = q_1 - q_2 \tag{3.6}
\]
\[
p3 = \Pr(\text{mode} \leq X \leq (\text{mode} + \text{highest})/2) = 1 - q1 - q3 \quad (3.7)
\]
\[
p4 = \Pr((\text{mode} + \text{highest})/2 \leq X \leq \text{highest}) = q3 \quad (3.8)
\]

It was not practical to ask experts to provide a series of estimates for \( PP_i \) for each prey item as done for \( BW_b \) and \( FIR \), so experts were asked instead for a single estimate of the proportion of each food item expected in the total weight of food consumed daily. Using the resulting expert input, a probability distribution for \( BW_b \), a probability distribution of \( FIR \), and a group of estimates of \( PP_i \) could then be generated for each individual expert.

To assess the general accuracy and precision of expert responses during elicitation, two calibration questions were included in each of the three sections. 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 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 above scores.

3.4.2.3 Monte Carlo Simulation

A Monte Carlo simulation approach used the values and distributions of the previously explained parameters from the field surveys and expert elicitation. Daily
mercury ingestion rate could be modeled using equation (1) for each expert and 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 this day (M_r) was then calculated by 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_r at which point the bird had eaten its maximum for the day. Then the daily mercury ingestion rate was calculated by dividing the sum of total mercury (M_{h(i)}) contained in the selected items by the bird body weight (M_{h(i)}/BW_b). This procedure was repeated 1000 or more times until the pre-set number of iterations had been reached, generating a distribution of daily mercury ingestion rates.

In order to obtain averaged daily mercury ingestion rate (ADMIR) during breeding season, N (days, equal to the approximate duration of breeding season) of randomly selected daily mercury ingestion rates from the distribution generated above were averaged. 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.

3.2.5 Sensitivity analysis

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

3.3 Results

3.3.1 Mercury Analysis

The mercury analytical quality at CEBAM (CEBAM Analytical, Inc., Bothell, WA USA) was 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=5.8%, n=36) for total mercury. 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 mercury respectively. Quality of analysis of samples in our lab was also gauged with sample splits and reference materials (Tort-2). The mean differences between sample splits were -0.8% (SD=11.2%, n=6). The mean recoveries for CRM analysis were 104.2% (SD=1.4%, n=24). All the results from the above procedures documented analytical accuracy and precision adequate for the intended modeling effort.

3.3.2 Prey Items Information

Prey body weight and mercury concentration were fit to log-normal distributions using the analytical and measured data, the parameters (Log Mean and
Log Standard deviation) of which were listed in Table 3.1. As indicated previously, simulation boundaries were set for each distribution in order to avoid inclusion of unrealistic body weight and mercury concentrations. The upper limit was set to be three standard deviation from the mean for all items but the maximum body weight of small birds, which was set at 40 g, assuming Eastern screech owl could not take items over 40 grams.

Table 3.1 Parameters of log-normal distributions for prey items

<table>
<thead>
<tr>
<th>Prey Items</th>
<th>Weight Log Mean</th>
<th>Weight Log SD</th>
<th>Weight Max</th>
<th>Weight N</th>
<th>Mercury Log Mean</th>
<th>Mercury Log SD</th>
<th>Mercury Max</th>
<th>Mercury N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caddisfly</td>
<td>-4.91</td>
<td>0.29</td>
<td>0.02</td>
<td>12</td>
<td>5.81</td>
<td>0.67</td>
<td>2465.13</td>
<td>12</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>-1.20</td>
<td>0.75</td>
<td>2.84</td>
<td>11</td>
<td>2.08</td>
<td>1.39</td>
<td>518.01</td>
<td>11</td>
</tr>
<tr>
<td>Crayfish</td>
<td>1.41</td>
<td>0.66</td>
<td>29.92</td>
<td>6</td>
<td>5.49</td>
<td>1.09</td>
<td>6393.26</td>
<td>6</td>
</tr>
<tr>
<td>Deer</td>
<td>2.99</td>
<td>0.23</td>
<td>39.02</td>
<td>12</td>
<td>3.64</td>
<td>0.74</td>
<td>350.72</td>
<td>10</td>
</tr>
<tr>
<td>Mouse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earthworm</td>
<td>-0.62</td>
<td>0.84</td>
<td>6.69</td>
<td>12</td>
<td>7.12</td>
<td>0.98</td>
<td>23395.06</td>
<td>12</td>
</tr>
<tr>
<td>Fruits</td>
<td>-2.09</td>
<td>0.86</td>
<td>1.63</td>
<td>5</td>
<td>1.37</td>
<td>0.88</td>
<td>55.20</td>
<td>15</td>
</tr>
<tr>
<td>Isopod</td>
<td>-3.59</td>
<td>0.59</td>
<td>0.16</td>
<td>12</td>
<td>6.21</td>
<td>0.50</td>
<td>2236.80</td>
<td>12</td>
</tr>
<tr>
<td>Ladybug</td>
<td>-3.47</td>
<td>0.19</td>
<td>0.06</td>
<td>10</td>
<td>2.59</td>
<td>0.78</td>
<td>138.80</td>
<td>10</td>
</tr>
<tr>
<td>Mayfly</td>
<td>-5.56</td>
<td>1.68</td>
<td>0.59</td>
<td>18</td>
<td>5.46</td>
<td>0.49</td>
<td>1017.39</td>
<td>18</td>
</tr>
<tr>
<td>Midge</td>
<td>-8.90</td>
<td>0.70</td>
<td>0.00</td>
<td>12</td>
<td>6.94</td>
<td>0.87</td>
<td>14234.16</td>
<td>12</td>
</tr>
<tr>
<td>Seeds</td>
<td>-5.15</td>
<td>0.74</td>
<td>0.05</td>
<td>4</td>
<td>2.97</td>
<td>1.11</td>
<td>543.96</td>
<td>12</td>
</tr>
<tr>
<td>Slug</td>
<td>-0.18</td>
<td>0.99</td>
<td>16.40</td>
<td>9</td>
<td>4.30</td>
<td>0.76</td>
<td>715.51</td>
<td>9</td>
</tr>
<tr>
<td>Spider</td>
<td>-3.32</td>
<td>0.87</td>
<td>0.49</td>
<td>17</td>
<td>6.13</td>
<td>0.78</td>
<td>4784.98</td>
<td>17</td>
</tr>
<tr>
<td>Small Birds</td>
<td>3.19</td>
<td>0.34</td>
<td>40</td>
<td>81</td>
<td>6.50</td>
<td>1.20</td>
<td>24348.12</td>
<td>40</td>
</tr>
</tbody>
</table>

3.3.3 Expert Input

A pool of approximately 40 candidate experts was compiled and nine experts expressed their willingness to contribute to the elicitation exercise. Due to schedule problems, 6 experts finished the original questionnaire with reliable input and 4 of
these experts revised their inputs after reviewing the report that had compiled the expert 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 3.1 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 three 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, b, c).

Estimates of food ingestion rate were less consistent across experts. Five of six 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, five of six 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 generally with previous research that small birds eat more food in proportion to their body weight than larger birds (Lack 1954).
Figure 3.1 Expert estimates of bird body weight and food ingestion rate
Figure 3.1 Expert estimates of bird body weight and food ingestion rate (Continued)
In order to get distributional information for bird body weight ($BW_b$) and food ingestion rate ($FIR$), we had expected 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 thirty-six expert distributions had gaps in their distributions with $p3$ being zero. Fourteen distributions had unrealistic patterns such as slightly concave shape instead of an expected peaked or flat shape. Due to these unexpected patterns, we used experts’ single estimates of lowest value, highest value and mode to build a triangular distribution as the input of Monte Carlo simulation to assess the mercury exposure. Daily mercury ingestion rate from 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 provide their estimates of the relative proportions of the potential prey items in a bird species’ diet ($PP_i$) (Figure 3.2). Despite differences among experts, experts did reach a consensus. Carolina wren were estimated to ingest primarily caterpillars (more than 15% of the Carolina wren’s diet) and spiders (more than 20 %), which was consistent with previous stomach content research on Carolina wren (Haggerty et al. 1995). Experts estimated the Eastern song sparrow ingested a large portion of plant tissue (seeds and fruits) and many insects and spiders, which also agreed with previous research (Judd 1901; Arcese et al. 2002). For Eastern screech owl, consistent with Van Camp and Henry (1975) and Turner and Dimmick
Figure 3.2 Expert estimations of proportion of prey items
(1981), experts opined that this owl took primarily small birds and small mammals such as deer mouse.

3.3.4 Expert Weightings

The elicitation gathered three 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 3.2 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 three species. Some experts got fair responses for the diet questions and more experts gave limited responses for food ingestion rate questions than for the other two sets of questions.

Table 3.2 Analysis of expert weighting questions (number of experts = 6)

<table>
<thead>
<tr>
<th>Section of Expert Elicitation</th>
<th>Carolina wren</th>
<th>Eastern song sparrow</th>
<th>Eastern screech owl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Weight</td>
<td>100%</td>
<td>83% 17%</td>
<td>83% 17%</td>
</tr>
<tr>
<td>Diet</td>
<td>17% 83%</td>
<td>33% 67% 17%</td>
<td>67% 17% 33% 67%</td>
</tr>
<tr>
<td>Composition Food Ingestion Rate</td>
<td>33% 50% 17%</td>
<td>17% 67% 33% 67%</td>
<td></td>
</tr>
</tbody>
</table>

Based on the scores that experts got in each section (body weight, food preference, and ingestion rate), a weighting was assigned to each expert. Composite distributions were based on these weightings.
3.3.5 Daily Mercury Ingestion Rate and Averaged Daily Mercury 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 Figure 3.3). Distributional statistics for simulation were listed in Tables 3.3 to 3.5. The variation among experts was adjusted with weightings to produce a composite exposure distribution for each bird.

According to the composite estimates (Figure 3.4), an adult Carolina wren consumed more mercury than Eastern song sparrow in daily foraging, but 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 (Galbach 1995)), there was less than 1% chance that any of the three species will consume a potentially harmful amount of mercury over breeding season with mean ADMIR of 50 ng/g(ww)-day, 31 ng/g(ww)-day and 65 ng/g(ww)-day for Carolina wren, Eastern song sparrow and Eastern screech owl, respectively (Figure 3.5).
Figure 3.3 Daily mercury ingestion rate from Monte Carlo simulations
<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>2.5%</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
<th>97.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert A</td>
<td>64.92</td>
<td>1.87</td>
<td>941.81</td>
<td>5.9</td>
<td>12.8</td>
<td>23.42</td>
<td>44.52</td>
<td>79.98</td>
<td>143.09</td>
<td>251.68</td>
</tr>
<tr>
<td>Expert B</td>
<td>70.85</td>
<td>1.1</td>
<td>3095.78</td>
<td>5.54</td>
<td>11.26</td>
<td>21.01</td>
<td>39.63</td>
<td>80.45</td>
<td>150.94</td>
<td>313.62</td>
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<tr>
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<td>3.21</td>
<td>853.77</td>
<td>6.9</td>
<td>13.44</td>
<td>21.99</td>
<td>38.87</td>
<td>67.42</td>
<td>133.55</td>
<td>253.82</td>
</tr>
<tr>
<td>Expert D</td>
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<td>1.23</td>
<td>3159.66</td>
<td>6.34</td>
<td>22.05</td>
<td>45.99</td>
<td>94.63</td>
<td>209.52</td>
<td>416.73</td>
<td>994.4</td>
</tr>
<tr>
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<td>&lt;1</td>
<td>105.02</td>
<td>&lt;1</td>
<td>1.4</td>
<td>2.98</td>
<td>5.71</td>
<td>11.03</td>
<td>21.16</td>
<td>35.26</td>
</tr>
<tr>
<td>Expert F</td>
<td>97.00</td>
<td>&lt;2</td>
<td>1395.39</td>
<td>3.26</td>
<td>7.65</td>
<td>22.25</td>
<td>52.09</td>
<td>119.63</td>
<td>233.02</td>
<td>456.44</td>
</tr>
<tr>
<td>Composite</td>
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<td>&lt;3</td>
<td>1235.93</td>
<td>0.96</td>
<td>2.55</td>
<td>6.19</td>
<td>23.4</td>
<td>66.19</td>
<td>164.19</td>
<td>474.07</td>
</tr>
<tr>
<td>Expert</td>
<td>Mean</td>
<td>Min</td>
<td>Max</td>
<td>2.5%</td>
<td>10%</td>
<td>25%</td>
<td>50%</td>
<td>75%</td>
<td>90%</td>
<td>97.5%</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>------</td>
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<td>------</td>
<td>------</td>
<td>------</td>
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<td>-------</td>
</tr>
<tr>
<td>Expert A</td>
<td>16.79</td>
<td>0.56</td>
<td>182.56</td>
<td>3.57</td>
<td>5.74</td>
<td>8.66</td>
<td>13.28</td>
<td>20.93</td>
<td>30.41</td>
<td>51.63</td>
</tr>
<tr>
<td>Expert B</td>
<td>62.95</td>
<td>0.26</td>
<td>1451.92</td>
<td>1.93</td>
<td>4.82</td>
<td>10.22</td>
<td>26.25</td>
<td>66.01</td>
<td>148.72</td>
<td>369.65</td>
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<tr>
<td>Expert C</td>
<td>33.48</td>
<td>1.04</td>
<td>287.95</td>
<td>3.56</td>
<td>7.01</td>
<td>11.43</td>
<td>21.28</td>
<td>41.21</td>
<td>71.76</td>
<td>129.93</td>
</tr>
<tr>
<td>Expert D</td>
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<td>2831.69</td>
<td>3.56</td>
<td>13.25</td>
<td>37.67</td>
<td>82.15</td>
<td>177.07</td>
<td>355.28</td>
<td>850.88</td>
</tr>
<tr>
<td>Expert E</td>
<td>30.27</td>
<td>0.05</td>
<td>689.22</td>
<td>&lt;1</td>
<td>1.55</td>
<td>3.99</td>
<td>11.1</td>
<td>35.22</td>
<td>77.75</td>
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<tr>
<td>Expert F</td>
<td>35.12</td>
<td>0.25</td>
<td>987.43</td>
<td>&lt;1</td>
<td>2.22</td>
<td>4.59</td>
<td>10.52</td>
<td>32.98</td>
<td>81.77</td>
<td>220.76</td>
</tr>
<tr>
<td>Composite</td>
<td>41.02</td>
<td>0.26</td>
<td>1783.56</td>
<td>&lt;1</td>
<td>2.31</td>
<td>4.78</td>
<td>12.39</td>
<td>36.35</td>
<td>91.9</td>
<td>256.19</td>
</tr>
</tbody>
</table>

Table 3.4 Statistics of daily mercury ingestion rate from Monte Carlo simulations for Eastern song sparrow
Unit: ng Hg/ g Body Weight/ day (unless otherwise indicated)
<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>2.5%</th>
<th>10%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
<th>97.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert A</td>
<td>109.58</td>
<td>&lt;1</td>
<td>2522.88</td>
<td>3.82</td>
<td>7.98</td>
<td>16.13</td>
<td>41.89</td>
<td>112.92</td>
<td>240.26</td>
<td>637</td>
</tr>
<tr>
<td>Expert B</td>
<td>60.53</td>
<td>&lt;1</td>
<td>1653.5</td>
<td>1.06</td>
<td>2.23</td>
<td>4.92</td>
<td>20.82</td>
<td>70.95</td>
<td>147.12</td>
<td>369.29</td>
</tr>
<tr>
<td>Expert C</td>
<td>234.67</td>
<td>3.64</td>
<td>8186.41</td>
<td>10.78</td>
<td>21.3</td>
<td>43.7</td>
<td>102.65</td>
<td>233.45</td>
<td>521.83</td>
<td>1300.22</td>
</tr>
<tr>
<td>Expert D</td>
<td>37.44</td>
<td>&lt;1</td>
<td>1272.32</td>
<td>&lt;1</td>
<td>1.6</td>
<td>2.91</td>
<td>6.76</td>
<td>29.47</td>
<td>105.92</td>
<td>268.27</td>
</tr>
<tr>
<td>Expert E</td>
<td>59.84</td>
<td>1</td>
<td>2858.9</td>
<td>2.37</td>
<td>4.17</td>
<td>8.03</td>
<td>18.26</td>
<td>48.32</td>
<td>140.03</td>
<td>393.6</td>
</tr>
<tr>
<td>Expert F</td>
<td>318.75</td>
<td>2.96</td>
<td>4212.95</td>
<td>15.5</td>
<td>34.57</td>
<td>66.53</td>
<td>143.86</td>
<td>318.08</td>
<td>747.42</td>
<td>1824.01</td>
</tr>
<tr>
<td>Composite</td>
<td>87.3</td>
<td>&lt;1</td>
<td>4312.21</td>
<td>1.44</td>
<td>2.86</td>
<td>6.08</td>
<td>19.95</td>
<td>72.53</td>
<td>216.66</td>
<td>519.39</td>
</tr>
</tbody>
</table>
Figure 3.4 Comparison of daily mercury ingestion rate. Mean DMIR of wren, sparrow and owl were approximately 68 ng/g(ww)-day, 41 ng/g(ww)-day and 87 ng/g(ww)-day, respectively.

Figure 3.5 Average daily mercury ingestion rate from Monte Carlo simulations. Mean ADMIR of wren, sparrow and owl were approximately 50 ng/g(ww)-day, 31 ng/g(ww)-day and 65 ng/g(ww)-day, respectively.
3.3.6 Sensitivity Analysis

Sensitivity analysis was intended to identify the contribution of input to the resulting output distribution of components of a Monte Carlo simulation. The current study compared the outputs of different types of input distributions of $BW_b$ and $FIR$, triangular distribution, uniform distribution and customized distribution (Figure 3.6). No material differences were observed between mean DMIR of the three species. The seventy-fifth 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(ww)-day respectively. For sparrow, the values were 36, 34, 39 ng/g(ww)-day and for owl, were 73, 69 and 77 ng/g(ww)-day, respectively. Again, no material differences were observed.

![Figure 3.6 Comparisons of Input Distributions by Means of DMIR for Each Species](image)

Figure 3.6 Comparisons of Input Distributions by Means of DMIR for Each Species
In order 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 (Table 3.6, Figure 3.7). Food ingestion rate of all the three species played the most important role in bird mercury exposure. The coefficients of $FIR$ for all three species were over 0.4. Bird body weight either ranked low as in the case of Eastern screech owl or not at all for the other two species. In sensitivity analysis of Eastern screech owl, body weight only ranked seventh, but its correlation with owl’s DMIR (coefficient of 0.04) was very low. In addition to food ingestion rate, different food items contributed differently. For Carolina wren, the size of Eastern tent caterpillar ranked as the second most important factor but with a negative coefficient. The mercury concentration of earthworm, the mercury concentration of caterpillar, the weight of earthworm and the weight of midge ranked from third to sixth with positive coefficients and p-values lower than 0.01 among the top 10 factors. For Eastern song sparrow, again the mercury concentration of earthworm ranked high (second) with a positive value and the weight of caterpillar ranked third with a negative value. Another detritivore (slug) also ranked high with a positive value for song sparrow. As indicated previously, song sparrows eat a large portion of vegetable matter which have relatively low mercury concentrations, leading to a high rank with a negative coefficient for fruits. For Eastern screech owl, in addition to food ingestion rate, mercury concentration of small birds, mice and crayfish ranked high in the sensitivity analysis.
Figure 3.7 Sensitivity analysis of input variables for each species
Table 3.6 Spearman rank correlation coefficients between input variables and DMIR. H0: \( \rho = 0 \)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Carolina Wren Spearman Coefficient</th>
<th>Carolina Wren p-Value</th>
<th>Eastern Song Sparrow Spearman Coefficient</th>
<th>Eastern Song Sparrow p-Value</th>
<th>Eastern Screech Owl Spearman Coefficient</th>
<th>Eastern Screech Owl p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Ingestion Rate</td>
<td>0.46594</td>
<td>&lt;.0001</td>
<td>0.43938</td>
<td>&lt;.0001</td>
<td>0.40769</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Weight of Caterpillar</td>
<td>-0.34657</td>
<td>&lt;.0001</td>
<td>0.1973</td>
<td>&lt;.0001</td>
<td>0.27023</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Mercury of Earthworm</td>
<td>0.20501</td>
<td>&lt;.0001</td>
<td>-0.19062</td>
<td>&lt;.0001</td>
<td>0.18659</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Mercury of Caterpillar</td>
<td>0.14463</td>
<td>&lt;.0001</td>
<td>0.17538</td>
<td>&lt;.0001</td>
<td>0.12267</td>
<td>0.0001</td>
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<tr>
<td>Weight of Earthworm</td>
<td>0.12937</td>
<td>&lt;.0001</td>
<td>-0.17358</td>
<td>&lt;.0001</td>
<td>0.07192</td>
<td>0.0229</td>
</tr>
<tr>
<td>Weight of Midge</td>
<td>0.10525</td>
<td>0.0009</td>
<td>0.12153</td>
<td>0.0001</td>
<td>-0.06937</td>
<td>0.0283</td>
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<tr>
<td>Mercury of Slug</td>
<td>0.05577</td>
<td>0.0780</td>
<td>0.11388</td>
<td>0.0003</td>
<td>0.04222</td>
<td>0.1822</td>
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<tr>
<td>Mercury of Ladybug</td>
<td>-0.04549</td>
<td>0.1506</td>
<td>0.07093</td>
<td>0.0249</td>
<td>0.03081</td>
<td>0.3303</td>
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<td>Mercury of Spider</td>
<td>-0.04177</td>
<td>0.1869</td>
<td>-0.04701</td>
<td>0.1374</td>
<td>0.02882</td>
<td>0.3627</td>
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<td>Mercury of Fruit</td>
<td>-0.03976</td>
<td>0.2090</td>
<td>-0.04037</td>
<td>0.2021</td>
<td>0.0284</td>
<td>0.3697</td>
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</tbody>
</table>
3.4 Discussion

Two questions posed at the beginning of this paper could be answered. This study used both the daily mercury ingestion rate and averaged daily mercury ingestion rate during breeding periods to describe mercury 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 consists principally of animals with much higher mercury concentrations than the floodplain plants. Consequently, Carolina wren tended to have higher mercury exposure than the Eastern song sparrow whose diet included more plants. Also, 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 have higher mercury concentrations in their tissues (Newman et al. 2011). But the wren consumed more food (normalized to body weight) than the owl. So the wren mercury exposure was comparable to that of the owl.

Daily mercury ingestion rate describes exposure for one 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 mercury dosing. So it is more suitable to compare this TRV value with averaged daily mercury ingestion rate simulated in this study. Averaged over breeding periods, mean ADMIR of three species dropped from 68
ng/g(ww)-day, 41 ng/g(ww)-day and 88 ng/g(ww)-day to 50 ng/g(ww)-day, 31
ng/g(ww)-day and 65 ng/g(ww)-day for wren, sparrow and owl, respectively. These
exposures reflected less than 1% probabilities that an adult bird from these three
species might ingest mercury exceeding the TRV value, suggesting that there might
be less than one out of a hundred chance that an adult bird would ingest harmful
amounts of mercury on South River floodplain during the breeding season. It is also
worth noticing that the probability density functions of DMIR of all the three species
were quite positively skewed while the probability density functions of ADMIR were
much more symmetrical.

This study also presented a good example of the advantage of probabilistic
risk assessment, which provides risk managers and other relevant groups the
distributions of exposure and allows them to select the best suitable criteria to judge
risk. There were inevitable differences between the current study site and the
experimental settings from which the TRV was derived, and also species variation
between waterfowl (ducks and egrets) and the three study species, which might both
result in inevitable uncertainty on risk decisions (Rumbold 2005).

Sensitivity analysis provided a prospective to discuss the influence of different
components of Monte Carlo simulations on the final results. As indicated previously,
the influence of distribution types from expert elicitation was regarded to be
immaterial relative to the goal of this study given the comparisons of means and
seventy-fifth percentiles from the three distributions; however more accurate input
distributions would improve the match between simulation scenario and environmental settings, which in turn could result in more accurate estimates.

According to Spearman rank correlation coefficient, food ingestion rate ($FIR$) played the most important role on daily mercury ingestion rate for all three species. In contrast, bird body weight ($BW_b$) did not have a substantial influence for these three birds. This was not unexpected given the structure of equation (1) and the magnitude and variation of $BW_b$. According to equation (1), daily mercury ingestion rate represents a ratio of mercury ingested (numerator) to $BW_b$ (denominator). The magnitude of $BW_b$, which was characterized using grams, is much larger than ingested mercury which was expressed as nanograms. Also $BW_b$ 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 mercury ingestion rate. In addition to $FIR$ and $BW_b$, interpretations of other factors were not quite as straightforward. Generally, caterpillar and earthworm might influence mercury ingestion rate substantially given that they listed high in the sensitivity analysis for both Carolina wren and Eastern song sparrow. (Eastern screech owl rarely eat caterpillars and earthworms according to the experts). The reason that prey got a negative Spearman coefficient such as that for caterpillars weight might be because mercury concentration of that item was below the average prey concentration: the larger it was, the more low mercury concentration materials were in a bird’s diet on a particular day. Besides, the reason that some prey items was 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 slug that experts estimated increased from 0.2% in diet of Carolina wren to 2.4% for Eastern song sparrow.

Although experts did not respond optimally in providing distributional information, expert elicitation in this study did provide 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 organism is small. Also, 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. In addition to this, expert elicitation mostly costs much less than field sampling.

Expert elicitation does have disadvantages. In this study, in order to elicit distributional information from experts’ knowledge, specific designed intervals were presented to experts requiring their estimates of the probabilities for these intervals. However, the complexity of question format reduced the quality of expert responses. So 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. Also, visual aids may be introduced to illustrate the intervals that require estimation (O’Hagan 2006).

3.5 Conclusion

Mercury exposure was modeled for three bird species on the South River floodplain based on expert elicitation and field surveys of mercury concentrations in potential food items. Monte Carlo simulation was applied to define the distributions of daily mercury 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 mercury. What was a harmful amount was defined using the TRV of 100 ng/g-day derived by Heinz (1979) and Spalding (2000). According to modeling 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.
CHAPTER IV. Summary and Conclusion

The studies involved in this thesis expanded the current project being conducted in Dr. Newman’s laboratory that aimed to define and quantify the impacts of mercury contamination to the South River (northwestern Virginia) biota; specifically, on mercury movement in contaminated aquatic and terrestrial food webs. This expansion generally included two directions.

Firstly, previous work in our laboratory had documented mercury biomagnification in aquatic and several floodplain locations of South River watershed and constructed models for predicting mercury concentrations in members of the associated food webs. Moreover, these studies reached a preliminary conclusion that mercury biomagnification in members of floodplain food webs was faster than that of the contiguous aquatic food web. To substantiate this finding and further understand the factors that might produce the differences observed among floodplain locations, two additional floodplain locations were sampled and modeled in 2010.

Acceptable prediction from each model was gauged with an *a priori* established prediction $r^2$ of approximately 0.80. Overall the models predicting methylmercury were superior to models for total mercury or the percentage of the mercury present as methylmercury. Including previous models for other river sites, four of five attempted methylmercury models based on $\delta^{15}N$ met this criterion for
useful prediction. For floodplain models, thermoregulatory strategy was observed to have substantial influence on mercury concentrations in members of food webs. The food web biomagnification factor from the four floodplain locations were of 17.4 (95% CI of 9.5 - 31.6), 9.3 (95% CI of 5.4 - 16.2), 6.2 (95% CI of 3.5 - 11.0) and 25.1 (95% CI of 12.6 - 50.1) for North Park, Augusta Forestry Center, Grand Cavern and Grottoes Town Park respectively. These results supported previous findings that the South River floodplain food webs had higher biomagnification rates than the adjacent aquatic food web (4.6, 95% CI of 3.6 - 5.7). Examining the variations among floodplain locations suggested that uniformity and homogeneity of habitats might influence mercury biomagnification. Moreover, the mercury concentrations in apex species of South River floodplain (avian species) did not generally exceed some benchmark values of adverse effects from other toxicity studies. Consequently, results from this study failed to support the conclusions that the studied avian species on the South River floodplain might experience harmful mercury exposure, as suggested by other studies.

Future studies on this direction could be done (1) to further examine the sources of interlocation variation with comprehensive sampling, and (2) to further examine the possible adverse effect of avian species with statistically reliable studies.

The second direction focused on description and determination of current mercury exposure to adults of three avian species during nesting on the South River floodplain and judgment of the risk of harmful mercury exposure to these species by comparing the mercury exposure distributions to published toxicity test results. This
study incorporated a formal expert elicitation involving a modified Delphi framework and a Monte Carlo simulation to accomplish a probabilistic risk assessment. Simulations from this study predicted the probability that an adult bird during breeding season would ingest harmful amounts of mercury during daily foraging and also the probability that the average mercury ingestion rate for the breeding season of an adult bird would exceed published rates found to cause harm to other birds (>100 ng total Hg/g body weight per day). The probabilities that these species’ average ingestion rates exceeded the threshold value were all less than 0.01. Sensitivity analysis indicated that overall food ingestion rate was the most important factor determining mercury ingestion rates. Again, results from this study failed to observe substantial risk of harmful mercury exposure to the studied avian species.
Birds can be exposed to a wide range of mercury concentrations in a variety of food items. However, individuals of a population nesting in a specific habitat will generally have similar feeding ecologies that can be characterized relative to general distributions of food items eaten and associated mercury concentration in each item. Such information can be used to predict the range of mercury exposures expected among individuals from an exposed population such as Carolina wrens nesting on the South River floodplain. Specifically, Monte Carlo simulations incorporating such distributions of toxicant concentrations and amounts of ingested food can be applied to determine mercury exposure of at-risk avian populations.
1.1 General Description

The Carolina wren, Thryothorus ludovicianus, is found mainly in the eastern United States and Central America where it frequents homes, gardens, and woodlands. It maintains territories and pair bonds year-round (Haggerty and Morton, 1995).

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

1. Please characterize your knowledge of the general ecology of the Carolina wren.
   - A. Specialist on this field with a thorough understanding of this bird's ecology.
   - B. I have been involved previously in ecological studies of these wrens.
   - C. I have some general understanding of its ecology.
   - D. I know very little about this particular bird's ecology.
   - E. Not applicable. Reason

2. Please characterize your knowledge of the feeding ecology of the Carolina wren.
   - A. Specialist on this field with a thorough understanding of this bird's feeding ecology.
   - B. I have some understanding of the feeding ecology of Carolina wren and have been involved in projects related to the feeding ecology of this bird.
   - C. I have some general understanding but never did feeding ecology research of this species.
   - D. I know little about this particular bird's feeding ecology.
   - E. Not applicable. Reason

Next (2/5)
1.1 General Description

The Carolina wren, Thryothorus ludovicianus, is found mainly in the eastern United States and Central America where it frequents homes, gardens, and woodlands. It maintains territories and pair bonds year-round (Haggerty and Morton, 1995).

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

3. Based on your knowledge, how would you describe the differences in body weights of Carolina wrens of different sexes?

- A. Male birds are more than 10 percent heavier than female birds.
- B. Male birds are heavier than female, but usually less than 10 percent heavier.
- C. There is no difference
- D. Male birds are more than 10 percent lighter than female birds.
- E. Male birds are lighter than female, but usually less than 10 percent lighter.

4. Of the following potential food items, please rank from 1 to 5. Here "1" means this item is the most commonly eaten of the listed items by the bird during breeding season, while a "5" means this item is the least commonly eaten by the bird. (Ties between items are acceptable).

<table>
<thead>
<tr>
<th>Food Items</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plants (Seeds, Fruits, Etc)</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Beetles</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Caterpillars</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Spiders</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Midge</td>
<td>1 2 3 4 5</td>
</tr>
</tbody>
</table>
1.1 General Description

The Carolina wren, *Thryothorus ludovicianus*, is found mainly in the eastern United States and Central America where it frequents homes, gardens, and woodlands. It maintains territories and pairs year-round (Haggerty and Morton, 1995).

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

5. Based on your knowledge, which of the following statements would you think is most likely to be true?
   - A. In proportion to their weight, small birds eat more food per day than do large birds.
   - B. In proportion to their weight, small birds eat less food per day than do large birds.
   - C. There is no substantial difference in the amount of eaten food in proportion to body weight between small birds and large birds.
1.2 Carolina Wren Body Weight

Haggerty and Morton (1995) gave the following sizes of Carolina wrens: Length, 4.7–5.5 in (12–14 cm); Wingspan, 11.4 in (29 cm); Weight, 0.6–0.8 oz (17–23 g). Male and females are identical in plumage, but males are often slightly heavier and have longer bills, wings, and legs.

1. What do you expect the lowest body weight (g) of an adult Carolina wren would be during breeding season on the South River floodplain? ________ g

2. What do you expect the highest body weight (g) of an adult Carolina wren would be during breeding season on the South River floodplain? ________ g
1.2 Carolina Wren Body Weight

Haggerty and Morton (1995) gave the following sizes of Carolina wrens: Length, 4.7-5.5 in (12-14 cm); Wingspan, 11.4 in (29 cm); Weight, 0.6-0.8 oz (17-23 g). Male and females are identical in plumage, but males are often slightly heavier and have longer bills, wings, and legs.

3. What do you expect the mode for body weight (g) (most frequent weight) of an adult Carolina wren would be during breeding season on the South River floodplain? [Blank]

4. Please provide your best estimate of distributional proportions (as percentages) associated with the following ranges of wren weights, e.g., approximate [Blank] percent of South River Carolina wrens have a weight falling in the range of (15 to 20 g).

<table>
<thead>
<tr>
<th>Body Weight (Low, High of Range, g)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15,21)</td>
<td></td>
</tr>
<tr>
<td>(15,18)</td>
<td></td>
</tr>
<tr>
<td>(25,25)</td>
<td></td>
</tr>
</tbody>
</table>
1.2 Carolina Wren Body Weight

Haggerty and Morton (1995) gave the following sizes of Carolina wrens: Length, 4.7-5.5 in (12-14 cm), Wingspan, 11.4 in (29 cm), Weight, 0.6-0.8 oz (17-23 g). Male and females are identical in plumage, but males are often slightly heavier and have longer bills, wings, and legs.

5. For the Carolina wren subpopulation breeding on the South River floodplain, what would you estimate the lower quantile (25%) and upper quantile (75%) of body weight to be?

   Lower Quantile  g
   Upper Quantile  g

Carolina Wren Body Weight Review

1. What do you expect the lowest body weight (g) of an adult Carolina wren would be during breeding season on the South River floodplain? 15
1.3 Diet of Carolina Wren

According to Kupinski and Kirschbaum (2001), Carolina wrens are ground-foraging insectivores that eat a large variety of insects and spiders without showing much preference.

According to Haggerty and Morton (1995), stomach content analyses of Carolina wrens showed that 94% of their diet is animal matter, and the other 6% is vegetable matter. Animal matter included lepidopterans (e.g., caterpillars and a few moths) 22%.

1. Please provide your best judgment of the percentage of the following food items to be expected in the diet of a Carolina wren from South River floodplain during breeding season? (Assume the wren nest is within 50 meters of the river. It is not necessary that your percentages sum to 100% because we will adjust the total later. Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds/Grains</td>
<td></td>
<td>Soil invertebrates (detritivores)</td>
<td></td>
</tr>
<tr>
<td>Fruits/ Berries</td>
<td></td>
<td>Herbivore Insects</td>
<td></td>
</tr>
<tr>
<td>Herbaceous Leafy Matter</td>
<td></td>
<td>Spiders</td>
<td></td>
</tr>
<tr>
<td>Insects Emerging from the River</td>
<td></td>
<td>Scale</td>
<td></td>
</tr>
</tbody>
</table>

2. Please provide your best estimate of the percentage of the total amount of food ingested each day by a breeding Carolina wren from the South River floodplain. (Again, it is not necessary that the percentages sum to 100%. Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Food Item</th>
<th>Percent</th>
<th>Food Item</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtotal</td>
<td>N/A</td>
<td>Subtotal</td>
<td>N/A</td>
</tr>
<tr>
<td>Seeds</td>
<td></td>
<td>Mayflies</td>
<td></td>
</tr>
<tr>
<td>Herbs</td>
<td></td>
<td>Caddisflies</td>
<td></td>
</tr>
<tr>
<td>Fruits</td>
<td></td>
<td>Midges</td>
<td></td>
</tr>
</tbody>
</table>
1.4 Food Ingestion Rate of Carolina Wren

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is the amount consumed expressed as a proportion of a bird's body weight.

Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily; Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; humming birds may eat twice their weight in nectar in a day.

Kendeigh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

1. What do you estimate is the lowest food ingestion rate of an adult Carolina wren during breeding season (g/g-day) on the South River floodplain?

2. What do you estimate is the highest food ingestion rate of an adult Carolina wren during breeding season (g/g-day) on the South River floodplain?
1.4 Food Ingestion Rate of Carolina Wren

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is the amount consumed expressed as a proportion of a bird's body weight. Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily; Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; hummingbirds may eat twice their weight in nectar in a day. Kendeigh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

3. What do you estimate is the mode for food ingestion rate of an adult Carolina wren during breeding season (g/g-day) on the South River floodplain?

4. Please provide your best estimate of distributional proportions associated with the following ranges of food ingestion rate (g/g-day).

<table>
<thead>
<tr>
<th>Food Ingestion Rate (Low, High of Range)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.3, 0.4)</td>
<td></td>
</tr>
<tr>
<td>(0.3, 0.45)</td>
<td></td>
</tr>
<tr>
<td>(0.3, 0.6)</td>
<td></td>
</tr>
</tbody>
</table>
1.4 Food Ingestion Rate of Carolina Wren

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is the amount consumed expressed as a proportion of a bird's body weight.

Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily, Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; hummingbirds may eat twice their weight in nectar in a day. Kendegh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

5. For the Carolina Wren breeding on the South River floodplain, what would you estimate the lower quartile (25%) and upper quartile (75%) of its food ingestion rate to be?

Lower Quartile  [ ] g/g-day  Upper Quartile  [ ] g/g-day

Carolina Wren Food Ingestion Rate Review

1. What do you estimate is the lowest food ingestion rate of an adult Carolina wren during breeding season (g/g-day) on the South River floodplain? 0.3 g/g-day

Save  Back

Finish (5/5)
Main Form-Part II Eastern Song Sparrow-2.1 Knowledge Evaluation

2.1 General Description

The Eastern Song Sparrow, Melospiza melodia, is one of the most widespread birds in North America. During breeding season, song sparrows build their nests in herbs, grasses and shrubs near fresh or salt water wherever they can find food. They defend territories and maintain pair bonds year-round (Arcese et al, 2002).

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

1. Please characterize your knowledge of the general ecology of the Eastern Song Sparrow.
   - A. Specialist on this field with a thorough understanding of this bird’s ecology.
   - B. I have been involved previously in ecological studies of these sparrows.
   - C. I have some general understanding of its feeding ecology.
   - D. I know very little about this particular bird’s ecology.
   - E. Not applicable. Reason

2. Please characterize your knowledge of the feeding ecology of the Eastern Song Sparrow.
   - A. Specialist on this field with a thorough understanding of this bird’s feeding ecology.
   - B. I have some understanding of the feeding ecology of Eastern Song Sparrow and have been involved in projects related to the feeding ecology of this bird.
   - C. I have some general understanding but never did feeding ecology research of this species.
   - D. I know little about this particular bird’s feeding ecology.
   - E. Not applicable. Reason
2.1 General Description

The Eastern Song Sparrow, Melospiza melodia, is one of the most widespread birds in North America. During breeding season, song sparrows build their nests in herbs, grasses and shrubs near fresh or salt water wherever they can find food. They defend territories and maintain pair bonds year-round (Arcese et al, 2002).

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

5. Based on your knowledge, which of the following statements would you think is most likely to be true?

A. In proportion to their weight, small birds eat more food per day than do large birds.
B. In proportion to their weight, small birds eat less food per day than do large birds.
C. There is no substantial difference of the amount food in proportion to body weight between small birds and large birds.

Finish (5/5)
Main Form-Part II Eastern Song Sparrow-2.2 Body Weight

2.2 Eastern Song Sparrow Body Weight

The Cornell Lab of Ornithology gave the following sizes of Eastern Song Sparrow: Length, 4.7-6.7 in (12-17 cm); Wingspan, 7.1-9.4 in (18-24 cm); Weight, 0.4-1.9 oz (12-53 g). Arcese et al. (2002) also indicated that the mass of song sparrows varies by season, region, their state of life stage, and even the time of the day. Males and females are sexually monomorphic in plumage, but males are often slightly heavier.

1. What do you expect the lowest body weight (g) of an adult Eastern Song Sparrow would be during breeding season on the South River floodplain?

2. What do you expect the highest body weight (g) of an adult Eastern Song Sparrow would be during breeding season on the South River floodplain?
2.2 Eastern Song Sparrow Body Weight

The Cornell Lab of Ornithology gave the following sizes of Eastern Song Sparrow: Length, 4.7-6.7 in (12-17 cm); Wingspan, 7.1-9.4 in (18-24 cm); Weight, 0.4-1.9 oz (12-53 g). Arcese et al (2002) also indicated that the mass of song sparrows varies by season, region, their state of life stage, and even the time of the day. Males and females are sexually monomorphic in plumage, but males are often slightly heavier.

3. What do you expect the mode for body weight (g) (most frequent weight) of an adult Eastern Song Sparrow would be during breeding season on the South River floodplain?

4. Please provide your best estimate of distributional proportions (as percentages) associated with the following range of sparrow weights, e.g., approximate percent of South River song sparrows have a weight falling in the range of (15 to 20g).

<table>
<thead>
<tr>
<th>Body Weight (Low, High of Range, g)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12,19)</td>
<td></td>
</tr>
<tr>
<td>(12,13.5)</td>
<td></td>
</tr>
<tr>
<td>(11.5,24)</td>
<td></td>
</tr>
</tbody>
</table>
2.2 Eastern Song Sparrow Body Weight

The Cornell Lab of Ornithology gave the following sizes of Eastern Song Sparrow: Length, 4.7-6.7 in (12-17 cm), Wingspan, 7.1-9.4 in (18-24 cm), Weight, 0.4-1.9 oz (12-53 g). Arcese et al (2002) also indicated that the mass of song sparrows varies by season, region, their state of life stage, and even the time of the day. Males and females are sexually monomorphic in plumage, but males are often slightly heavier.

5. For the Eastern Song Sparrow population breeding on the South River floodplain, what would you estimate the lower quantile (25%) and upper quantile (75%) of body weight to be?

Lower Quantile  g  Upper Quantile  g

Eastern Song Sparrow Body Weight Review

1. What do you expect the lowest body weight (g) of an adult Eastern Song Sparrow would be during breeding season on the South River floodplain?

12  g
Main Form-Part II Eastern Song Sparrow-2.3 Diet

2.3 Diet of Eastern Song Sparrow

According to Arcese et al. (2002), song sparrows have different diets during breeding and non-breeding periods. During the non-breeding period, the primary foods are seeds, fruits and invertebrates. During breeding period, the primary foods are insects. Their prey includes weevils, leaf beetles, ground beetles, caterpillars, dragonflies, grasshoppers, midges, crane flies, spiders, snails, and earthworms. Plant foods include buckwheat, ragweed, clover, sunflower, wheat, rice, blackberries, blueberries.

1. Please provide your best judgment of the percentage of the following food items to be expected in the diet of an Eastern Song Sparrow from South River floodplain during breeding season? (Assume the sparrow nest is within 50 meters of the river. It is not necessary that your percentages sum to 100% because we will adjust the total later.

Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds/Grains</td>
<td></td>
<td>Soil invertebrates ( detrivores)</td>
<td></td>
</tr>
<tr>
<td>Fruits/ Berries</td>
<td></td>
<td>Herbivore Insects</td>
<td></td>
</tr>
<tr>
<td>Herbaceous Leafy Matter</td>
<td></td>
<td>Spiders</td>
<td></td>
</tr>
<tr>
<td>Insects Emerging from the River</td>
<td></td>
<td>Scale</td>
<td></td>
</tr>
</tbody>
</table>

2. Please provide your best estimate of the percentage of the total amount of food ingested each day by a breeding Eastern Song Sparrow from the South River floodplain. (It is not necessary that the percentages sum to 100%, because we will adjust the total later. Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Food Item</th>
<th>Percent</th>
<th>Food Item</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtotal</td>
<td>N/A</td>
<td>Subtotal</td>
<td>N/A</td>
</tr>
<tr>
<td>Seeds</td>
<td></td>
<td>Mayflies</td>
<td></td>
</tr>
<tr>
<td>Herbs</td>
<td></td>
<td>Caddisflies</td>
<td></td>
</tr>
<tr>
<td>Fruits</td>
<td></td>
<td>Midges</td>
<td></td>
</tr>
</tbody>
</table>
Diet of Eastern Song Sparrow Review

1. Please provide your best judgment of the percentage of the following food items to be expected in the diet of an Eastern Song Sparrow from South River floodplain during breeding season? (Assume the sparrow nest is within 50 meters of the river. It is not necessary that your percentages sum to 100% because we will adjust the total later. Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds/Grains</td>
<td>1</td>
<td>Soil invertebrates (detritivores)</td>
<td>5</td>
</tr>
<tr>
<td>Fruits/Berries</td>
<td>2</td>
<td>Herbivore Insects</td>
<td>6</td>
</tr>
<tr>
<td>Herbaceous Leafy Matter</td>
<td>3</td>
<td>Spiders</td>
<td>7</td>
</tr>
<tr>
<td>Insects Emerging from the River</td>
<td>4</td>
<td>Scale</td>
<td></td>
</tr>
</tbody>
</table>

Save  Next
2.4 Food Ingestion Rate of Eastern Song Sparrow

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is a proportion of a bird's body weight that is consumed each day.

Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily; Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; humming birds may eat twice their weight in nectar in a day; Kendig (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

1. What do you estimate is the lowest food ingestion rate of an adult Eastern Song Sparrow during breeding season (g/g-day) on the South River floodplain?

2. What do you estimate is the highest food ingestion rate of an adult Eastern Song Sparrow during breeding season (g/g-day) on the South River floodplain?
2.4 Food Ingestion Rate of Eastern Song Sparrow

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is a proportion of a bird's body weight that is consumed each day. Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily; Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily. Humming birds may eat twice their weight in nectar in a day. Kendeigh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

3. What do you estimate is the mode for food ingestion rate of an adult Eastern Song Sparrow during breeding season (g/g-day) on the South River floodplain?

4. Please provide your best estimate of distributional proportions associated with the following range of food ingestion rate (g/g-day).

<table>
<thead>
<tr>
<th>Food Ingestion Rate (Low, High of Range)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.1,3)</td>
<td></td>
</tr>
<tr>
<td>(1.1,15)</td>
<td></td>
</tr>
<tr>
<td>(1.4,15)</td>
<td></td>
</tr>
</tbody>
</table>
2.4 Food Ingestion Rate of Eastern Song Sparrow

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is a proportion of a bird's body weight that is consumed each day.

Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily. Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; hummingbirds may eat twice their weight in nectar in a day. Kendeigh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

5. For the Song Sparrow breeding on the South River floodplain, what would you estimate the lower quartile (25%) and upper quartile (75%) of its food ingestion rate to be?

Lower Quantile __ g/g-day

Upper Quantile __ g/g-day

---

Eastern Song Sparrow Food Ingestion Rate Review

1. What do you estimate is the lowest food ingestion rate of an adult Eastern Song Sparrow during breeding season (g/g-day) on the South River floodplain?

Comments

Save  Back
Main Form-Part III Eastern Screech Owl-3.1 Knowledge Evaluation

3.1 General Description
The Eastern Screech Owl, Otus asio, occupies a wide variety of habitats from east of the Rocky Mountains to the eastern coast of the U.S. They maintain their territories in winter and summer from south of Canadian boreal forest to near the Tropic of Cancer in Mexico (Gehlbach, 1995). According to Gehlbach, eastern.

Knowledge Level Evaluation
Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

1. Please characterize your knowledge of the general ecology of the Eastern Screech Owl.
   - A. Specialist on this field with a thorough understanding of this bird's ecology.
   - B. I have been involved previously in studies of these owls.
   - C. I have some general understanding of its feeding ecology.
   - D. I know very little about this particular bird's ecology.
   - E. Not applicable. Reason

   Next (1/5)

2. Please characterize your knowledge of the feeding ecology of the Eastern Screech Owl.
   - A. Specialist on this field with a thorough understanding of this bird's feeding ecology.
   - B. I have some understanding of the feeding ecology of Eastern Screech Owl and have been involved in projects related to the feeding ecology of this bird.
   - C. I have some general understanding but never did feeding ecology research of this species.
   - D. I know little about this particular bird's feeding ecology.
   - E. Not applicable. Reason

   Next (2/5)
3.1 General Description

The Eastern Screech Owl, *Otus asio*, occupies a wide variety of habitats from east of the Rocky Mountains to the eastern coast of the U.S. They maintain their territories in winter and summer from south of Canadian boreal forest to near the Tropic of Cancer in Mexico (Gehlbach, 1995). According to Gehlbach, eastern

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

3. Based on your knowledge, how would you describe the differences in body weights of Eastern Screech Owls of different sexes?
- A. Male birds are more than 10 percent heavier than female birds.
- B. Male birds are heavier than female, but no more than 10 percent heavier.
- C. There is no difference
- D. Male birds are more than 10 percent lighter than female birds.
- E. Male birds are lighter than female, but no more than 10 percent lighter.

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

4. Of the following potential food items, please rank from 1 to 5. Here "1" means that this item is the most commonly eaten by the bird of the listed items, while a "5" means this item is the least commonly eaten by the birds during breeding season. (Ties between items are acceptable).

<table>
<thead>
<tr>
<th>Food Items</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant (Seeds, Fruit, Etc)</td>
<td>1</td>
</tr>
<tr>
<td>Crayfish</td>
<td>2</td>
</tr>
<tr>
<td>Earthworms</td>
<td>3</td>
</tr>
<tr>
<td>Deer mouse</td>
<td>4</td>
</tr>
<tr>
<td>Small birds</td>
<td>5</td>
</tr>
</tbody>
</table>
3.1 General Description

The Eastern Screech Owl, Otus asio, occupies a wide variety of habitats from east of the Rocky Mountains to the eastern coast of the U.S. They maintain their territories in winter and summer from south of Canadian boreal forest to near the Tropic of Cancer in Mexico (Gehlbach, 1995). According to Gehlbach, eastern

Knowledge Level Evaluation

Please rate your level of knowledge of this species. Your answers will provide insight about your background relative to the other participating experts and will be used to calibrate your answers during pooling of responses. Please pick the best answer for each question.

5. Based on your knowledge, which of the following statements would you think is most likely to be true?

- A. In proportion to their weight, small birds eat more food per day than do large birds.
- B. In proportion to their weight, small birds eat less food per day than do large birds.
- C. There is no substantial difference of the amount of food in proportion to body weight between small birds and large birds.
3.2 Eastern Screech Owl Body Weight
The Cornell Lab of Ornithology gave the following sizes of Eastern Screech Owl Length, 6.3-9.8 in (16-25 cm); Wingspan, 18.9-24 in (48-61 cm); Weight, 4.3-8.6 oz (121-244 g). According to Gehlbach (1995), like most of owl species, the female screech owl is larger than male.

1. What do you expect the lowest body weight (g) of an adult Eastern Screech Owl would be during breeding season on the South River floodplain? 

2. What do you expect the highest body weight (g) of an adult Eastern Screech Owl would be during breeding season on the South River floodplain?
3.2 Eastern Screech Owl Body Weight

The Cornell Lab of Ornithology gave the following sizes of Eastern Screech Owl Length, 6.3-9.8 in (16-25 cm); Wingspan, 18.9-24 in (48-61 cm); Weight, 4.3-8.6 oz (121-244 g). According to Gehl (1995), like most of owl species, the female screech owl is larger than male.

3. What do you expect the mode for body weight (g) (the most frequent weight) of an adult Eastern Screech Owl would be during breeding season on the South River floodplain?

4. Please provide your best estimate of distributional proportions (as percentages) associated with the following ranges of owl weights, e.g., approximate percent of South River Screech Owls have a weight falling in the range of (15 to 20)g.

<table>
<thead>
<tr>
<th>Body Weight (Low, High of Range, g)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(15,250)</td>
<td></td>
</tr>
<tr>
<td>(150,300)</td>
<td></td>
</tr>
<tr>
<td>(275,300)</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Eastern Screech Owl Body Weight

The Cornell Lab of Ornithology gave the following sizes of Eastern Screech Owl: Length, 6.3-9.8 in (16-25 cm); Wingspan, 18.9-24 in (48-61 cm); Weight, 4.3-8.6 oz (121-244 g). According to Gehlbach (1995), like most of owl species, the female screech owl is larger than male.

5. For the Eastern Screech Owl population breeding on the South River floodplain, what would you estimate the lower quantile (25%) and upper quantile (75%) of body weight to be?

Lower Quantile: __________ g  Upper Quantile: __________ g

Eastern Screech Owl Body Weight Review

1. What do you expect the lowest body weight (g) of an adult Eastern Screech Owl would be during breeding season on the South River floodplain? 150 g

Options:
- Q1
- Q2
- Q3
- Q4
- Q5
- Comments

Save  Next
3.3 Diet of Eastern Screech Owl

Eastern screech owls eat the most varied diet of any North American owl. Their diet includes large evening active insects, like moths and katydids, crayfish, earthworms, amphibians, reptiles, small mammals such as mice and bats, and small birds. These owls have symmetrical ears, which suggest that they hunt primarily using their vision. They do, however, have excellent hearing as they often capture prey hidden by leaf litter. They hunt by sitting on a tree branch and waiting to see or hear prey. Eastern.

1. Please provide your best judgment of the percentage of the following food items to be expected in the diet of an Eastern Screech Owl from South River floodplain during breeding season. (Assume the owl nest is within 50 meters of the river. It is not necessary that the percentages sum to 100% because we will adjust the total later. Click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds/Grains</td>
<td></td>
<td>Soil invertebrates (detritivores)</td>
<td></td>
</tr>
<tr>
<td>Fruits/Berries</td>
<td></td>
<td>Herbivore Insects</td>
<td></td>
</tr>
<tr>
<td>Small Birds</td>
<td></td>
<td>Mammals</td>
<td></td>
</tr>
<tr>
<td>Spiders</td>
<td></td>
<td>Aquatic Invertebrates</td>
<td></td>
</tr>
</tbody>
</table>

2. Please provide your best estimate of the percentage of the total amount of food ingested each day by a breeding Eastern Screech Owl from the South River floodplain. (It is not necessary that the percentages sum to 100%, because we will adjust the total later, click Scale if you want to sum to 100% automatically)

<table>
<thead>
<tr>
<th>Food Item</th>
<th>Percent</th>
<th>Food Item</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtotal</td>
<td>N/A</td>
<td>Subtotal</td>
<td>N/A</td>
</tr>
<tr>
<td>Seeds</td>
<td></td>
<td>Slugs</td>
<td></td>
</tr>
<tr>
<td>Fruits</td>
<td></td>
<td>Isopods</td>
<td></td>
</tr>
<tr>
<td>Earthworms</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Diet of Eastern Screech Owl

1. Please provide your best judgment of the percentage of the following food items to be expected in the diet of an Eastern Screech Owl from South River floodplain during breeding season. (Assume the owl nest is within 50 meters of the river. It is not necessary that the percentages sum to 100% because we will adjust the total later. Click Scale if you want to sum to 100% automatically.)

<table>
<thead>
<tr>
<th>Category</th>
<th>Percent</th>
<th>Category</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeds/Grains</td>
<td>1</td>
<td>Soil invertebrates (detritivores)</td>
<td>5</td>
</tr>
<tr>
<td>Fruits/Berries</td>
<td>2</td>
<td>Herbivore Insects</td>
<td>6</td>
</tr>
<tr>
<td>Small Birds</td>
<td>3</td>
<td>Mammals</td>
<td>7</td>
</tr>
<tr>
<td>Spiders</td>
<td>4</td>
<td>Aquatic Invertebrates</td>
<td>8</td>
</tr>
</tbody>
</table>

Save  Next
3.4 Food Ingestion Rate of Eastern Screech Owl

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is a proportion of a bird’s body weight that is consumed each day.

Lack (1954) estimates that landbirds weighing between 100 and 1000 grams eat from 5 to 9 percent of their body weight daily; Songbirds weighing 10 to 90 grams eat from 10 to 30 percent of their own daily; humming birds may eat twice their weight in nectar in a day. Kendeigh (1934) reported that adult seed eating birds eat about 10 percent of their weight and that insectivorous birds eat an amount equal to 40 percent of their weight daily.

1. What do you estimate is the lowest food ingestion rate of an adult Eastern Screech Owl during breeding season (g/g-day) on the South River floodplain? g/g-day

Next (1/5)

2. What do you estimate is the highest food ingestion rate of an adult Eastern Screech Owl during breeding season (g/g-day) on the South River floodplain? g/g-day

Next (2/5)
3.4 Food Ingestion Rate of Eastern Screech Owl

Food ingestion rate is defined as the number of grams of food consumed per gram of bird body weight daily (g/g-day) (wet weight). In other words, food ingestion rate (FIR) is a proportion of a bird's body weight that is consumed each day.

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3. What do you estimate is the mode for food ingestion rate of an adult Eastern Screech Owl during breeding season (g/g-day) on the South River floodplain?

4. Please provide your best estimate of distributional proportions associated with the following ranges of food ingestion rate (g/g-day).

<table>
<thead>
<tr>
<th>Food Ingestion Rate (Low, High of Range)</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.3, 0.4)</td>
<td></td>
</tr>
<tr>
<td>(0.3, 0.35)</td>
<td></td>
</tr>
<tr>
<td>(0.45, 0.5)</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Food Ingestion Rate of Eastern Screech Owl

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5. For the Screech Owl breeding on the South River floodplain, what would you estimate the lower quartile (25%) and upper quartile (75%) of its food ingestion rate to be?

Lower Quartile: ______ g/g-day  Upper Quartile: ______ g/g-day

1. What do you estimate is the lowest food ingestion rate of an adult Eastern Screech Owl during breeding season (g/g-day) on the South River floodplain?

Eastern Screech Owl Food Ingestion Rate Review

<table>
<thead>
<tr>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Modified Delphi Expert Elicitation
Mercury Exposure of South River Floodplain Birds

Jincheng Wang, Michael C Newman
Virginia Institute of Marine Science
College of William and Mary

Introduction
Part I Carolina Wren
Part II Eastern Song Sparrow
Part III Eastern Screech Owl
Exit
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VITA

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Born in Lanzhou, Gansu Province, People’s Republic of China, on the 27th of August 1986. Graduated from the No. 1 high school of the Qingdao Development Area in June of 2005. Earned a B.S. in Environmental Science from Tongji University in 2009. Entered the masters program of the College of William and Mary, School of Marine Science in Fall of 2009.