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# Methylmercury Bioaccumulation within Terrestrial Food Webs in the Adirondack Park of New York State

## Final Report

October 2015

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# Methylmercury Bioaccumulation within Terrestrial Food Webs in the Adirondack Park of New York State

***Final Report***

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# Notice



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# Abstract

Mercury (Hg), a potent neurotoxin, has been shown to impact the behavior, growth and reproductive success of wildlife through bioaccumulation within food webs. The detrimental effects of mercury contamination have been extensively documented in aquatic ecosystems, but it is equally important to understand the impacts of mercury deposition, methylation, and bioaccumulation on biota within the adjacent, surrounding terrestrial landscape. Unfortunately, relatively few studies have focused on the mechanisms of Hg bioaccumulation in terrestrial ecosystems. However, regional studies have documented elevated blood mercury concentrations within several Northeastern songbird species, specifically those inhabiting wetland habitats and high-elevation boreal forests.

The overall goal of this research was to investigate patterns of biotic mercury exposure and identify pathways for methylmercury bioaccumulation within terrestrial habitats in the Adirondack Park of New York State. From 2008 to 2011, intensive field studies were conducted within several *Sphagnum* bog, northern hardwood forest, and montane habitats within the Adirondack Park. Biotic samples, including songbird blood and forest-floor invertebrates, were collected and analyzed for total mercury, methylmercury (MeHg), and stable isotope signatures to better define the connections between methylmercury biomagnification and trophic connectivity among songbirds and their prey items within Adirondack food webs. Overall results indicate that dietary selection, seasonal prey availability, and habitat type were important factors contributing to mercury exposure levels in regional songbird communities.



# Keywords

Mercury, songbirds, *Sphagnum* Bog, Whiteface Mountain, Adirondack Park

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# Acronyms and Abbreviations

| | |
|---|---|
| µg | micrograms |
| dw | dry weight |
| g | gram |
| EMEP | Environmental Monitoring, Evaluation, and Protection |
| Hg | mercury |
| $km^2$ | square kilometers |
| LOAEL | Lowest observed adverse effect level |
| MeHg | methylmercury |
| ng | nanogram |
| NYS | New York State |
| NYS DEC | New York State Department of Environmental Conservation |
| NYSERDA | New York State Energy Research and Development Authority |
| PBT | persistent, bioaccumulative, and toxic |
| ww | wet weight |

# 1 Introduction

Mercury (Hg) deposition is a critical environmental issue for New York State and beyond that needs further study to fully understand and define its impacts on terrestrial ecosystems. Many investigations have been conducted relating to the effects of mercury contamination in aquatic habitats, but few studies have been done to establish baseline information on the mechanisms of mercury transport and transfer through terrestrial food chains. This lack of information greatly limits our understanding of the connectivity and overall impacts of atmospheric mercury deposition on sensitive terrestrial ecosystems and regional wildlife populations.

## 1.1 Atmospheric Mercury Transport and Deposition

Mercury contamination in the northeastern United States is the result of atmospheric deposition arising from local, regional, and global sources (Fitzgerald et al. 1998, Driscoll et al. 2007). These sources include primary human sources, such as coal-fired power plants, incinerators, and industrial emissions; natural sources, such as soil and mineral weathering and volcanos; and secondary emissions (or re-emissions) (Driscoll et al. 2013). Emissions can be transported tens to thousands of kilometers, and deposition upon the landscape can reflect meteorological characteristics, such as prevailing wind patterns and precipitation rates, as well as stochastic seasonal fluctuations, elevation, and vegetation type (Miller et al. 2005, VanArsdale et al. 2005, Demers et al. 2007, Yu et al. 2013). Therefore, deposition patterns and the resulting impacts upon wildlife health can be the result of multiple processes occurring across various spatial and temporal scales.

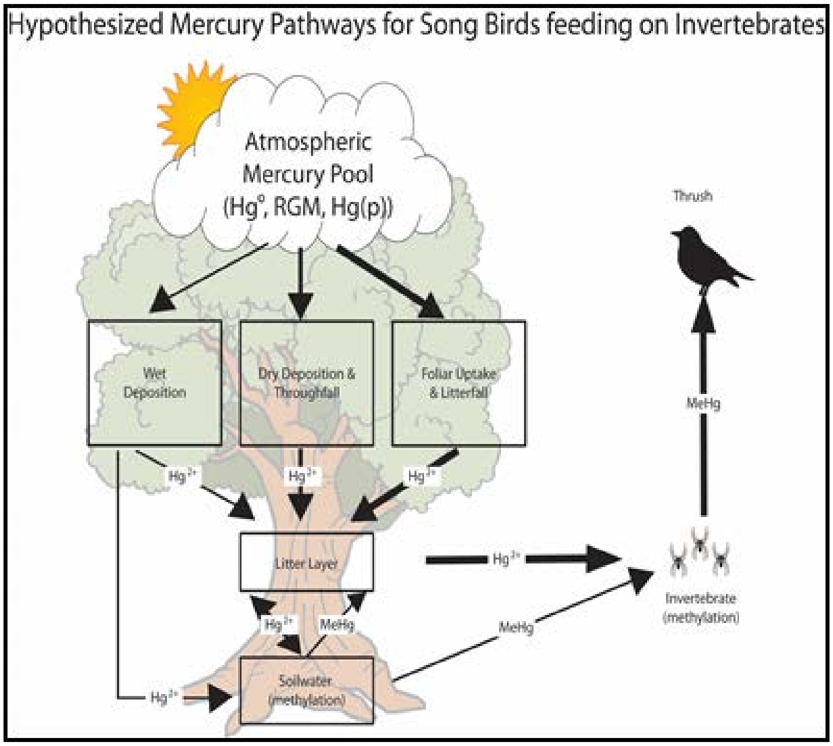
Once deposited upon the landscape, sulfate- and iron-reducing bacteria convert inorganic mercury into an organic, biologically available form called methylmercury (MeHg; Podar et al. 2015), which bioaccumulates to toxic levels through both aquatic and terrestrial food chains. It is through these processes of transfer and biomagnification from prey species, at lower trophic levels, to predator species, positioned at higher trophic levels, that the detrimental behavioral and physiological effects resulting from mercury toxicity become evident. Cumulatively, these resulting impacts, due to chronic or episodic mercury exposure, may alter the structure and function of the associated food chains and affect the long-term population dynamics of those species affected. Although the effects of mercury contamination have been extensively documented in aquatic ecosystems, it is equally important to establish information on biotic exposure levels and the dynamics of mercury transport through terrestrial food chains within the adjacent, surrounding landscape. Methylmercury has been designated by the U.S. Environmental Protection Agency as a persistent, bioaccumulative, and toxic (PBT) pollutant and has become a globally recognized conservation concern due to its ability to biomagnify and bioaccumulate within the environment and cause adverse effects to wildlife and human health (USEPA 2013).

## 1.2 Mercury Cycling and Wildlife Health

Mercury contamination in the northeastern U.S. is widespread and the associated effects on wildlife species and their habitats is a concern for the long-term viability of these populations (Bank et al. 2007, Driscoll et al. 2007, Evers et al. 2007). Several studies have established that the neurotoxin biomagnifies as it is transferred through aquatic and terrestrial food webs, and compromises the reproductive success, behavior, growth, development, and survivorship of those individuals affected through various lethal and sublethal effects (Evers 2005a, Jackson et al. 2011a).

Species, such as songbirds, located at the top of the food chain make excellent bio-indicators of the health of the environment they inhabit. Therefore, many investigations have focused on the connection between top-level trophic species and lower-level prey items as a means to investigate the transport and bioaccumulation of environmental contaminants, such as mercury. It is commonly hypothesized that mercury is transported to top predators, such as songbirds, through consumption of invertebrate, prey species located at lower trophic levels within terrestrial food webs (Figure 1). Seasonally, birds are able to reduce the concentrations of mercury in their bodies through feather growth and egg deposition (Heinz 1979, Furness et al. 1986, Thompson and Furness 1989, Scheuhammer et al. 2001). However, through continued ingestion of prey species high in mercury content, these individuals may accumulate mercury faster than they depurate excess body burdens through natural processes. Considering that insectivores, such as songbirds, are widespread across the landscape and may be possible vectors of mercury transport into the surrounding environment, it is necessary to understand the role that these species may represent in regards to the regional health of the Northern Forest.

**Figure 1. Hypothesized pathways of mercury bioaccumulation within a terrestrial, insectivore food web**




Within the northeastern U.S., a region widely impacted by atmospheric mercury deposition, significant individual and population level impacts have been documented in studies relating to terrestrial amphibian and avian communities (Bank et al. 2005, 2006, 2007; Evers et al. 2005b; Townsend and Driscoll 2013). To date, many regional studies documenting mercury impacts and exposure levels in avian populations have focused on top-predator, fish-eating birds, such as the common loon, as methylmercury bioaccumulates to high levels within their tissues (Scheuhammer et al. 2007, Evers et al. 2008, Schoch et al. 2014a, Schoch et al. 2014b). However, research efforts have also demonstrated that songbird species foraging upon aquatic-based food webs can also bioaccumulate methylmercury to levels that are similar to or exceed piscivorous bird species (Evers et al. 2005b, Cristol et al. 2008, Jackson et al. 2011b).

Various research studies conducted in the northeastern United States, to assess mercury exposure levels in songbird communities across a wide variety of species and habitat types, have identified blood mercury concentrations in several species elevated to levels that exceed thresholds where adverse physiological effects become evident. Results have indicated that wetland songbirds, particularly those species foraging on insects during the breeding season, are at the greatest risk to the impacts of mercury contamination (Edmonds et al. 2010, Lane et al. 2011, Evers et al. 2012, Jackson et al. 2015). Additionally, studies targeting songbirds inhabiting upland forests, not associated with aquatic habitats, have documented elevated body burdens of methylmercury, specifically within high-elevation boreal specialists, such as the Bicknell's thrush (Rimmer et al. 2005 and 2009, Townsend et al. 2014). Numerous toxicology studies have also established that birds are sensitive to the multi-system effects of methylmercury exposure, including: endocrine and immune system disruption (Heath and Frederick 2005, Adams et al. 2009, Hawley et al. 2009, Wada et al. 2009), skewed sex ratios (Bouland et al. 2012), altered songs (Hallinger et al. 2010), reproductive impairment (Brasso et al. 2008, Evers et al. 2008, Frederick and Jayasena 2011, Hallinger and Cristol 2011, Jackson et al. 2011a), asymmetrical feather growth (Evers et al. 2008), reduced body condition (Ackerman et al. 2012), and decreased survival rates (Hallinger et al. 2011). Therefore, research designed to utilize songbirds as critical indicators of terrestrial mercury contamination will effectively improve the ability to more accurately define and monitor levels of methylmercury bioavailability across the landscape, which is crucial to evaluate the risk this PBT poses to regional songbird populations.

Here the results are presented from two studies conducted to investigate and evaluate patterns of biotic methylmercury exposure within data-limited *Sphagnum* bog and northern hardwood forests, and high-elevation, montane habitats. For the following investigations, all study sites were located in the Adirondack Park of New York State. This region is of particular interest as previous research has designated portions of the Adirondack Park as a "biological mercury hotspot." These locations are defined as areas that are subject to moderate mercury deposition and possess landscape characteristics, such as thin soils, abundant forest and wetlands, and highly acidic habitats, which facilitate the transport of inorganic mercury, its conversion to methylmercury, and transfer into aquatic and terrestrial food webs (Driscoll et al. 2007, Evers et al. 2007). As a result, it was expected that the trophic transfer and bioaccumulation of mercury from prey to predator would be evident and quantifiable within the selected study areas. Ultimately, it is intended that the results from this research will advance scientific understanding and better define the links between trophic connectivity and methylmercury bioaccumulation for songbird species and their prey items within sensitive habitat types in the Adirondack Park.

The overall goal of this research was to improve understanding of the fundamental mechanisms of methylmercury transfer within terrestrial-based, insectivore food webs and to share findings with fellow scientists, landscape managers and policy makers. The specific objectives were to:

1. Develop and implement an intensive field research study to examine spatial and temporal patterns, and the transfer of methylmercury within *Sphagnum* bog and northern hardwood forest habitats.
2. Conduct an intensive field study to investigate total and methylmercury concentrations with respect to elevation, aspect and seasonal variation within montane, terrestrial food webs.
3. Identify trophic pathways for methylmercury bioaccumulation in sensitive, terrestrial food webs using stable isotope analysis.

It is intended that this research will link data from established studies, complement on-going research projects, direct future research initiatives, and provide much-needed information focusing on the connections between mercury deposition as an environmental stressor and its impact on terrestrial ecosystems and wildlife communities in the northeastern United States.

# 2 Methods

## 2.1 Songbird Capture and Sampling Methodology

For this project, songbird blood and feather samples were collected using standardized methodologies from *Sphagnum* bogs, hardwoods forests, and montane habitats in the Adirondack Mountains of New York State from 2008 through 2011. Sampling occurred during May through August, which corresponds with periods of peak breeding activity for Northeast songbird species. Insectivorous songbirds were captured using nonlethal methods including: mist nets, decoys, and playback calls. At each study site, 6- and 12- meter (36-millimeter black nylon mesh) mist nets were temporarily erected along with decoys and playback calls to encourage a territorial response for each target species. Once captured, each bird was carefully removed from the net and evaluated for any signs of injury or obvious trauma to the body and wings. Each net was checked every 20-30 minutes.

During processing, each bird was banded, weighed, morphological measurements were recorded, blood and feather samples were collected, and individuals were released. Each bird was fitted with an aluminum U.S. Geological Survey (USGS) leg band that contains a unique number and these records are submitted to the USGS Patuxent Wildlife Center for use in the North American Bird Banding Program (Figure 2). Songbirds are banded during processing as a means to identify the individual bird during future on-site captures or if found at another location during their life history. If captured again, the band serves as an individual record of its history and may yield information related to life span, wintering or breeding site fidelity, and dispersal or migratory patterns.

**Figure 2. Nashville warbler being banded with U.S. Geological Survey aluminum leg band**

To assess individual mercury concentrations, blood samples were acquired using sterile collection techniques and are representative of recent dietary uptake of methylmercury, thereby reflecting available methylmercury levels within the associated breeding habitat (French et al. 2010). Blood was collected from the ulnar vein, using a sterile, 27-gauge needle and pressure was applied to the vein immediately after collection (Figure 3). The sampled blood was collected in 1-3 heparinized, micro-hematocrit capillary tubes for a total of 30-50 microliters. The volume of blood is dependent upon the weight of the bird, but constitutes no more than 1% of total body mass (Fair et al. 2010). For this study, individuals may have been captured on multiple occasions during the field season, but blood was not collected more than once per month from May to August. In contrast to blood mercury, feather samples represent long-term mercury exposure and are indicative of mercury body burdens over the bird's lifetime, as well as dietary uptake during periods of feather molt. Two outer rectrices (tail feathers) were also collected and archived for possible future analysis. All songbird blood and feather samples were frozen and transported to Syracuse University for mercury and stable isotope analyses.

**Figure 3. Blood sample collection from a red-eyed vireo**

## 2.2 Invertebrate Sampling Methodology

Dietary input of mercury was determined by collecting forest invertebrates that typically comprise prey items of the selected songbird species, including: spider (*Araneae),* millipede (*Polydesmida),* ant (*Hymenoptera),* slug (*Pulmonata),* beetle (*Coleoptera),* caterpillar (*Lepidoptera),* daddy long legs (*Opiliones),* true bug (*Hemiptera),* grasshoppers (*Orthoptera),* and flies (*Diptera).* At each location, invertebrate species were sampled using several commonly used techniques including: pitfall traps, sweep netting and opportunistic collection. Collected whole-body invertebrate samples were frozen and transported to Syracuse University for identification, sample preparation, and mercury and stable isotope analysis.

## 2.3 Laboratory Analysis

### 2.3.1 Mercury Analysis

Songbird and forest invertebrate samples were analyzed for total mercury concentrations with a Milestone Direct Mercury Analyzer (DMA-80), according to U.S. Environmental Protection Agency Method 7473, in the Center for Environmental Systems Engineering laboratory (CESE) at Syracuse University. Research has documented that approximately 95% of total mercury in songbird blood is in the form of methylmercury, therefore additional methylmercury analyses were not conducted for songbird blood (Rimmer et al. 2005, Edmonds et al. 2010). All blood mercury concentrations are reported as micrograms per gram (µg/g), wet weight (ww).

Forest invertebrates were sorted and identified to the lowest taxonomic level. Prior to analysis, all invertebrates were cleaned with a methanol solution and freeze-dried. Individual samples were homogenized with a stainless steel spatula and composited if dry weights were below 0.01 grams. Mercury concentrations are expressed as nanograms per gram (ng/g), dry weight (dw).

Quality assurance for each analytical run of 10 samples was determined with a method blank, instrument blank, duplicate sample, and verification with certified reference standards for curve calibration and quality control using the following materials: apples leaves (NIST SRM 1515), mussel tissue (NIST SRM 2976), bovine blood (NIST SRM 966), caprine blood (NIST SRM 955c), and seronorm.

### 2.3.2 Stable Isotope Analysis

Stable isotope analyses were conducted at the Environmental Science Stable Isotope Laboratory (EaSSIL) under the supervision of Dr. Mark Teece at SUNY College of Environmental Science and Forestry (SUNY-ESF). For this investigation, $\delta^{15}N$ and $\delta^{13}C$ values were analyzed from selected songbird and invertebrate samples collected from *Sphagnum* bog and northern hardwood forest study sites. A ThermoFinnigan Delta XL Plus Stable Isotope Mass Spectrometer attached to a Costech Elemental Analyzer was used to measure stable isotope values in each sample. Prior to analysis, all samples were freeze-dried, ground to a fine powder, and transferred to a tin capsule for analysis. To ensure equipment accuracy and precision of the stable isotope measurements, instrument response was evaluated following every eight samples through verification of internal laboratory standards, including: acetanilide, valine and daphnia. Isotopic ratios are reported as parts per mil (‰) and were calculated using Equation 1:

**Equation 1** $$\delta X = [\,(R_{sample}/ R_{standard}) - 1] \times 1000$$

where:

- X is the values of $^{15}N$ or $^{13}C$
- R is the ratio of heavy to light isotopes in each sample and standard will reflect the ratios of $^{15}N/^{14}N$ and $^{13}C/^{12}C$.

## 2.4 Statistical Analysis

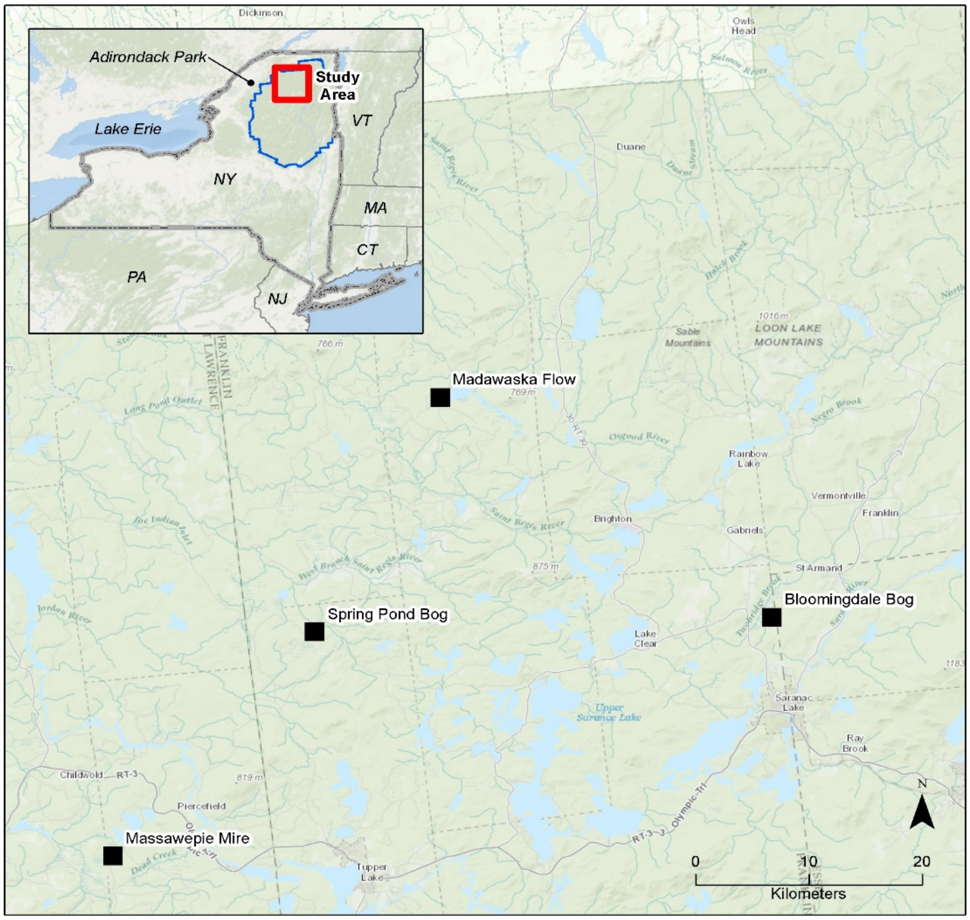
Data analysis was conducted using descriptive statistics, t-tests, linear regression, ANOVA, and post-hoc Tukey's HSD test to evaluate songbird and invertebrate mercury levels at Adirondack study sites. Songbird mercury results are representative of adult individuals, as juveniles were excluded from statistical analyses. Data were log-transformed prior to analysis and all statistical tests were considered significant at a p value of $<0.05$. Statistical analyses were conducted in JMP 9.0 (SAS Institute, Cary, NC).

# 3 Methylmercury Bioaccumulation within *Sphagnum* Bog and Northern Hardwood Forest Terrestrial Food Webs

## 3.1 Study Area

Four study sites were selected for sample collection during 2008, 2009, and 2011 in the Adirondack Park (Figure 4). Massawepie Mire (44.23˚N, 74.66˚W) is located on the Massawepie Boy Scout Camp property in the town of Piercefield, and is the largest boreal peatland bog complex in New York State with an estimated total size of 5,000 acres (20.2 $km^2$), including 900 acres (3.6 square kilometers [$km^2$]) of open peatland. Spring Pond Bog (44.37˚N, 74.50˚W) is owned by The Nature Conservancy and located in the town of Altamont, and is the second largest *Sphagnum* bog in New York State at 500 acres (2.0 $km^2$) with a total complex acreage of 4,200 acres (17 $km^2$). Madawaska Flow (44.51˚N, 74.40˚W), located on NYS DEC Conservation Easement property in the town of Santa Clara, contains a series of open bogs within an estimated 3,000-acre (12.1 $km^2$) wetland complex. Bloomingdale Bog (44.38˚N, 74.14˚W) is also managed by NYS DEC in the town of St. Armand, and is a large bog complex that contains a mix of peatland and forested community types. All study sites contain extensive wetland systems, diverse plant communities, and provide essential habitat for a wide variety of resident and migratory boreal songbird species.

**Figure 4. Songbird sampling locations in Adirondack Park in 2008, 2009, and 2011**




## 3.2 Research Approach and Study Design

To complete the objectives of the study, this project was divided into two phases. During the first phase, intensive field studies were conducted at four study Adirondack study sites in 2008, 2009, and 2011. The second phase included detailed mercury and stable isotope analyses to document biotic mercury exposure levels and the transfer of methylmercury within terrestrial food webs in the Adirondack Park of New York State.

### 3.2.1 Phase One: Development and implementation of *Sphagnum* Bog and Northern Hardwood field study

This phase of the research project was developed based on the need to further investigate and better understand the dynamics of mercury cycling through insectivore food webs in New York State. Sampling protocols were developed and standardized based on established terrestrial research projects conducted by Biodiversity Research Institute and Syracuse University. The overall design of the field study was to examine patterns of mercury concentrations in selected vertebrate and invertebrate prey species within sensitive terrestrial ecosystems in the Adirondack Park of New York State. The hypothesis of the project suggests that mercury is transferred to songbirds, at the top of the food chain, through consumption of invertebrates located at lower trophic levels. As a result, this study was designed to sample and compare mercury exposure levels in songbird communities and invertebrate prey items at study sites within *Sphagnum* bogs and surrounding hardwood forests. Despite similar rates of estimated atmospheric deposition (Appendix A and Appendix B; Yu et al. 2013), it was hypothesized that methylmercury concentrations would be elevated within bog ecosystems when compared to adjacent northern hardwood forests because of increased conversion rates of ionic mercury to methylmercury in oxygen-poor, low pH, wetland habitats. Therefore, it was anticipated that these two habitat types support different rates of mercury methylation, and levels of bioavailable methylmercury would be reflected in biotic exposure levels and documented as a result of this study.

Project sampling to identify avenues for methylmercury bioaccumulation in terrestrial habitats was conducted during the 2008, 2009, and 2011 field seasons. In 2008, sampling efforts were focused in Adirondack *Sphagnum* bogs at Massawepie Mire and Spring Pond Bog. In 2009, sampling was conducted at Madawaska Flow and Bloomingdale Bog. During 2011, samples were collected from within all previously sampled *Sphagnum* bog and northern hardwood forest study locations. Considering that montane study sites, as part of an accompanying project on Whiteface Mountain, had been sampled for a period of two consecutive years (2009 and 2010), the *Sphagnum* bog sites were re-surveyed for an additional field season, so that all boreal and *Sphagnum* bog sites were sampled over the course of two complete breeding seasons. Additional collection efforts were designed to complement and strengthen existing project data, and contribute to a more thorough Adirondack wildlife mercury dataset. In an effort to capture potential temporal variation, all sites were intensively sampled multiple times during the course of the field season.

Based on similar regional studies conducted during previous years, several avian species of concern were targeted to examine species-specific mercury body burdens:

- *Sphagnum* Bog – yellow palm warbler (*Setophaga palmarum*), Lincoln's sparrow (*Melospiza lincolnii*), Nashville warbler (*Oreothlypis ruficapilla*).
- Northern Hardwood Forest – hermit thrush (*Catharus guttatus*), ovenbird (*Seiurus aurocapillus*), red-eyed vireo (*Vireo olivaceus*).

Forest invertebrate prey items were also collected from study sites during each sampling event throughout the course of the field season.

### 3.2.2 Phase Two: Mercury and Stable Isotope Analyses

To investigate patterns of biotic mercury exposure, songbird and forest invertebrate samples collected during the 2008, 2009, and 2011 field seasons were analyzed for total mercury concentrations at the Center for Environmental Systems Engineering (CESE) laboratory at Syracuse University.

Stable isotope technology can serve as a valuable tool to decipher the complexities of predator-prey dynamics and the bioaccumulation of contaminants occurring within food webs. A stable isotope analysis was conducted at SUNY-ESF on collected samples to evaluate food web pathways and identify mercury and trophic connectivity between predators and their prey resources. This analysis examined the $\delta^{15}N$ and $\delta^{13}C$ values for selected invertebrate and songbird samples collected from both *Sphagnum* bog and hardwood forest habitats at Madawaska Flow and Bloomingdale Bog during 2009 field surveys. The $\delta^{15}N$ values acquired from invertebrate and songbird samples are used to determine relative trophic position, with an anticipated incremental +3‰ enrichment factor occurring at each ascending trophic level. The $\delta^{13}C$ values serve as a baseline carbon source for the associated system. In addition, $\delta^{15}N$ values for songbird and invertebrate species were examined relative to mercury concentrations as a means to link trophic structure and mercury bioaccumulation. The results from the stable isotope component will provide the first observations linking mercury concentrations with stable isotope signatures from songbird and invertebrate communities within *Sphagnum* bogs and northern hardwood forests in the Adirondack Park. Stable isotope analyses were conducted in collaboration with the Environmental Science Stable Isotope Laboratory (EaSSIL) at SUNY-ESF.

## 3.3 Results

### 3.3.1 Avian Mercury Exposure

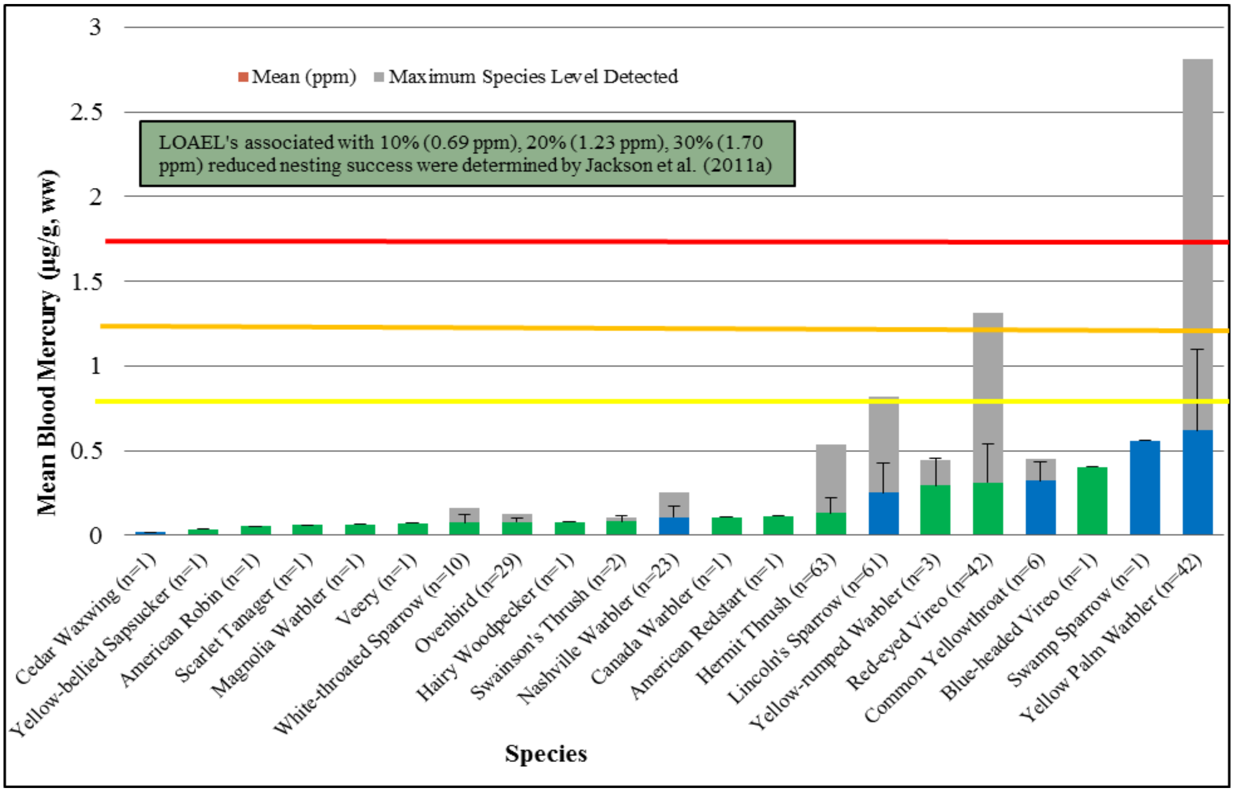
#### *3.3.1.1 All Species*

During 2008, 2009, and 2011, a total of 244 adult songbirds, representing 21 species, were captured, banded, and analyzed for total mercury exposure (N=292) from *Sphagnum* bog and northern hardwood forest habitats at Bloomingdale Bog, Massawepie Mire, Madawaska Flow, and Spring Pond Bog (Figure 5 and Appendix C). Of the species sampled, seven songbird families were represented: Emberizids/New World sparrows (*Emberizidae*), tanagers (*Cardinalidae*), thrushes (*Turdidae*), vireos (*Vireonidae*), waxwings (*Bombycillidae*), woodpeckers (*Picidae*), and wood-warblers (*Parulidae*). Additionally, all songbirds were classified within four dietary foraging guilds, including: frugivore, insectivore, omnivore, and vermivore (De Graaf 1985). Across all *Sphagnum* bog habitats (N=134), blood mercury levels ranged from 0.018 µg/g in a cedar waxwing at Madawaska Flow, to 2.815 µg/g for a yellow palm warbler at Massawepie Mire. Within the forested study sites (N=158), mean mercury levels ranged from 0.020 µg/g for a hermit thrush at Spring Pond Bog, to a high of 1.313 µg/g for a red-eyed vireo at Massawepie Mire. Overall, yellow palm warblers and red-eyed vireos demonstrated the highest mercury concentrations within their respective habitats, as compared to other associated bog and forest species. Therefore, these species may likely be at a higher risk to the physiological impacts of mercury contamination as a biological stressor.

Results are presented for adult songbird mercury concentrations, therefore 48 juveniles, from 11 species, were sampled during the 2009-2010 field efforts, but were excluded from statistical analyses (Appendix C).

**Figure 5. Mean blood mercury concentrations for songbird species at Bloomingdale Bog, Madawaska Flow, Massawepie Mire, and Spring Pond Bog: 2008, 2009, 2011**

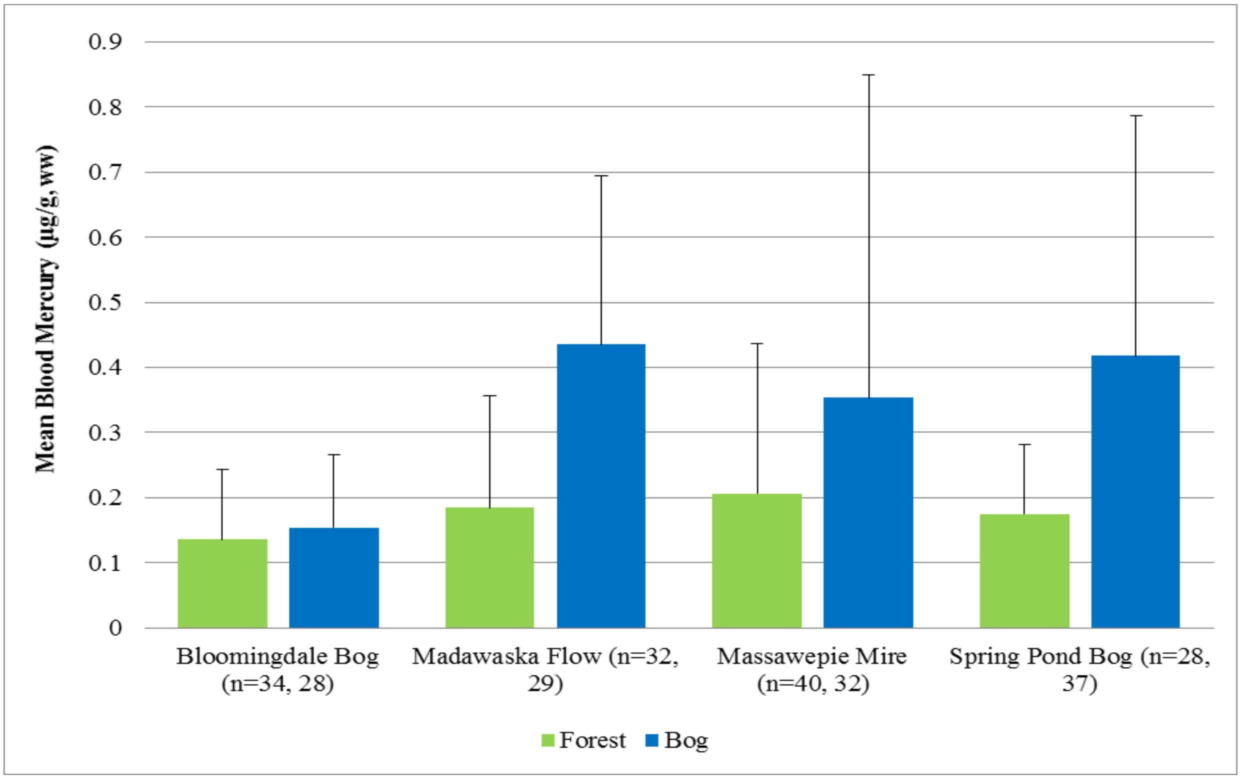
Species shaded in green represent forested songbirds and those in blue are bog-obligate species. Gray shading reflects the maximum mercury levels detected for each species. Colored lines represent established mercury threshold concentrations (LOAEL's) associated with adverse impacts on songbird reproductive success (Jackson et al. 2011a).




## *3.3.1.2 Mercury Concentrations in Sphagnum Bog and Northern Hardwood Forest Habitats*

To evaluate differences in blood mercury concentrations between *Sphagnum* bog and northern hardwood forests, six species were targeted for comparative analysis which were common among all study sites and served as a representative species for each habitat type. Lincoln's sparrow, Nashville warbler, and yellow palm warbler were selected as bog-obligate species. Hermit thrush, ovenbird, and red-eyed vireo were targeted in forested cover types. For all target species collected across study sites, songbird blood was significantly higher in the *Sphagnum* bog (N=126; 0.347 µg/g) as compared to the surrounding hardwood forests (N=134; 0.177 µg/g; t=5.5 DF=258, P<0.0001). At each study site, songbird blood mercury concentrations were significantly higher in *Sphagnum* bogs as compared to adjacent forest sites at Madawaska Flow (0.435 µg/g, 0.185 µg/g; P=0.0002), Massawepie Mire (0.353 µg/g, 0.206 µg/g; P=0.0255), and Spring Pond Bog (0.417 µg/g, 0.175 µg/g; P=0.0002; Figure 6). Blood mercury concentrations for songbirds sampled at Bloomingdale Bog did not differ between habitat types (0.154 µg/g, 0.135 µg/g; P=0.5572). Across all *Sphagnum* bog sites, blood mercury concentrations were found to be significantly elevated at Madawaska Flow, Massawepie Mire, and Spring Pond Bog over songbirds at Bloomingdale Bog (F=9.8, DF=3, P<0.0001). There was no difference in blood mercury for forest songbirds between study sites (F=1.7, DF=3, P=0.1709).

**Figure 6. Mean blood mercury concentrations in *Sphagnum* bog and northern forest habitats at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**



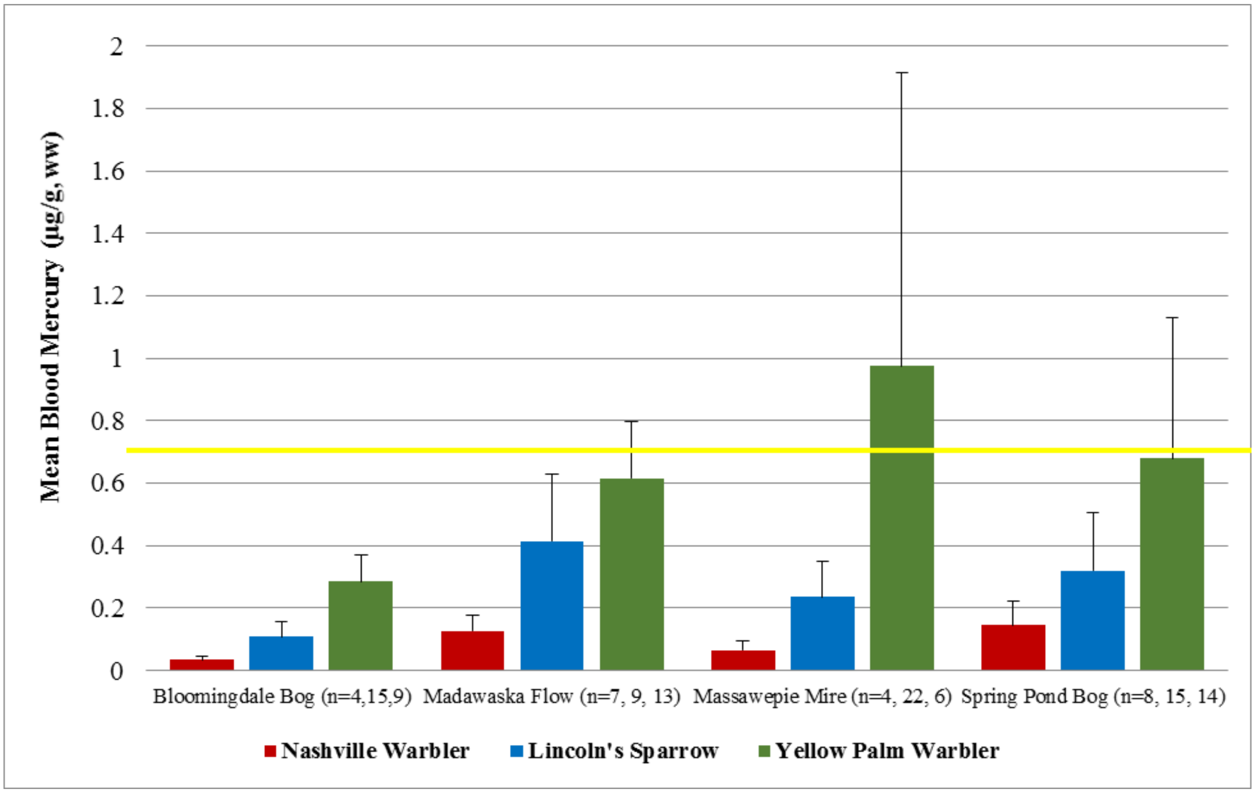

## 3.4 Mercury Concentrations and Species Patterns

### 3.4.1 *Sphagnum* Bog

To better understand species-specific exposure levels for songbirds sampled at the study sites, patterns of blood mercury concentrations were evaluated within each habitat type. Across all *Sphagnum* bog sites, mean blood mercury concentrations were significantly different among each targeted species (F=53.7, DF=2, P<0.0001; Figure 7). Nashville warbler exhibited the lowest blood mercury concentrations (N=23; 0.106 µg/g), followed by Lincoln's sparrow (N=61; 0.251 µg/g), and yellow palm warbler had the highest blood levels across all sites (N=42; 0.617 µg/g). This species pattern was documented within each study site and suggests that certain bog-obligate species, like the yellow palm warbler, may have generally higher mercury exposure as compared to other associated species. Small samples sizes precluded reliable statistical comparisons among species for individual study sites.

**Figure 7. Mean blood mercury concentrations for *Sphagnum* bog songbird species at Bloomingdale Bog, Madawaska Flow, Massawepie Mire, and Spring Pond Bog: 2008, 2009, 2011**

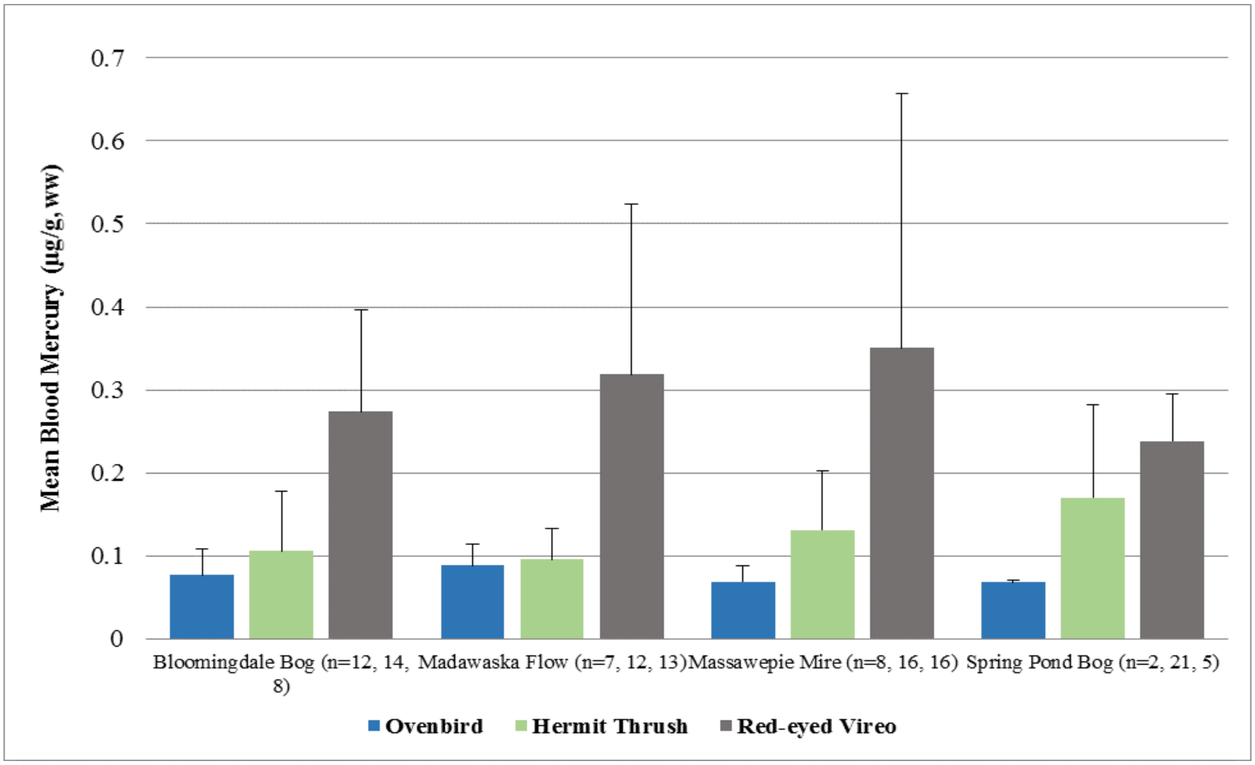
The yellow line represents documented mercury threshold concentrations (LOAEL's) associated with a 10% reduction in songbird nesting success (Jackson et al. 2011a).




## 3.4.2 Northern Hardwood Forests

Mean blood mercury concentrations varied significantly among each targeted species across all forested study locations (F=43.5, DF=2, P<0.0001; Figure 8). Ovenbirds had the lowest blood mercury concentrations (N=29; 0.077 µg/g), followed by hermit thrush (N=63; 0.131 µg/g), and the highest mercury concentrations were found in the red-eyed vireo (N=42; 0.312 µg/g). This consistent pattern of increasing mercury concentrations across species was also evident across study sites and similar to the pattern observed in the *Sphagnum* bog species, which reflects that mercury bioaccumulation differs among individual songbird species within the same habitat type. Small samples sizes did not allow for statistical analysis among species at individual study sites.

**Figure 8. Mean blood mercury concentrations for northern hardwood forest songbird species at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**




## 3.5 Mercury Concentrations and Seasonal Effects

### 3.5.1 *Sphagnum* Bog

Across all target species combined in the *Sphagnum* bog sites, there was no overall relationship between sampling date and blood mercury concentrations, therefore songbird mercury was not detected to significantly increase or decrease over the course of the field season (F=0.3, DF=1, P=0.5659, $R^2$=0.003; N=126). However, when each species was examined separately, Lincoln's Sparrow blood mercury declined during the field season (P=0.0281, $R^2$=0.08), while yellow palm warbler showed an increase (P=0.0208, $R^2$=0.13) and Nashville warbler showed no relationship between blood mercury and capture date (P=0.7325, $R^2$=0.006).

To further examine mercury bioaccumulation in individual songbirds, 18 birds were recaptured within the same field season. Of these sampled birds, blood mercury concentrations increased in three Lincoln's sparrows, six yellow palm warblers, and two Nashville warblers. Five Lincoln's sparrows and one yellow palm warbler decreased, and one Lincoln Sparrow was found to maintain the same blood concentrations. Of this total, one Lincoln's sparrow at Spring Pond Bog was found to increase its mercury body burdens from 0.200 µg/g to 0.821 µg/g during the course of the 2011 field season. Another yellow palm warbler captured at Massawepie Mire increased from 0.562 µg/g to 1.110 µg/g during the 2011 field season. Additionally, five songbirds were captured during different sampling years. Body burdens in one Lincoln's sparrow and two yellow palm warblers were found to decrease; however, two Lincoln's sparrows exhibited increasing mercury concentrations between years.

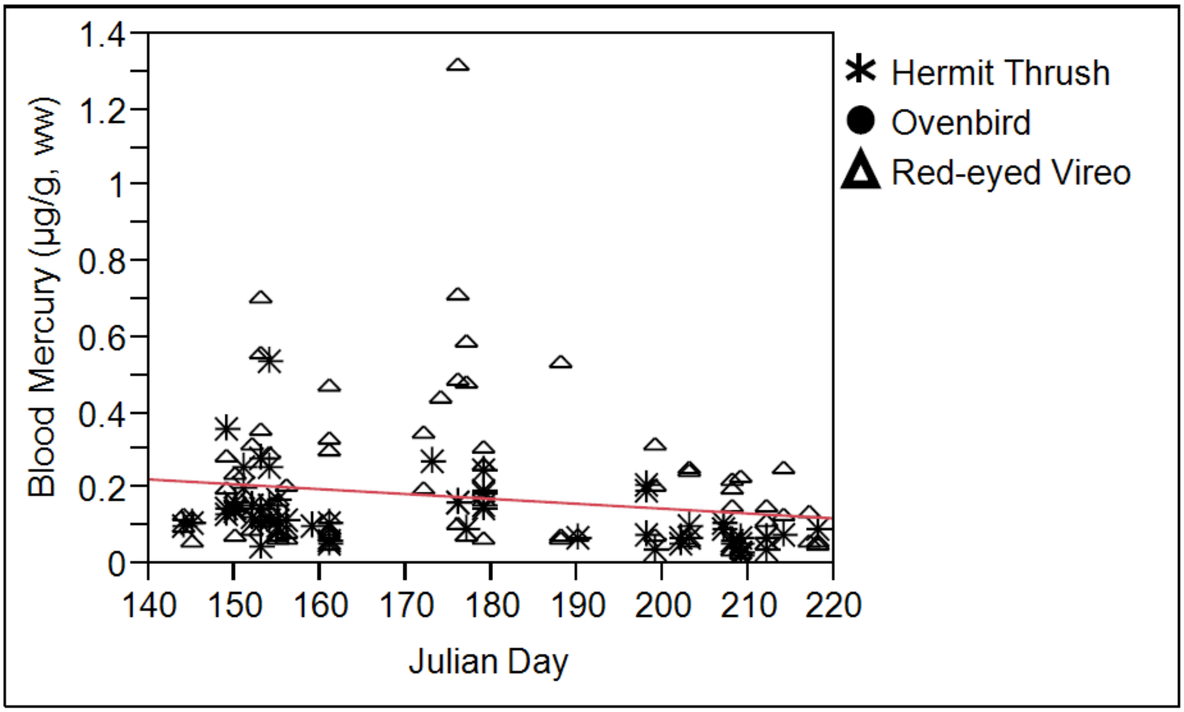
### 3.5.2 Northern Hardwood Forests

For target species within the northern hardwood sites, there was a negative relationship between capture date and blood mercury, as concentrations were found to decline during the field season ($F=13.8$, $DF=1$, $P=0.0003$, $R^2=0.095$; $N=134$; Figure 9). Blood mercury concentrations in the hermit thrush ($P<0.0001$, $R^2=0.32$), red-eyed vireo ($P=0.0437$, $R^2=0.10$), and ovenbird ($P<0.0001$, $R^2=0.53$) were all found to decline during the field season.

To further assess patterns of mercury bioaccumulation within sampled individuals, 16 songbirds were captured more than once during the field season. Of this total, blood mercury in two red-eyed vireo increased, eight hermit thrush and one red-eyed vireo decreased, two ovenbirds stayed the same, and mercury concentrations in three hermit thrushes increased, followed by a decrease. Additionally, six songbirds were recaptured during subsequent field seasons and are reflective of mercury bioaccumulation between years. Blood mercury decreased in one hermit thrush between years, and increased in all remaining birds, including: one hermit thrush, one yellow-rumped warbler, one red-eyed vireo and two ovenbirds. The recaptured red-eyed vireo from Madawaska Flow exhibited the greatest increase in blood mercury concentrations from 0.054 µg/g in 2009 to 0.475 µg/g in 2011. The hermit thrush was initially captured at Madawaska Flow as a first-year juvenile in 2009 with blood mercury concentrations of 0.033 µg/g, which had increased to 0.157 µg/g upon its subsequent recapture in 2011.

**Figure 9. Seasonal blood mercury concentrations in northern hardwood forest songbird species at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**

y (log) = -0.141 - 0.004 * Julian day
$R^2 = 0.10$; $P = 0.0003$

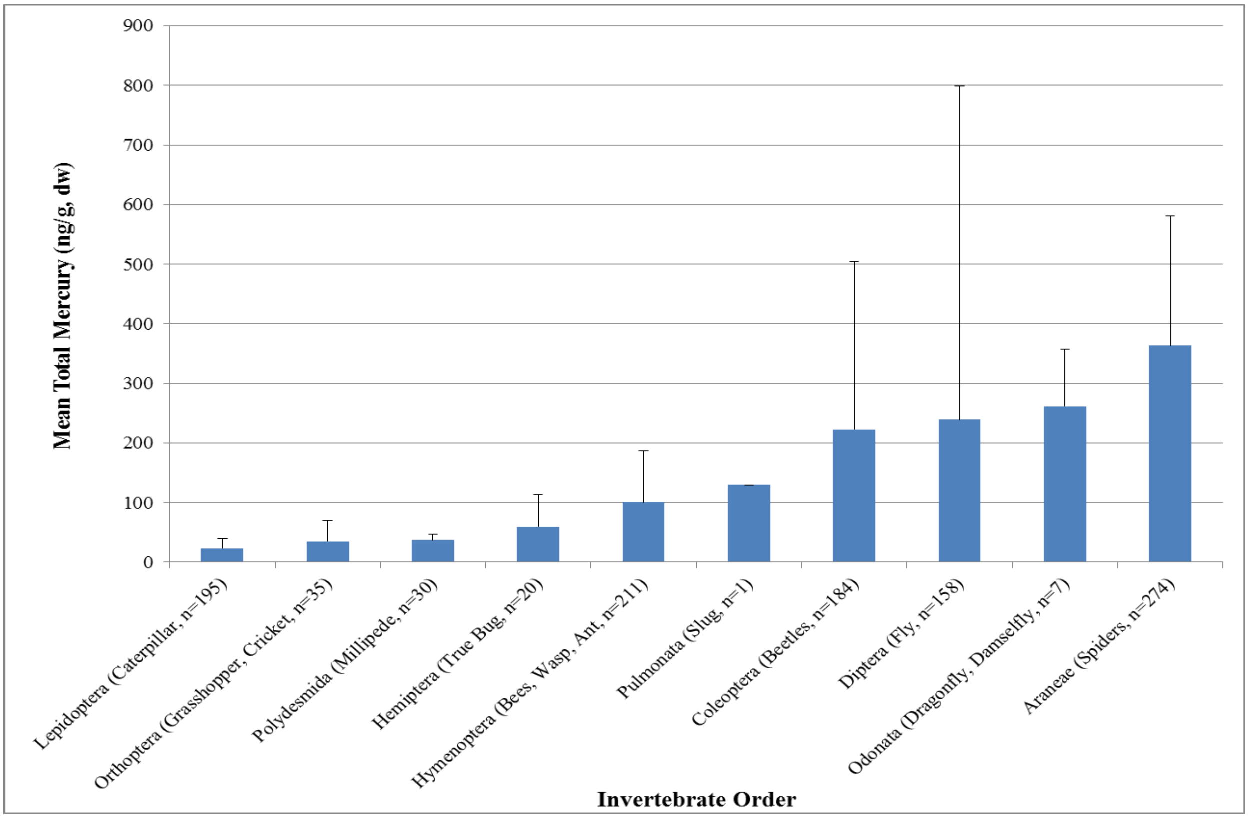


## 3.6 Invertebrate Mercury Exposure

### 3.6.1 *Sphagnum* Bog

A total of 1,115 invertebrates, representing 10 orders, were collected and analyzed for total mercury (ng/g, dw), through both whole-body and composited samples, from *Sphagnum* bog habitats at Bloomingdale Bog, Massawepie Mire, Madawaska Flow, and Spring Pond Bog during 2008, 2009 and 2011 (Figure 10 and Appendix D). Predatory invertebrates within the Araneae (spider; N=274; Hg=363.3 ng/g) and Odonata (dragonfly and damselfly; N=7; Hg=261.9 ng/g) orders exhibited the highest mean mercury values. Lower trophic level, herbivorous invertebrates within the Lepidoptera (caterpillar; N=195; Hg=23.6 ng/g) and Orthoptera (grasshopper; N=35; Hg=35.1 ng/g) were found to have the lowest mean mercury values.

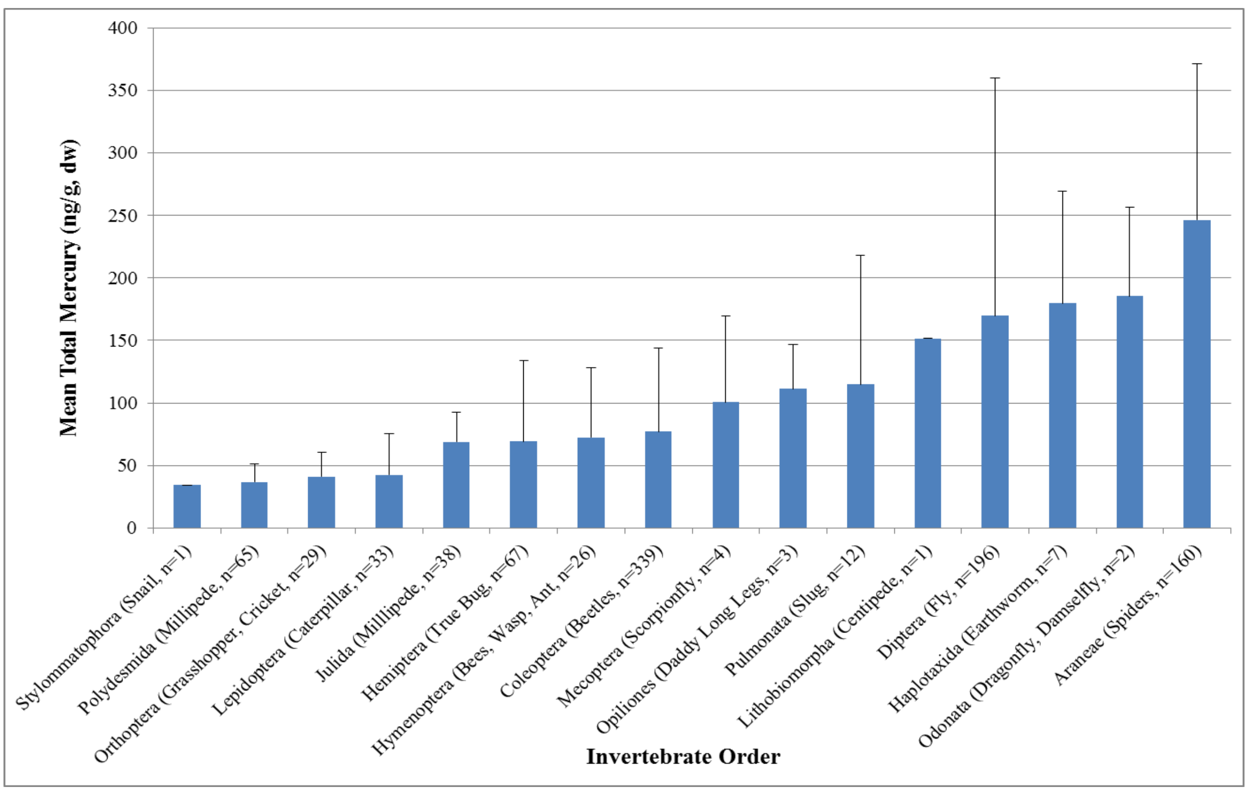
**Figure 10. Mean total mercury concentrations for *Sphagnum* bog invertebrates at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**



### 3.6.2 Northern Hardwood Forest

During 2008, 2009, and 2011, 983 invertebrates representing 16 orders were sampled from within northern hardwood habitats at Bloomingdale Bog, Massawepie Mire, Madawaska Flow, and Spring Pond Bog and analyzed for total mercury concentrations (ng/g, dw) with individual and composited samples (Figure 11 and Appendix D). Similar to the *Sphagnum* bog, high trophic level, predatory invertebrates within the Araneae (spider; N=160; Hg=246.2 ng/g) and Odonata (damselfly; N=2; Hg=185.6 ng/g) orders exhibited the highest mean mercury values. Invertebrates within the Stylommatophora (snail; N=1; Hg=34.2 ng/g), Polydesmida (milllipede; N=65; Hg=37.0 ng/g), and Orthoptera (grasshopper, cricket; N=29; Hg=41.2 ng/g), consisting primarily of detritivore, herbivore, and omnivore invertebrates, were found to have the lowest mean mercury values.

**Figure 11. Mean total mercury concentrations for northern hardwood forest invertebrates at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**



## 3.7 Mercury Bioaccumulation in Terrestrial Food Webs

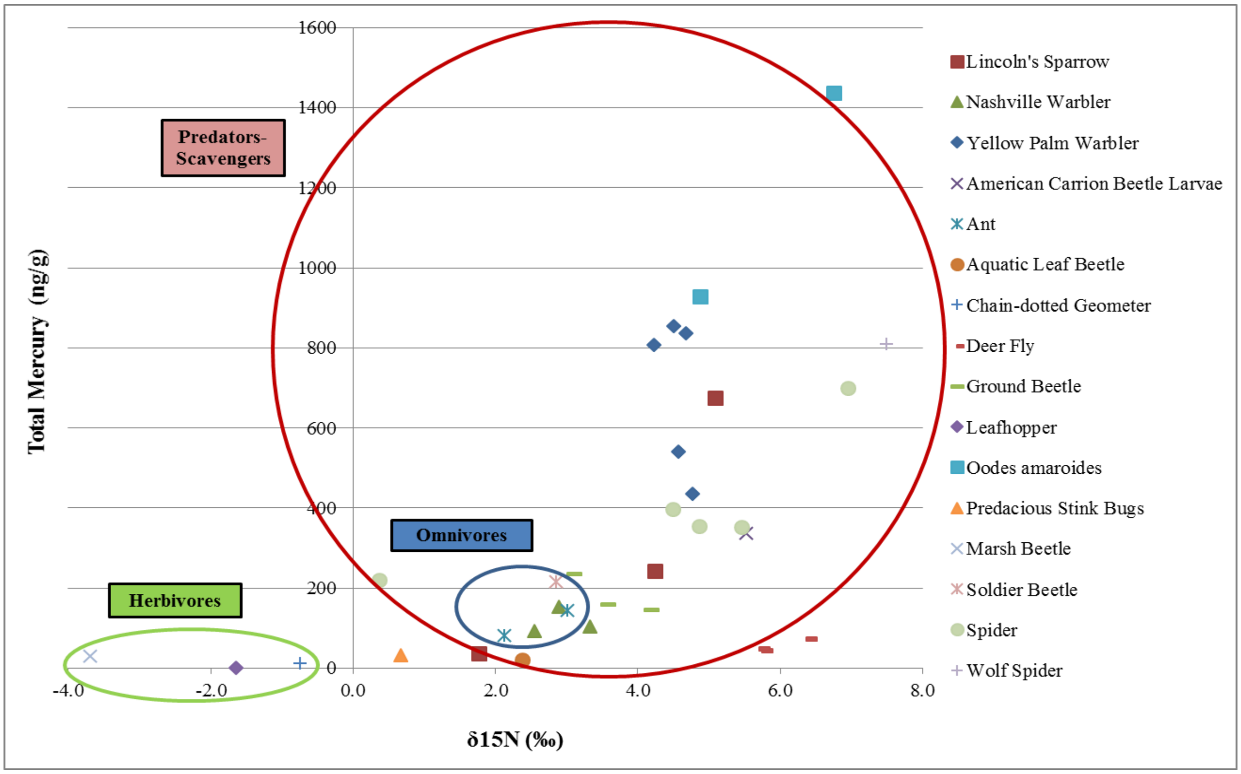
To better understand the transfer of mercury through terrestrial food webs, a subset of songbird and invertebrate samples collected from Madawaska Flow and Bloomingdale Bog in 2009 were selected for a stable isotope analysis of nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$). These values were used to examine the primary sources of carbon within the associated food web ($\delta^{13}C$), and to correlate relative trophic position ($\delta^{15}N$) with the biomagnification of mercury at each study site. Small sample sizes precluded reliable statistical comparisons.

### 3.7.1 Madawaska Flow – *Sphagnum* Bog

A total of 11 songbirds and 23 invertebrate whole-body and composite (N=164) samples were analyzed from within the *Sphagnum* bog habitat at Madawaska Flow (Figure 12). For the selected songbird species, mean $\delta^{13}C$ values ranged from -24.57 to -26.78 ‰ (Appendix E). Across the three targeted songbird species, mean $\delta^{15}N$ values were found to increase with associated increases in average Hg values. Mean $\delta^{15}N$ (‰) and mercury (ng/g) values for the Nashville warbler (N=3) were 2.92 ‰ and 116.6 ng/g, Lincoln's sparrow (N=3) was 3.7‰ and 318.2 ng/g, and the yellow palm warbler (N=5) was 4.55 ‰ and 694.8 ng/g. Of the invertebrate species sampled, mean $\delta^{13}C$ values ranged from -24.57 to -31.76 ‰. High trophic level, predatory invertebrates exhibited the highest mean $\delta^{15}N$ concentrations, including: wolf spider ($\delta^{15}N$=7.49 ‰, Hg=809.53 ng/g); deer fly ($\delta^{15}N$=5.94 ‰, Hg=54.67 ng/g); and the *Oodes amaroides* beetle ($\delta^{15}N$=5.82 ‰, Hg=1181.84 ng/g). Marsh beetles, classified within the herbivore foraging guild, exhibited the lowest, or most depleted, mean $\delta^{15}N$ values at -3.69‰ (Hg=30.38 ng/g).

**Figure 12. Stable isotope values (δ15N) and total mercury concentrations for songbird and invertebrate species sampled within *Sphagnum* bog habitat at Madwaska Flow: 2009**

Shaded lines encompass generalized foraging guilds and relative trophic levels for selected songbirds and invertebrates within each habitat type.

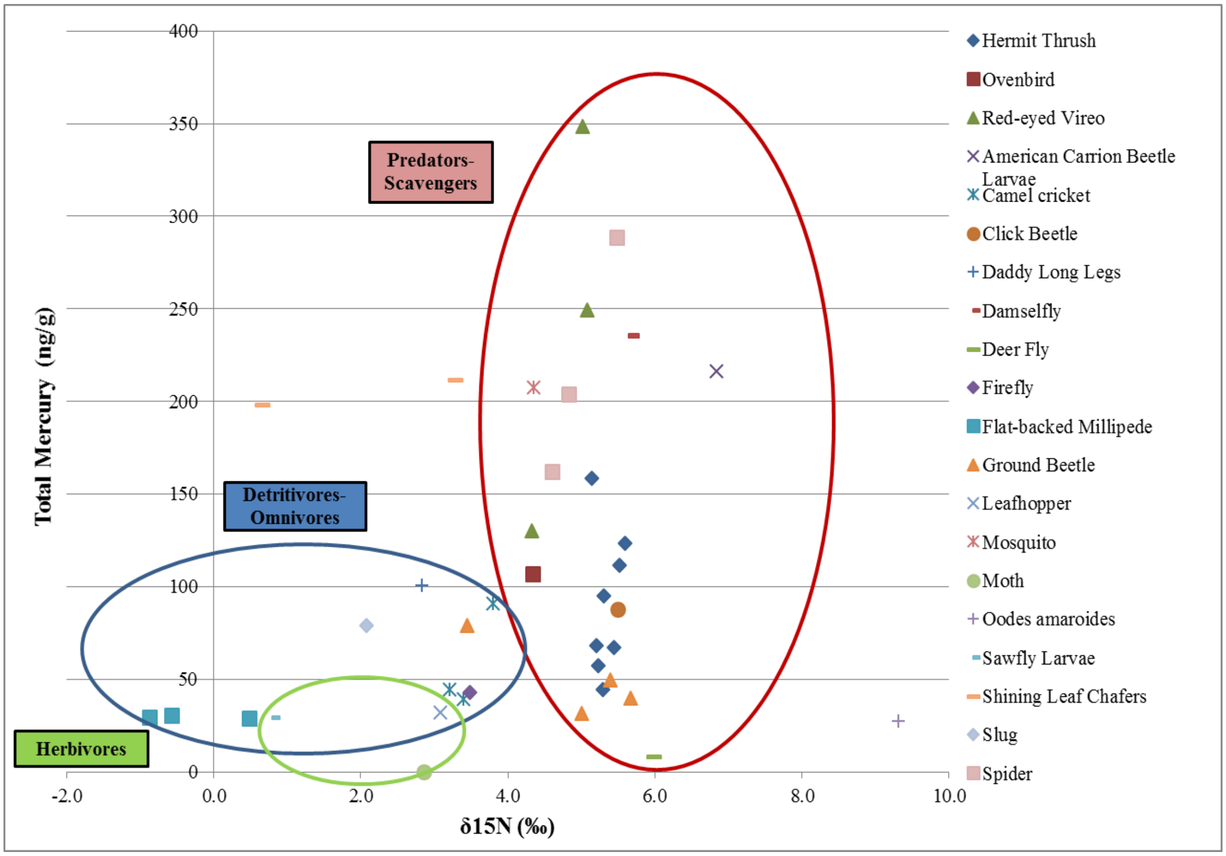



## 3.7.2 Madawaska Flow – Northern Hardwood Forest

Within the forested habitat at Madawaska Flow, a total of 12 songbirds and 28 invertebrate whole-body and composite (N=113) samples were analyzed for carbon and nitrogen stable isotope signatures (Figure 13). Due to a high mercury concentration, the axis on Figure 13 was adjusted to exclude one deer fly sample ($\delta^{15}$N=6.59‰; Hg=1499.9 ng/g). Mean $\delta^{13}$C values ranged from -25.01 to -25.45 ‰ for the three songbird species (Appendix F). For the targeted species, mean $\delta^{15}$N (‰) and mercury (ng/g) values for the ovenbird (N=1) were 4.34 ‰ and 107.1 ng/g, red-eyed vireo (N=3) was 4.81 ‰ and 242.7 ng/g, and the hermit thrush (N=8) was 5.34‰ and 90.77 ng/g. Mean $\delta^{13}$C values ranged from -24.67 to -34.62 ‰ for the invertebrate species sampled. Invertebrates categorized within scavenger and predatory foraging guilds exhibited the highest mean $\delta^{15}$N and Hg concentrations, including the: *Oodes amaroides* beetle ($\delta^{15}$N=9.31 ‰; Hg=27.16 ng/g); American carrion beetle larvae ($\delta^{15}$N=6.83 ‰; Hg=216.1 ng/g); and the deer fly ($\delta^{15}$N=6.29 ‰; Hg=754.1 ng/g). The lowest mean $\delta^{15}$N values of -0.33 ‰ (Hg = 29.64 ng/g) were found for the flat-backed millipede within the detritivore foraging guild.

**Figure 13. Stable isotope values (δ15N) and total mercury concentrations (ng/g) for songbird and invertebrate species sampled within northern hardwood forests at Madawaska Flow: 2009**

Shaded lines encompass generalized foraging guilds and relative trophic levels for selected songbirds and invertebrates within each habitat type.

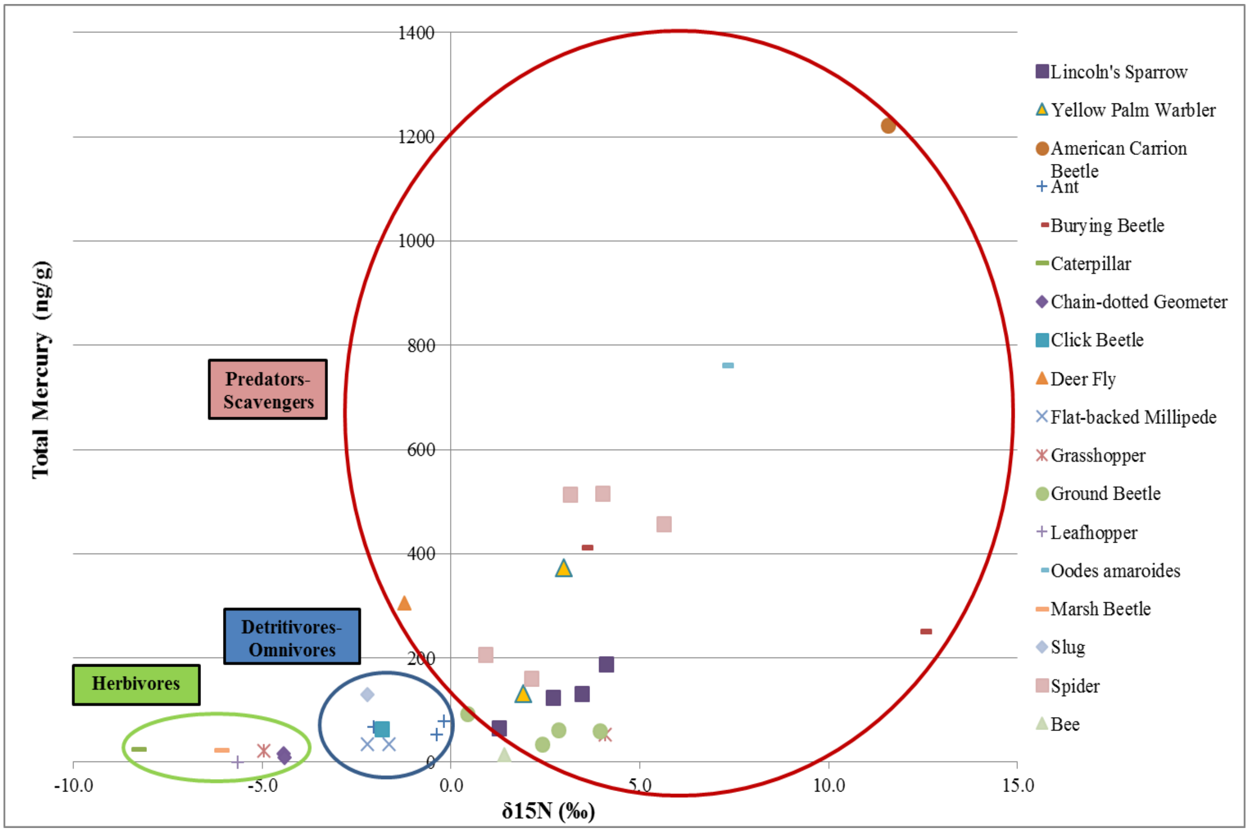



## 3.7.3 Bloomingdale Bog – *Sphagnum* Bog

A total of six songbirds and 30 invertebrate whole-body and composite (N=163) samples were analyzed from within the *Sphagnum* bog habitat at Bloomingdale Bog (Figure 14). Mean $\delta^{13}C$ values for the songbirds ranged from -26.2 to -27.03‰ (Appendix G). Mean $\delta^{15}N$ (‰) and mercury (ng/g) values for the yellow palm warbler (N=2) were 2.4‰ and 252.6 ng/g, while values for the Lincoln's sparrow (N=4) were 2.8‰ and 127.7 ng/g. Across all invertebrates sampled, mean $\delta^{13}C$ values ranged from -24.64 to -54.54‰. The highest mean $\delta^{15}N$ and mean Hg concentrations were found in predatory and scavenger beetles, including the American carrion beetle ($\delta^{15}N$= 11.57‰, Hg=1221.83 ng/g); burying beetle ($\delta^{15}N$=7.9 ‰, Hg=331.3 ng/g); and the *Oodes amaroides* beetle ($\delta^{15}N$=7.2‰, Hg=761.4 ng/g). Caterpillars, classified within the herbivore foraging guild, exhibited the lowest mean $\delta^{15}N$ values at -8.27 ‰ (Hg=25.2 ng/g).

**Figure 14. Stable isotope values ($\delta^{15}N$) and total mercury concentrations for songbird and invertebrate species sampled within *Sphagnum* bog habitat at Bloomingdale Bog: 2009**

Shaded lines encompass generalized foraging guilds and relative trophic levels for selected songbirds and invertebrates within each habitat type.

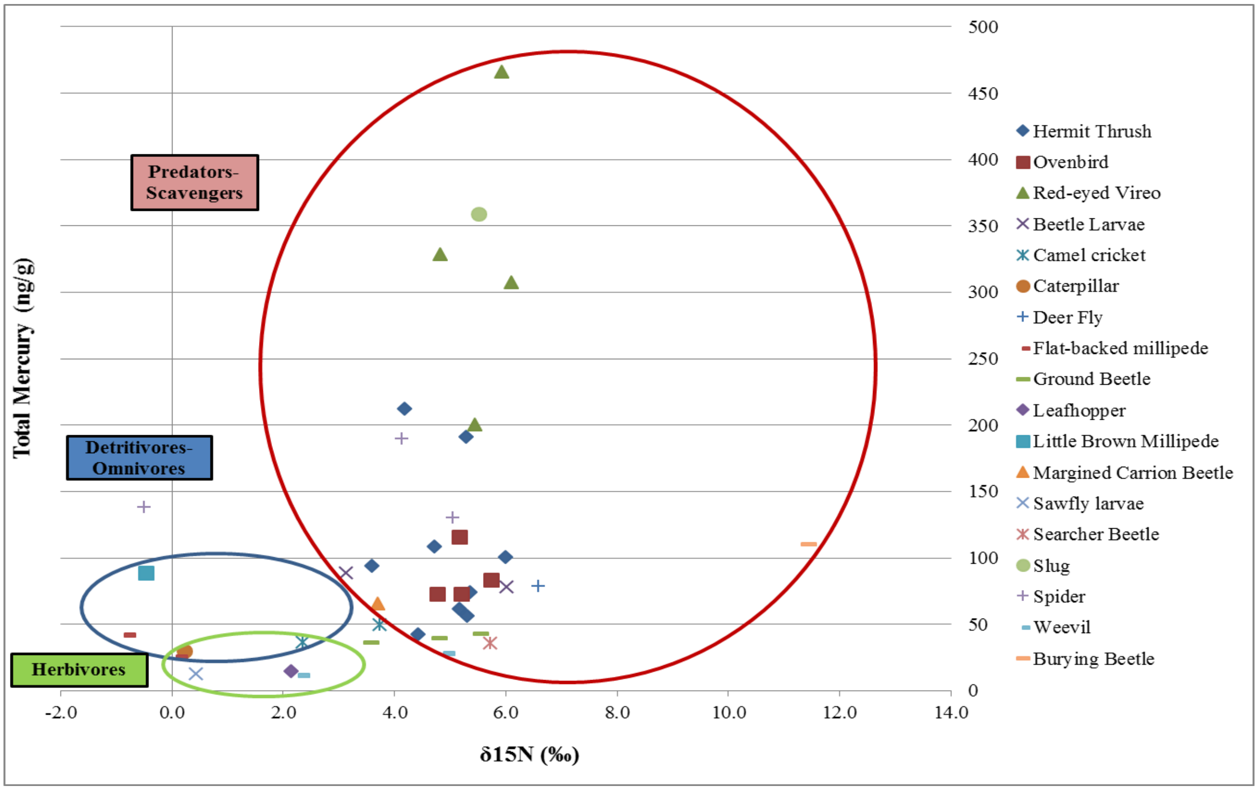



### 3.7.4 Bloomingdale Bog – Northern Hardwood Forest

A total of 17 songbirds and 23 invertebrate whole-body and composite (N=162) samples were analyzed for carbon and nitrogen stable isotope signatures from forested study sites at Bloomingdale Bog (Figure 15). Mean $\delta^{13}C$ values ranged from -24.25 to -24.78‰ for three sampled songbird species (Appendix H). Mean $\delta^{15}N$ (‰) and mercury (ng/g) values for the hermit thrush (N=9) were 4.88‰ and 104.6 ng/g, the ovenbird (N=4) was 5.21‰ and 86.3 ng/g, and the red-eyed vireo (N=4) was found to be 5.57‰ and 325.8 ng/g. Mean $\delta^{13}C$ values for the sampled invertebrates ranged from -24.08 to -29.72‰. Scavenger and predatory invertebrates exhibited the highest mean $\delta^{15}N$ concentrations, including the burying beetle ($\delta^{15}N$=11.44‰, Hg=110.7 ng/g); deer fly ($\delta^{15}N$=6.5‰, Hg=78.6 ng/g); and the searcher beetle ($\delta^{15}N$=5.72‰; Hg=35.9 ng/g). Little brown (Julida) millipedes, classified within the detritivore foraging guild, were determined to have the lowest mean $\delta^{15}N$ values of -0.47‰ (Hg = 89.01 ng/g).

**Figure 15. Stable isotope values (δ15N) and total mercury concentrations for songbird and invertebrate species sampled within northern hardwood forest at Bloomingdale Bog: 2009**

Shaded lines encompass generalized foraging guilds and relative trophic levels for selected songbirds and invertebrates within each habitat type.




## 3.8 Discussion

### 3.8.1 Mercury Bioaccumulation within Adirondack *Sphagnum* Bog and Northern Hardwood Forests

Overall results of this study provide valuable quantitative information relating to patterns of mercury exposure for songbird communities inhabiting sensitive *Sphagnum* bog and hardwood forests in the Adirondack Park. The compilation of information from this data set allows for both among-species and between-habitat comparisons of mercury concentrations, as well as evaluation with established threshold levels associated with adverse physiological health impacts to aid in the identification of potentially at-risk songbird species. Current estimates for blood mercury concentrations developed to represent the risk factor and lowest observed adverse effects levels (LOAELs) associated with songbird reproductive impairment include: <0.7 µg/g (low risk); 0.7-1.2 µg/g (moderate risk); 1.2-1.7 µg/g (high risk); and >1.7 µg/g (very high) (Jackson et al. 2011a, Evers et al. 2012). Across all 21 species sampled, yellow palm warbler, swamp sparrow (*Melospiza georgiana*), and common yellowthroat (*Geothlypis trichas*) were found to have the most elevated average mercury concentrations for species sampled within *Sphagnum* bog study sites (Figure 5). Within adjacent forest systems, the blue-headed vireo (*Vireo solitarius*), red-eyed vireo and yellow-rumped warbler *(Setophaga coronata*) exhibited the highest mean mercury concentrations. Of the total birds sampled (N=292), 12 individuals were found to exceed blood mercury concentrations that placed them within the moderate risk level associated with 10-20% reductions in nesting success, which include: one Lincoln's sparrow, two red-eyed vireos, and nine yellow palm warblers. One yellow palm warbler and one red-eyed vireo were categorized as being at high risk (20-30% reductions in nesting success), and two yellow palm warblers at Massawepie Mire (2.82 µg/g) and Spring Pond Bog (1.86 µg/g) were classified as being at very high risk (>30% reduction in nesting success) to the impacts of mercury on reproductive success. Additionally, red-eyed vireos and yellow palm warblers were documented to have the highest mean mercury values across target species within each study site (Figure 7, 8). While most songbird blood samples are categorized to be at a generally low risk, it is important to consider that species identified as exhibiting elevated mercury levels, like the red-eyed vireo and yellow palm warbler, may be potentially at-risk and vulnerable to the documented multi-systemic effects of mercury exposure, and could serve as valuable focal species for future songbird monitoring and research efforts.

Across all study sites, blood mercury concentrations in *Sphagnum* bog target species were consistently higher than those songbirds sampled within the nearby forested sites (Figure 6). These results are consistent with regional studies that have documented elevated mercury levels in wetland songbird species as compared to upland forested species, resulting from processes associated with higher methylation rates and subsequent increased methylmercury bioavailability within wetland ecosystems (Cristol et al. 2008, Evers et al. 2012, Jackson et al. 2015). Additionally, similar species patterns of increasing mercury exposure were documented for target species across all study sites (Figure 7 and Figure 8). At all *Sphagnum* bog sites, Hg concentrations increased from Nashville warbler to Lincoln's sparrow to yellow palm warbler, and at all forested sites Hg concentrations increased from ovenbird to hermit thrush to red-eyed vireo. Although other studies have documented species differences in mercury concentrations among foraging guilds, with insectivore species generally demonstrating higher mercury values than omnivorous species, all of the targeted species for this study were classified as insectivores, with the exception of the omnivorous Lincoln's sparrow (Jackson et al. 2015). Therefore, this consistent pattern of increasing mercury exposure at each study site may be linked to species-specific dietary differences in prey selection. Overall, these results reinforce that patterns of mercury exposure within songbirds are influenced by habitat type and the associated processes of methylation and mercury bioavailability, and suggest that variation across species may be linked to species-specific foraging strategies.

There was no evidence of an overall seasonal effect of blood mercury exposure levels for songbird species sampled within the *Sphagnum* bog habitat. However, when examined separately the Lincoln's sparrow showed a slight decrease, and the yellow palm warbler showed an increase during the course of the field season. In contrast, there was a significant overall decline in blood mercury concentrations across all three forested target species throughout the field season (Figure 9). The ovenbird was found to have the steepest decrease in mercury concentrations. This declining seasonal pattern in mercury levels is similar to the results documented by other regional studies of boreal songbird species (Rimmer et al. 2009, Townsend 2011). These studies suggest that seasonal mercury decline in songbird blood is attributed to a dietary shift based on temporal prey availability, which involves the consumption of high-mercury, arthropod prey items in the early summer, with a transition to lower-mercury, foliage-based (caterpillars, fruit) food items later in the season. Although the selected target species between research projects vary, all species are classified as either omnivores or insectivores. Therefore, it seems likely that similar mechanisms for foraging strategies, staggered emergence of invertebrates, and a subsequent shift in prey base would be applicable across other northeastern forested songbird species. Additionally, blood mercury concentrations for both individual within-year and between-year captures provide further documentation of the temporal variability associated with the sampled songbirds. Although there was a significant decline of mercury concentrations in forested songbirds, it is important to consider the lack of seasonal patterns within the *Sphagnum* bog systems, along with the level of variability associated with repeated individual site captures documented as a result of this study. Considering the limited amount of field research that has been conducted to specifically examine temporal changes in songbird mercury concentrations, future research would be beneficial to further identify and better assess patterns of seasonal mercury fluctuations in regional songbird communities.

Within both the *Sphagnum* bog and forested study sites, predatory invertebrates positioned at high trophic levels, (spiders, dragonflies, and damselflies) exhibited the highest total mercury concentrations, whereas herbivore and detritivore invertebrates (caterpillars, millipedes, and grasshoppers), were documented to have the lowest total mercury concentrations (Figure 10 and Figure 11). These results suggest that songbirds consuming prey items at higher trophic levels would be exposed to increased mercury levels as compared to selection of invertebrates in lower trophic levels. Additionally, mercury concentrations were similar between the *Sphagnum* bog and forested sites for invertebrates occupying lower trophic level positions, Lepidoptera, Orthoptera and Polydesmida; however, invertebrates within the Araneae (spiders) and Odonata (dragonflies) were comparatively higher in the *Sphagnum* bog than the surrounding forest (Appendix D). Therefore, bog-obligate songbird species foraging on predatory invertebrates would likely have elevated mercury exposure levels as compared to forested species consuming similar invertebrates within the same order, resulting from increased levels of methylmercury bioavailability within wetland systems as compared to forested ecosystems.

A stable isotope analysis was conducted to examine patterns of mercury transfer and bioaccumulation within terrestrial food webs at Bloomingdale Bog and Madawaska Flow (Figures 12, 13, 14, and 15). Many studies have documented that species at higher trophic levels have greater $\delta^{15}N$ values than species at lower trophic levels, and an incremental +3‰ enrichment factor occurs at each ascending trophic level (Minagawa and Wada 1984, Gannes et al. 1998, Kelly 2000). Considering that top predators within a food chain often have the highest $\delta^{15}N$ values relative to prey species, the bioaccumulation of contaminants can be evaluated in the context of $\delta^{15}N$ values (Cabana and Rasmussen 1994, Jarman et al. 1996, Thompson et al. 1998, Bearhop et al. 2000). Although there was inherent variability associated with the data presented across all study sites, these analyses demonstrate a general pattern of mercury biomagnification across trophic levels, from herbivores at the base of the food web to predators at the top of the food chain. Additionally, mercury levels in several predatory and scavenger beetles within the *Sphagnum* bog habitat were found to exceed LOAEL thresholds associated with adverse reproductive impacts in songbirds. Therefore, these high mercury beetles could represent strong trophic pathways for mercury bioaccumulation in songbirds consuming these prey items. Overall, dietary selection, seasonal prey availability, and habitat type are important factors contributing to mercury exposure levels in regional songbird communities.

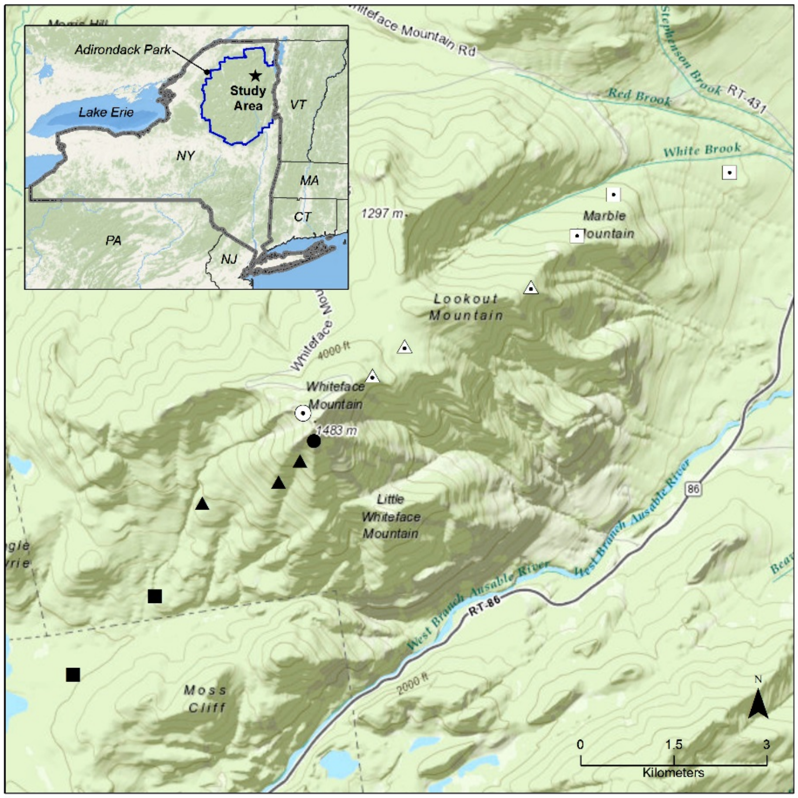
# 4 Methylmercury Bioaccumulation within Montane, Terrestrial Food Webs in the Adirondack Park of New York State

## 4.1 Study Area

Project sampling to investigate pathways for biotic mercury bioaccumulation within montane terrestrial habitats was conducted during the 2009-2010 field seasons at established study sites along an elevation gradient on Whiteface Mountain (44.36˚N, 73.90˚W) in the Adirondack Park of New York State (Figure 16). Whiteface Mountain, located in the Wilmington Wild Forest of the Adirondack High Peaks Region, is the fifth highest peak (4,867 feet; 1,483 meters) in New York State. Whiteface Mountain is also the site of the SUNY-Albany Atmospheric Sciences Research Center (ASRC), which coordinates and administers long-term research of cloud-water chemistry and atmospheric monitoring stations at both low elevation and summit locations. A National Atmospheric Deposition Program (NADP) station that monitors regional precipitation chemistry is also located on-site. Whiteface Mountain is intensively utilized as a year-round recreational area, which includes extensive hiking trails and a year-round ski resort, as well as seasonal vehicle access to the summit via the Veteran's Memorial Highway. Undeveloped portions of Whiteface are currently classified as Wild Forest and all areas are managed under the jurisdiction of the NYS DEC.

**Figure 16. Sampling locations on Whiteface Mountain, New York, 2009-2010**

Study sites are located on the southwest (black symbols) and northeast (white dot symbols) sides of the mountain. Square symbols represent hardwood forests, triangles are spruce-fir forests, and circles are alpine zones.




## 4.2 Research Approach and Study Design

To document methylmercury concentrations in terrestrial biota along an elevational gradient in the Adirondack Park, this project was divided into two phases. A multi-year field study, conducted in 2009 and 2010, to assess mercury concentrations in songbird and invertebrate communities was completed during the first phase, and the second phase included a detailed mercury analysis of biotic samples.

### 4.2.1 Phase One: Montane Field Study

Beginning in 2008, an intensive field study was initiated at several northern hardwood forest and *Sphagnum* bog habitats in the Adirondack Park to examine and compare patterns of mercury and stable isotope signatures within selected invertebrate and songbird species. To supplement this research and better define the avenues for mercury bioaccumulation within sensitive Adirondack habitats, invertebrate and songbird samples were collected from June-August 2009 and 2010 along an elevational gradient at 13 established study sites (450-1,400 meters) located on Whiteface Mountain in the Adirondack High Peaks Region.

To evaluate the hypothesis that mercury concentrations increase with a corresponding increase in elevation, samples were collected from three vegetation zones located along the elevational gradient, which included northern hardwood forest, spruce-fir forest, and alpine zone. To most accurately define the relationship between mercury and elevation, Whiteface Mountain was selected as the study site for this research as it possesses an elevation of 4,867 feet (1,483 meters), with a prominence of 3,110 feet (948 meters). This approach was used to ensure the presence of all three vegetation zones and to provide the necessary elevation range to document changes in mercury concentrations and the potential impacts on associated food webs. In addition, NYS DEC designated Whiteface Mountain as an Adirondack Sub-Alpine Forest Bird Conservation Area. Considering that previous research has been conducted in relation to atmospheric mercury deposition (Blackwell and Driscoll 2015) and songbird communities (Rimmer et al. 2005) at this site, this work provides valuable information to improve the understanding of effects of mercury deposition in the Adirondack Park.

In alignment with sampling methodologies utilized as part of the *Sphagnum* bog-northern hardwood study, songbird blood, feathers and forest invertebrates were collected at each study site for mercury analysis. To investigate differences in mercury concentrations due to elevation, the following ground-foraging, songbird species, within the same genus, were targeted in the corresponding elevation zones:

- Low elevation - northern hardwood forest: hermit thrush (*Catharus guttatus*).
- Mid-elevation - spruce-fir forest: Swainson's thrush (*Catharus ustulatus*).
- High elevation - alpine zone: Bicknell's thrush (*Catharus bicknelli*).

When present, both the dark-eyed junco (*Junco hyemalis)* and white-throated sparrow (*Zonotrichia albicollis)* were sampled in each elevation zone along the entire gradient to obtain a within-species pattern of blood mercury. In addition, the red-eyed vireo and ovenbird were sampled at low- and mid-elevation sites for comparative analysis of mercury values between the *Sphagnum* bog and montane study sites.

Forest invertebrates, similar to those collected in the *Sphagnum* bog study, were sampled at each study site. An additional survey of mercury in soils, leaf litter, fresh vegetation, throughfall and cloudwater was also conducted at the same study sites during 2009-2010 (Blackwell and Driscoll 2015).

In addition to changes in mercury due to elevation, it was also anticipated that variation in mercury concentrations would be documented as a result of aspect and temporal change. Therefore, plots were located in each vegetation zone along western and eastern facing slopes to account for any variation in mercury deposition patterns that may exist with aspect. Considering that windward, or western-facing, slopes generally receive higher rates of deposition due to the orographic effect, it was hypothesized that biota sampled on western-facing slopes would reflect higher mercury concentrations than those on leeward, or eastern-facing, slopes. Additionally, all plots were sampled multiple times during the 2009 and 2010 field seasons in an effort to document any detectable seasonal patterns that occurred during the course of the field season.

### 4.2.2 Phase Two: Mercury Sample Analysis

Collected samples of forest invertebrates and songbird blood from the 2009 and 2010 Whiteface study sites were analyzed for total mercury concentrations at Syracuse University following the protocols outlined in Section 2.3.

## 4.3 Results

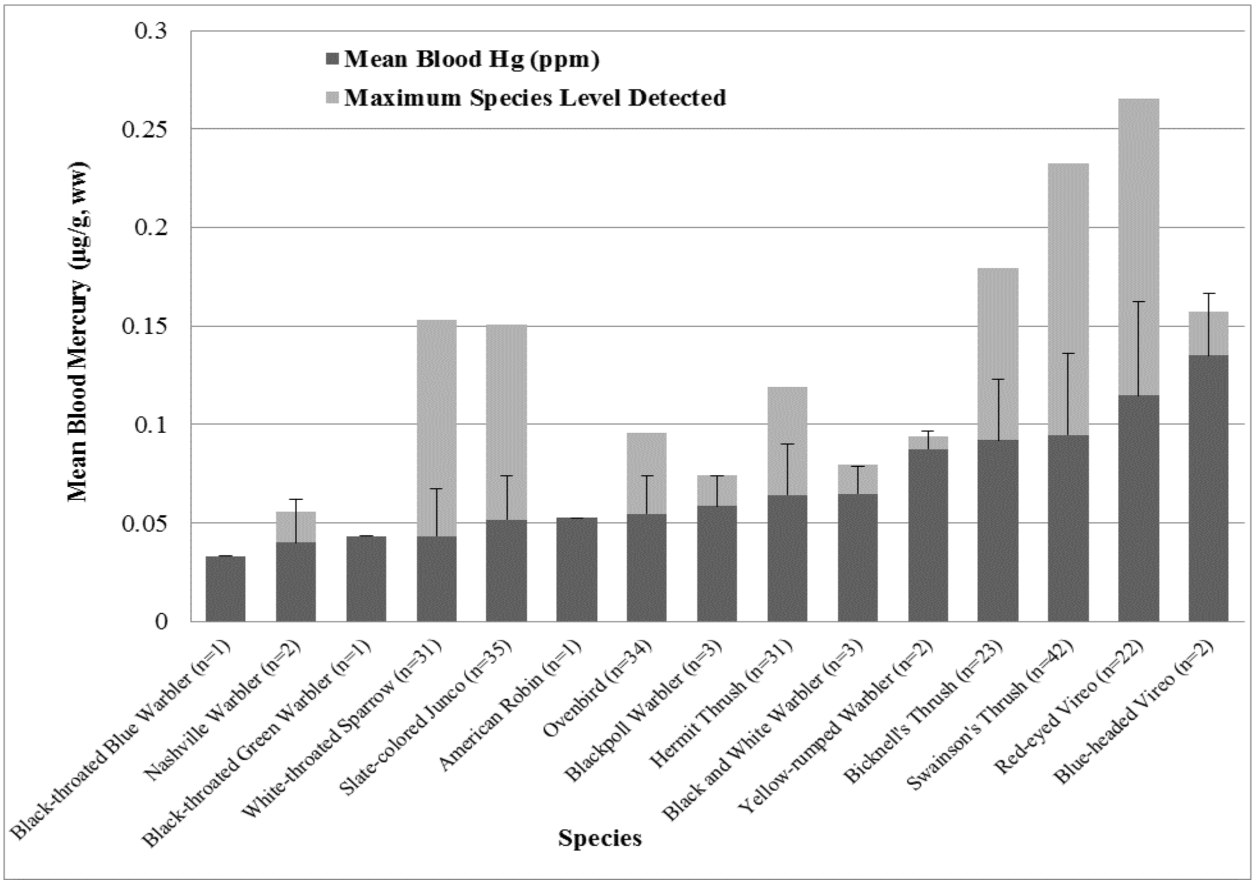
### 4.3.1 Avian Mercury Exposure

#### *4.3.1.1 All Species*

During 2009-2010, a total 207 adult songbirds, representing 15 species, were captured, banded, and analyzed for total mercury exposure (N=233) along an elevational gradient on Whiteface Mountain (Figure 17 and Appendix I). Of the species sampled, four songbird families were represented, including Emberizids/New World sparrows, thrushes, vireos, and wood warblers. Additionally, all songbirds were classified within three dietary foraging guilds, including insectivore, omnivore, and vermivore (De Graaf 1985). Blood mercury levels ranged from 0.018 µg/g in an ovenbird to 0.265 µg/g for a red-eyed vireo. Overall, songbirds sampled within the vireo and thrush families exhibited higher mean mercury concentrations as compared to warbler and sparrow species.

**Figure 17. Mean blood mercury concentrations for songbird species on Whiteface Mountain: 2009-2010**

Light gray shading reflects the maximum mercury levels detected for each species.




Project results are only representative of adult songbird mercury concentrations, therefore the following individuals were sampled during the 2009-2010 field efforts, but were excluded from statistical analyses: two sharp-shinned hawks (*Accipiter striatus)*; one winter wren (*Troglodytes hiemalis*) of unknown age; and 12 juveniles (one winter wren, one white-throated sparrow, two hairy woodpeckers [*Picoides villosus]* and eight dark-eyed juncos) (see Appendix I).

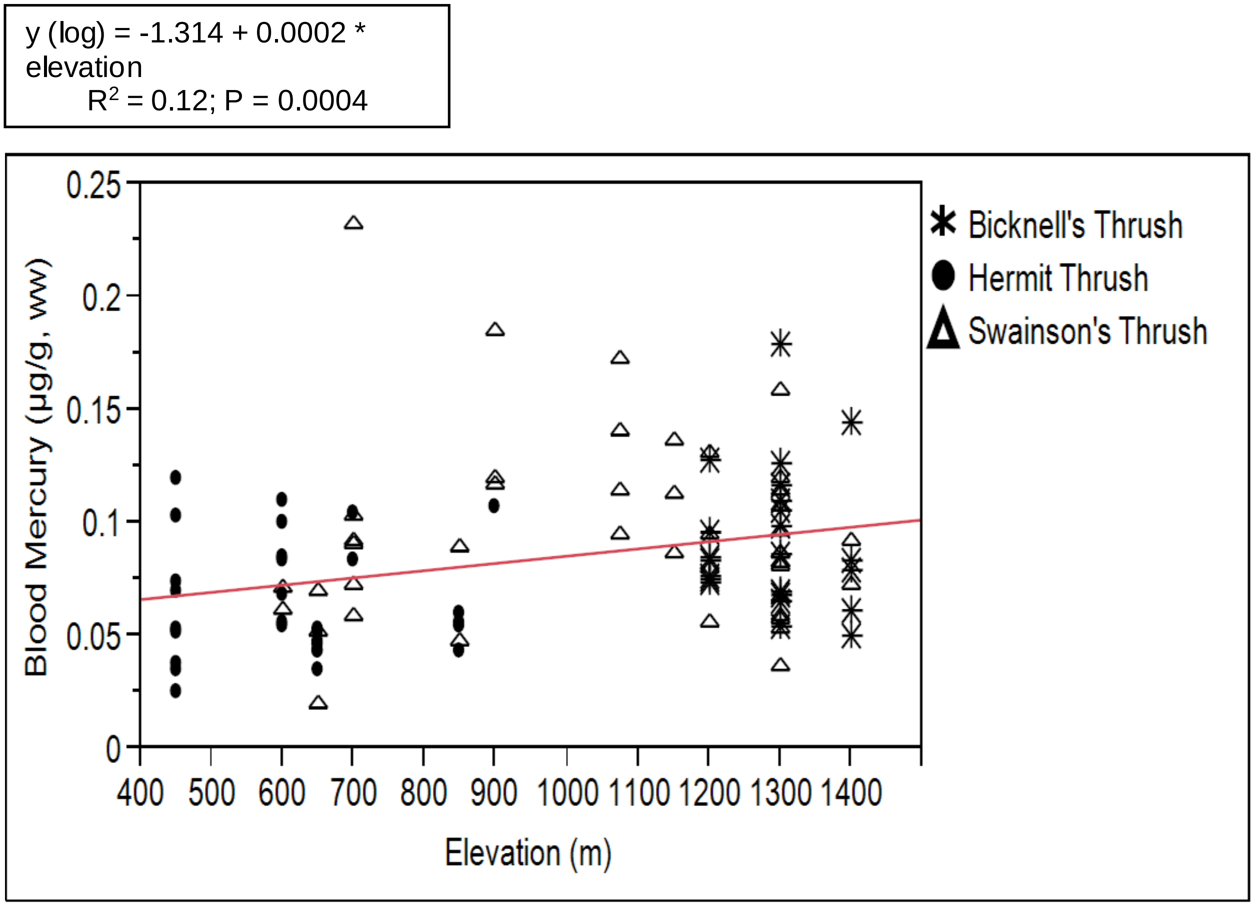
### 4.3.2 Mercury Concentrations in Thrush Species Along an Elevational Gradient

To assess mercury bioavailability within boreal songbird communities, the following three thrush species were targeted for capture and analysis of blood mercury concentrations (N=96) along an elevational gradient on Whiteface Mountain from 2009 to 2010: hermit thrush, Swainson's thrush, and Bicknell's thrush. Mean blood mercury concentrations in adult thrushes varied significantly among species (F=8.9, DF=2, P=0.0003), as hermit thrush had lower blood mercury concentrations than both Swainson's thrush and Bicknell's thrush, which did not differ from each other. Across all study sites, hermit thrush (N=31) mean blood mercury concentrations were 0.064 µg/g, Swainson's thrush (N=42) had mean Hg concentrations of 0.094 µg/g, and Bicknell's thrush (N=23) mercury concentrations were 0.092 µg/g (Appendix I).

Study sites were divided into three general elevation zones and songbirds were categorized within the respective low-, mid- or high-elevation classes. Low-elevation thrushes (N=43) included 30 hermit thrush and 13 Swainson's thrush. Mid-elevation birds (N=21) were comprised of 1 hermit thrush, 13 Swainson's thrush and seven Bicknell's thrush, while high elevation songbirds (N=32) included 16 Swainson's thrush and 16 Bicknell's thrush. Blood mercury concentrations varied significantly among elevation zones (F=14, DF=2, P<0.0001). Low-elevation songbirds had lower blood mercury concentrations (0.068 µg/g) as compared to both mid- (0.108 µg/g) and high- (0.089 µg/g) elevation songbirds, which did not differ from each other. Sampled along the entire elevational gradient, Swainson's thrush exhibited significantly higher blood mercury concentrations at mid-elevation (0.119 µg/g) as compared to low elevation (0.081 µg/g), but did not differ from birds captured in high-elevation zones (0.085 µg/g).

There was a positive relationship between elevation and blood mercury concentrations across all thrush species (F=13.4, DF=1, P=0.0004, $R^2$=0.12; Figure 18). When examined separately, there was no relationship between blood mercury and elevation for the hermit thrush (P=0.7115, $R^2$=0.005), Swainson's thrush (P=0.4269, $R^2$=0.02) and Bicknell's thrush (P=0.6713, $R^2$=0.01), which is likely due to the limited elevational span occupied by each individual species along the entire gradient.

**Figure 18. Relationship between elevation and blood mercury concentrations in thrush species on Whiteface Mountain: 2009-2010**



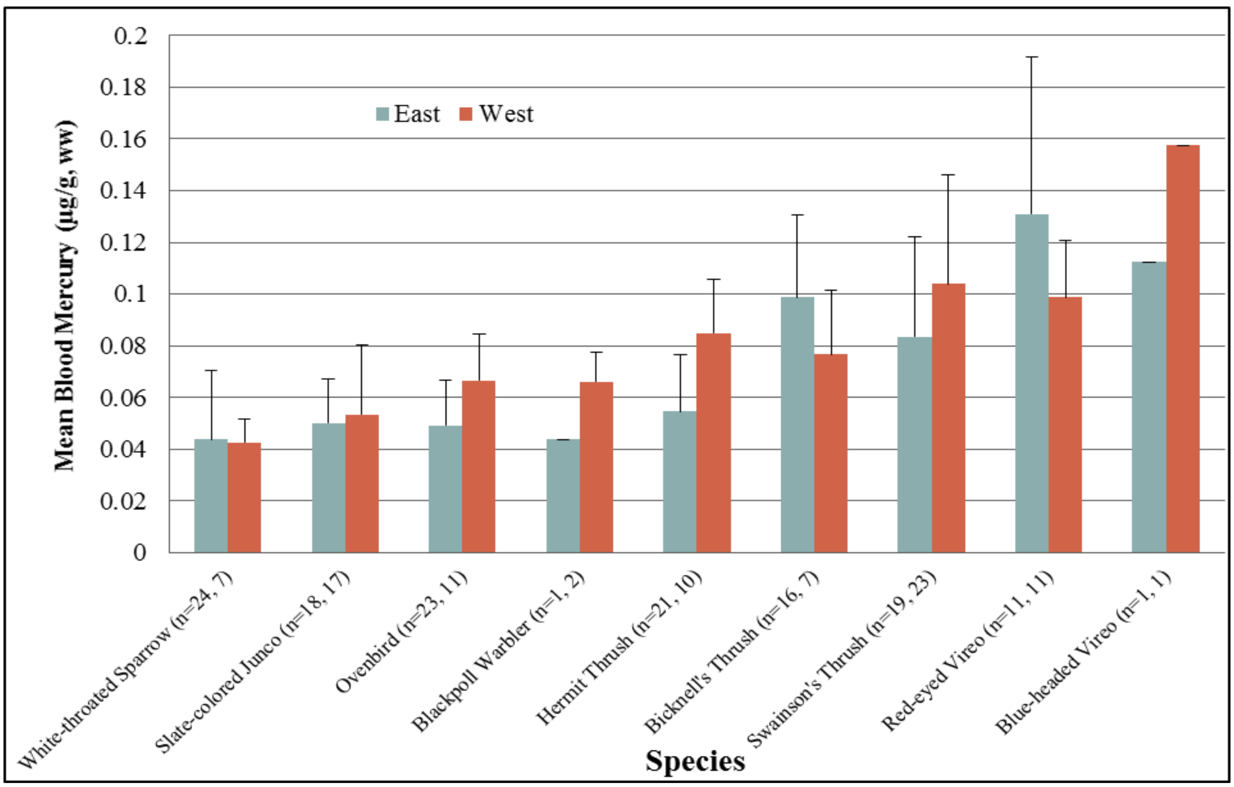

Across all species sampled, both target and non-target, (N=233), there was a negative relationship between elevation and blood mercury concentrations (F=4.4, DF=1, P=0.0379, $R^2$=0.02). This pattern in the larger data set is likely influenced by the inclusion of white-throated sparrows and dark-eyed juncos sampled at mid- and high elevations, which typically exhibit low mercury concentrations due to their dietary preference for seeds.

### 4.3.3 Mercury Concentrations and Slope Aspect

Of the 15 species sampled during 2009-2010, nine species of songbirds were collected on both the east and west side of Whiteface mountain (Figure 19). Across all species of songbirds collected, mean blood mercury concentrations varied significantly between the east and west side of the mountain (t=3.5, DF=231, P=0.0006). Songbirds on the west side (0.079 µg/g; N=89) exhibited higher mercury concentrations than those captured on the east side (0.066 µg/g; N=144) of the mountain. Ovenbirds were the only non-target species that demonstrated significantly higher mercury concentrations on the western side of the mountain (t=2.5, DF=32, P=0.0173), while small sample sizes precluded statistical comparisons for the blackpoll warbler and blue-headed vireo.

Across the three targeted thrush species combined, blood mercury was also significantly higher on the west side (0.094 µg/g; N=40) than on the east side (0.076 µg/g; N=56; t=2.8, DF=94, P=0.0056). When examined separately, both the hermit thrush and Swainson's thrush exhibited higher mercury concentrations on the west side of the mountain as compared to the east side. There was no difference in blood concentrations for the Bicknell's thrush due to slope aspect.

**Figure 19. Mean blood mercury concentrations for songbird species on east and west side of Whiteface Mountain: 2009-2010**



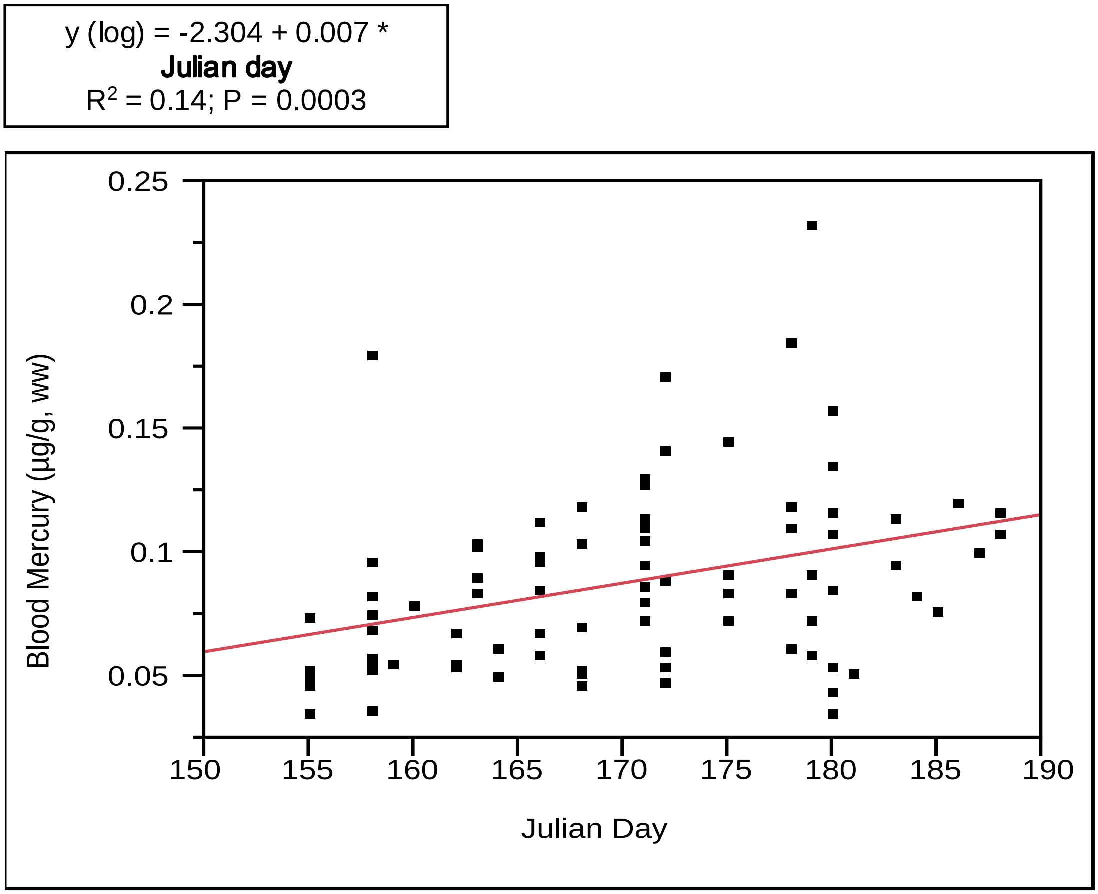
### 4.3.4 Mercury Concentrations and Seasonal Effects

For all thrush species combined, there was a positive relationship between sampling date and blood mercury concentrations, as levels were found to increase during the field season ($F=14.1$, $DF=1$, $P=0.0003$, $R^2=0.14$, $N=87$; Figure 20). To standardize sampling time frames with other regional elevation studies that have examined seasonal patterns of mercury concentrations in Northeastern songbird communities, samples are presented through Julian day 200, which is representative of periods of peak breeding activity and capture success for boreal songbirds. When each thrush species was considered separately, the Swainson's thrush ($P=0.0054$, $R^2=0.19$) showed an increase in blood mercury during the course of the field season, whereas the hermit thrush and Bicknell's thrush showed no significant seasonal effects.

Across all songbird species combined, there was also a positive relationship between blood mercury concentrations and capture date ($F=12.7$, $DF=1$, $P=0.0005$, $R^2=0.06$; $N=205$). When analyzed separately, ovenbirds were the only non-target species that exhibited a within-species increase in mercury concentrations during the course of the field season ($P=0.0178$, $R^2=0.19$). No relationship for blood mercury and date was determined for additional non-target species, including red-eyed vireo, dark-eyed junco, and white-throated sparrow.

To further assess within-season bioaccumulation of individual mercury levels, 11 songbirds were recaptured during the same year, including five hermit thrush, two red-eyed vireo, two ovenbird, one white-throated sparrow, and one Bicknell's thrush. Of the recaptured birds, five were found to decrease, three maintained similar blood levels, two were found to increase, followed by a decrease, and one red-eyed vireo increased. Additionally, 13 songbirds were captured in both 2009 and 2010 and blood levels were compared to examine between years, which included four ovenbird, four dark-eyed junco, two hermit thrush, two white-throated Sparrow, and one Swainson's thrush. Of this sample, six birds were found to decrease between years, five increased, and two stayed approximately the same.

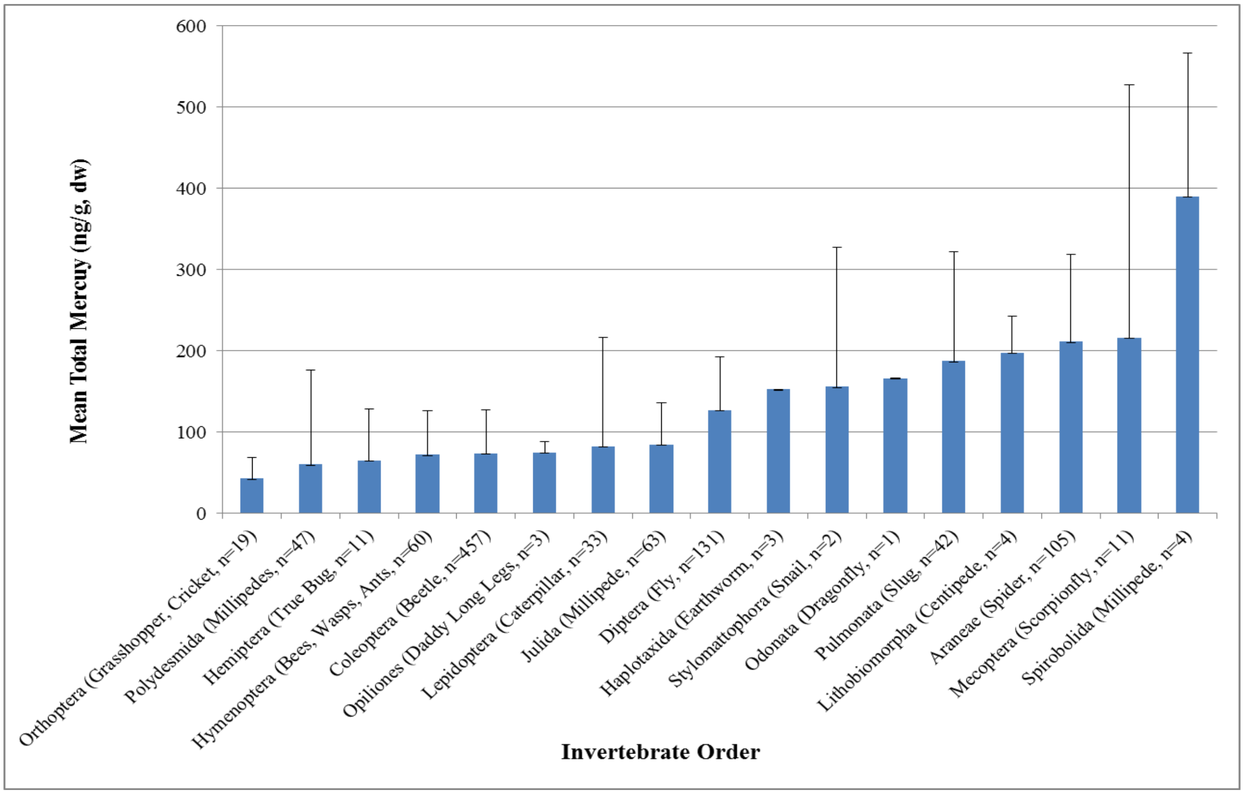
**Figure 20. Seasonal blood mercury concentrations in thrush species on Whiteface Mountain: 2009 – 2010**




### 4.3.5 Invertebrate Mercury Exposure

A total of 996 invertebrates, representing 17 orders, were collected and analyzed for total mercury concentrations (ng/g, dw) through both whole-body and composited samples, from study sites on Whiteface Mountain during 2009-2010 (Figure 21 and Appendix J). The highest mean mercury concentrations were determined for detritivore millipedes within the Spirobolida order (N=4, Hg=390.1 ng/g). Similar to the *Sphagnum* bog and northern hardwood forest sites, high trophic level, predatory and scavenger invertebrates also exhibited high mean mercury concentrations including: Mecoptera (scorpionfly; N=11, Hg=216.3 ng/g); Araneae (spider; N=105; Hg=211.4 ng/g); and Lithobiomorpha (centipede; N=4; Hg=197.6 ng/g). Invertebrates within the Orthoptera (grasshopper, cricket; N=19; Hg=43.2 ng/g) and Polydesmida (millipede; N=47; Hg=60.3 ng/g) orders, which includes detritivores, herbivores, and omnivores, were found to have the lowest mean mercury concentrations.

**Figure 21. Mean total mercury concentrations for invertebrates at Whiteface Mountain: 2009-2010**




## 4.4 Discussion

### 4.4.1 Mercury Bioaccumulation within Montane Forests at Whiteface Mountain

This project was designed to provide a better understanding and assessment of mercury exposure patterns within terrestrial food webs in montane forests in the Adirondack Park. Although limited high-elevation analyses have been conducted within the context of regional songbird research, this project complements current, long-term studies and contributes to a more thorough northeastern wildlife mercury database. Of the 15 songbird species sampled on Whiteface Mountain, insectivore species from the thrush and vireo families, exhibited the highest mean mercury concentrations including: blue-headed vireo, red-eyed vireo, Swainson's thrush, and Bicknell's thrush (Figure 17). In contrast to the *Sphagnum* bog and forested study sites, there were no individuals captured along the elevational gradient on Whiteface Mountain that approached established LOAEL mercury concentrations associated with adverse reproductive impacts. The highest mercury concentrations for all songbirds sampled (N=233), were for a low-elevation red-eyed vireo (0.266 µg/g) and a mid-elevation Swainson's thrush (0.233 µg/g). Therefore, songbirds sampled at study sites on Whiteface Mountain are considered to be generally low risk to the documented effects of mercury exposure (Jackson et al. 2011a, Evers et al. 2012). However, currently listed under the

International Union for Conservation of Nature (IUCN) Red List as a vulnerable species and classified by the NYS DEC as a Species of Special Concern due to declining population levels and habitat loss, the Bicknell’s thrush is a long-distance, migratory species, whose limited breeding habitat is restricted to high-elevation spruce-fir forests (Rimmer 2015). Documented breeding locations in New York State for this high-elevation specialist are limited to the Adirondack and Catskill Mountains, and while mercury concentrations documented for this species on Whiteface Mountain do not approach LOAEL threshold levels associated with adverse reproductive effects, the Bicknell’s thrush may be particularly vulnerable to the impacts of mercury exposure in consideration of declining population levels.

Mean blood mercury concentrations exhibited detectable differences among the three targeted songbird species (hermit thrush, Swainson’s thrush, and Bicknell’s thrush) on Whiteface Mountain. When examined separately, average blood mercury concentrations for the low-elevation hermit thrush were significantly lower than both Swainson’s and Bicknell’s thrush. Mean mercury concentrations for thrush species sampled as part of research efforts conducted by Townsend, in the Catskill Mountains, and Rimmer, in southern Vermont, were found to be comparable to concentration levels documented for Adirondack songbirds, indicating similar regional mercury exposure levels (Rimmer et al. 2009, Townsend 2011).

When categorized across three general elevation zones, songbirds sampled within low-elevation sites exhibited lower mercury body burdens than those species inhabiting both mid- and high-elevation zones. Overall, a significant increase in blood mercury concentrations was found with increasing elevation across all targeted songbird species sampled along the elevational gradient (Figure 18). High-elevation boreal forests are subjected to elevated levels of atmospheric mercury deposition resulting from increased precipitation rates, cloud cover and deposition, and the presence of forest cover types that promote the year-round uptake of atmospheric pollutants, which are likely important factors influencing the elevated mercury exposure levels documented in songbird species inhabiting these sensitive, high elevation zones as compared to those in lower-elevation forests (Lovett et al. 1982, Miller et al. 2005, Sheehan et al. 2006). This pattern of increasing songbird blood mercury concentrations with elevation was also detected by Townsend as part of a similar research project examining mercury concentrations in thrush species along an elevational gradient in the Catskill Mountains of New York State (Townsend 2011; Townsend et al. 2014). This study also documented corresponding elevational increases in mean mercury concentrations for various biotic and abiotic food web compartments, including: leaf litter, organic soils, and salamanders.

Additionally, data collected as part of a concurrent site-intensive study conducted at the same study sites in 2009-2010 on Whiteface Mountain to assess mercury deposition loads, indicated that both overall atmospheric mercury deposition and surface organic soil Hg concentrations increased along the elevational gradient (Blackwell and Driscoll 2015). Overall, this study provides the first observations to examine increases in songbird blood mercury concentrations along an elevation gradient in the Adirondack Park. Although information for biological mercury exposure levels along an elevation gradient is limited, the research results suggest that elevated atmospheric deposition rates in high-elevation forests likely influence and control mercury bioavailability and elevated exposure levels documented in those songbird species inhabiting sensitive, montane habitats.

Across all species of songbirds sampled (N=233), songbird blood was significantly higher on the west side of Whiteface Mountain as compared to the east side (Figure 19). When combined, blood mercury levels for the three targeted species were also elevated on the western side; however, Bicknell's thrush exhibited no difference in mercury levels between the east and west side when examined separately. No significant differences in mercury concentrations due to aspect were detected for atmospheric deposition, soils, leaf litter, and canopy foliage collected as part of the simultaneous research project conducted during 2009-2010 on Whiteface Mountain (Blackwell and Driscoll 2015). Therefore, documented differences in songbird mercury concentrations due to slope aspect may be related to potential variability in prey communities or availability, but would require additional sampling efforts to more definitely assess this pattern, as sample sizes were generally small and precluded statistical comparisons on some species.

There was a significant overall seasonal increase in blood mercury levels for the three combined targeted species during the course of the field season (Figure 20). When analyzed separately only Swainson's thrush demonstrated an increase in blood mercury during the sampling period, while hermit and Bicknell's thrush showed no significant seasonal effects. This pattern of seasonal increase is contrary to the results collected within other forested project study sites, as well as similar research conducted by Rimmer and Townsend, which attributed seasonal declines in songbird mercury concentrations to a shift in dietary selection based on prey availability (Rimmer et al. 2009, Townsend 2011). This working hypothesis seems logical and applicable across sites within the Northeast, which suggests that songbirds rely primarily on a foraging base of high-mercury invertebrate prey items that are available in the early season, as compared to the late season emergence of invertebrates, such as Lepidoptera (caterpillars) and an increased prevalence of fruit, which are low-mercury food items that are highly available during the late summer. Further, considering that the previous studies by Rimmer and Townsend also utilized thrushes as their focal target species, it is unclear whether this contrasting pattern of increasing seasonal mercury concentrations for thrushes on Whiteface Mountains may be related to site-specific differences in prey items, variation within foraging selection of sampled individuals, or unexplained processes operating within the associated food webs. Similar to the *Sphagnum* bog and forested sites, fluctuations in blood mercury concentrations were highly variable for songbirds captured within and between years. While the mechanisms for this seasonal pattern of increase are uncertain, additional recapture efforts as part of future monitoring studies would allow for a better understanding of the complexities associated with mercury body burdens in songbird communities during the breeding season.

Similar to patterns demonstrated by invertebrates sampled within the *Sphagnum* bog and forested study sites, high trophic level predatory and scavenger invertebrates exhibited the highest mean mercury concentrations on Whiteface Mountain, including scorpionflies, spiders, and centipedes (Figure 21). Four individuals within the Spirobolida order, a low-elevation detritivore millipede, were found to have the highest mean mercury concentrations. Alternatively, herbivore and detritivore invertebrates within the Orthoptera (grasshopper, cricket), Polydesmida (millipedes) and Hemiptera (true bug) orders exhibited the lowest mean mercury concentrations. Overall, average mercury concentration levels were found to biomagnify across invertebrate trophic levels, and individual dietary selection would correspondingly influence mercury exposure levels documented within songbird communities on Whiteface Mountain.

# 5 Conclusion

The results of these studies provide valuable quantitative data relating to mercury exposure levels within regional songbird and invertebrate communities, and contribute much needed information to better define the connections between mercury deposition as an environmental stressor and its impact on terrestrial ecosystems. The analysis of data from these projects was one of the first to examine the linkages between atmospheric mercury deposition and trophic transfer within various habitat types in the Adirondack Park. The following summarize the overall findings related to mercury bioaccumulation within *Sphagnum* bog, northern hardwood forests and high-elevation montane food webs and recommendations for future research efforts:

- **Approximately 5% of the songbirds sampled were documented to exceed established lowest observed adverse effects levels (LOAEL) associated with impacts on reproductive success due to mercury exposure.** These species were primarily composed of wetland-obligate species, including the yellow palm warbler and Lincoln's sparrow, as well as the red-eyed vireo, a common forest songbird. Considering the potential impacts on reproductive impairment and subsequent implications on long-term population dynamics for these at-risk species, our study reinforces the need to incorporate and monitor these focal songbird species as part of mercury contaminant research initiatives.
- **Habitat type was demonstrated to influence biotic mercury exposure levels, as songbird species occupying *Sphagnum* bog habitats exhibited significantly higher mercury levels than those inhabiting adjacent forest systems.** Songbird mercury levels are reflective of variables such as habitat bioavailability, which is comparatively elevated within wetland systems, and mercury concentrations within selected dietary prey items. At each study site, the yellow palm warbler and red-eyed vireo exhibited elevated mercury levels, as well as additional species including the common yellowthroat, swamp sparrow, blue-headed vireo and yellow-rumped warbler. Therefore, these species, which may be particularly vulnerable to the documented multi-systemic impacts of mercury exposure, should be prioritized as avian species of concern and included as part of sampling protocols for future mercury research studies. Given the limited base of scientific data relating to songbird exposure levels across the Adirondack Park, research efforts emphasizing study sites within identified high mercury habitat types, specifically wetland systems, would be beneficial to better estimate site-specific exposure levels, locations of potential biological hotspots, and possible spatial gradients of songbird mercury contamination across the Adirondack landscape.

- **Seasonal patterns in songbird mercury concentrations varied between project locations, and repeated captures of individuals both within and between sampling years indicated highly variable fluctuations in blood mercury levels.** These results suggest that temporal patterns are influenced by a number of complex and dynamic variables, such as individual foraging strategies and seasonal prey availability. Considering that few field investigations have been conducted to examine seasonal mercury fluctuations in avian species, additional studies would be necessary to more definitively assess temporal trends and depuration patterns of mercury body burdens in regional songbird communities.
- **Songbirds occupying mid- and high-elevation habitats on Whiteface Mountain were found to have higher blood mercury concentrations than songbird species inhabiting lower elevations.** These exposure patterns are likely driven by elevated levels of atmospheric mercury deposition and increased mercury bioavailability within high-elevation habitats as compared to low-elevation forests. Although the Bicknell's thrush, a high-elevation specialist experiencing declining population levels, was not documented to exhibit mercury concentrations that approached the LOAEL threshold levels established for impacts on reproductive success, monitoring studies to more accurately define the extent of mercury as a biological stressor within data-limited alpine forests would contribute valuable quantitative data regarding the ecological health of breeding habitat for this declining migratory songbird, as well as associated songbird species occupying these sensitive montane habitats.
- **Songbirds inhabiting the western slope of Whiteface Mountain exhibited elevated mercury levels over those species occupying eastern slopes.** Results of a simultaneous study, conducted at the same study sites, did not document significant differences in atmospheric deposition levels or mercury concentrations in organic soils, leaf litter, and canopy foliage along the western elevational gradient as compared to values determined for the eastern aspect. Therefore, the specific mechanisms contributing to the relationship between songbird blood mercury concentrations and slope aspect remain unclear and would require additional sampling efforts to further investigate the underlying processes related to this spatial pattern.
- **Results from invertebrate and stable isotope analyses indicated an overall pattern of mercury biomagnification from herbivorous invertebrates to predatory invertebrates to songbirds within *Sphagnum* bog and forested food webs.** In particular, spiders and predatory and scavenger beetles, positioned at high trophic levels, demonstrated elevated mercury levels and may represent strong pathways of mercury bioaccumulation for songbirds foraging on these invertebrate prey items. Few studies have examined mercury concentrations within invertebrate communities, and the collection and analysis of invertebrate prey items would provide much-needed information regarding the transfer and bioaccumulation of mercury within terrestrial food webs.

The results of this study provide evidence of the varying extent and magnitude of mercury contamination within several ecologically distinct habitat types located in the Adirondack Park. All habitats are geographically well-removed from regional emissions sources, but all are also categorized as part of a biological mercury hotspot. These data illustrate the ability of atmospherically deposited mercury (a persistent and bioaccumulative toxin) to be transferred and biomagnify from invertebrate species at the base of the food web to detrimental levels within songbird communities, and further reinforce the critical need for policymakers to support legislation designed to improve regional air quality emissions standards. Although songbirds face global population declines due to a myriad of interconnected direct and indirect stressors, regulations promoting reductions in mercury emissions, such as the Mercury and Air Toxics Standards (MATS) at the national level and the Minamata Convention supported through the United Nations Environmental Programme at the global level, will ultimately work to limit both wildlife exposure levels and minimize the associated impacts on affected habitats. As wildlife managers comply with requirements implemented through environmental policy initiatives and build upon existing scientific information to develop effective wildlife conservation and monitoring plans, the following general guidelines may be beneficial to direct studies relating to the assessment of mercury levels across the northeastern landscape:

- Conduct multi-year studies incorporating annual sampling regimes for both targeted and generalized capture of songbird species, across a wide variety of ecosystems and at established long-term ecological research sites to further identify and monitor exposure patterns within at-risk songbirds and sensitive habitat types.
- Additional collection of biotic food web samples, including multitrophic invertebrate prey items, for mercury and stable isotope analysis to better characterize the mechanisms and complexities associated with mercury cycling and transfer through terrestrial food webs.
- Regional collaborations to develop standardized collection protocols and monitoring networks to improve understanding of the relationships between mercury deposition, biotic exposure levels, and patterns of mercury contamination across the landscape.

Ideally, the results from these studies can serve to supplement and inform future research efforts, and be utilized by policymakers to support legislation and rules designed to protect critical issues of air quality, environmental integrity, and wildlife health in the northeastern United States. Ultimately, it is intended that this research will contribute valuable scientific information on mercury dynamics in forested ecosystems and advance understanding of the ecological links between mercury deposition and wildlife communities in New York State.

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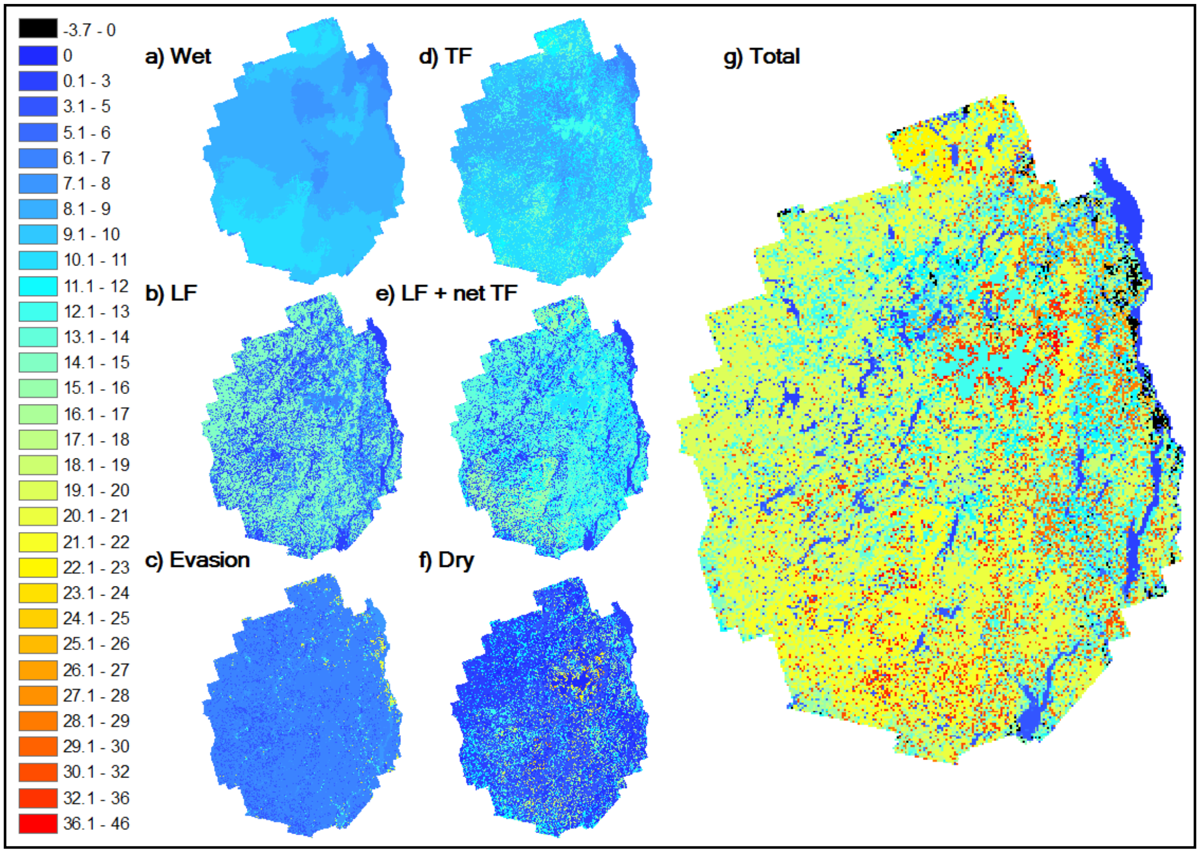
# Appendix A

**Figure A-1. Spatial distribution patterns and pathways of atmospheric mercury deposition (µg/m2 yr) in the Adirondack Park (Yu et al. 2013).**

Inset maps include: a) wet deposition; b) litterfall deposition (LF); c) surface evasion; d) throughfall deposition (TF); e) the sum of LF and net TF (TF - wet deposition); f) the modeled dry deposition (sum of GEM, GOM and PBM deposition); and g) the total net Hg deposition (wet + dry - evasion).



# Appendix B

**Table B-1. Estimated Atmospheric Mercury Deposition (μg/m$^2$yr) at Study Sites Location in the Adirondack Park, New York (Yu et al. 2013)**

| Study Site | Habitat/Location | Elevation (m) | Dry Deposition | Wet Deposition | Surface Evasion | Litterfall Deposition | Throughfall Deposition | Total Net Deposition (μg m-2 yr-1) |
|---|---|---|---|---|---|---|---|---|
| Bloomingdale Bog | *Sphagnum* Bog | 473 | 11.86 | 7.47 | 4.56 | 0.00 | 7.47 | 14.77 |
| Bloomingdale Bog | Hardwood Forest | 473 | 2.78 | 7.40 | 7.00 | 14.70 | 7.62 | 18.10 |
| Madawaska Flow | *Sphagnum* Bog | 487 | 0.00 | 8.47 | 7.00 | 7.00 | 12.11 | 12.11 |
| Madawaska Flow | Hardwood Forest | 487 | 0.00 | 8.53 | 7.00 | 7.00 | 12.19 | 12.19 |
| Massawepie Mire | *Sphagnum* Bog | 467 | 11.83 | 8.46 | 4.56 | 0.00 | 8.46 | 15.73 |
| Massawepie Mire | Hardwood Forest | 467 | 11.83 | 8.46 | 4.56 | 0.00 | 8.46 | 15.73 |
| Spring Pond Bog | *Sphagnum* Bog | 471 | 11.86 | 8.45 | 4.56 | 0.00 | 8.45 | 15.74 |
| Spring Pond Bog | Hardwood Forest | 471 | 2.72 | 8.44 | 7.00 | 14.70 | 8.70 | 19.11 |
| Whiteface Mountain | Hardwood Forest - East | 450 | 2.94 | 9.24 | 7.00 | 14.70 | 9.51 | 20.15 |
| Whiteface Mountain | Hardwood Forest - East | 650 | 2.94 | 9.24 | 7.00 | 14.70 | 9.51 | 20.15 |
| Whiteface Mountain | Hardwood Forest - East | 850 | 2.94 | 9.24 | 7.00 | 14.70 | 9.51 | 20.15 |
| Whiteface Mountain | Spruce/Fir Forest - East | 1075 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Spruce/Fir Forest - East | 1200 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Spruce/Fir Forest - East | 1300 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Alpine Zone - East | 1400 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Hardwood Forest - West | 600 | 3.07 | 8.21 | 7.00 | 14.70 | 8.45 | 19.22 |
| Whiteface Mountain | Hardwood Forest - West | 700 | 2.95 | 9.18 | 7.00 | 14.70 | 9.46 | 20.10 |
| Whiteface Mountain | Spruce/Fir Forest - West | 900 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Spruce/Fir Forest - West | 1150 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Spruce/Fir Forest - West | 1300 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |
| Whiteface Mountain | Alpine Zone - West | 1400 | 0.00 | 8.74 | 7.00 | 7.00 | 12.49 | 12.49 |

# Appendix C

**Table C-1. Blood Mercury Concentrations (µg/g, ww) for Songbird Species Sampled at Bloomingdale Bog Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**

| Species | Number of Individuals | Site | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| **Bog** | **134** | | **0.345 ± 0.351** | **0.018 - 2.815** | | | |
| Cedar Waxwing | 1 | Madawaska Flow | 0.018 | | Bombycillidae | Frugivore | Upper Canopy |
| Common Yellowthroat | 6 | All | 0.321 ± 0.112 | 0.157 - 0.450 | Parulidae | Insectivore | Lower Canopy |
| | 5 | Madawaska Flow | 0.312 ± 0.124 | 0.157 - 0.450 | | | |
| | 1 | Massawepie Mire | 0.359 | | | | |
| Lincoln's Sparrow | 61 | All | 0.251 ± 0.173 | 0.020 - 0.821 | Emberizidae | Omnivore | Ground |
| | 15 | Bloomingdale Bog | 0.107 ± 0.05 | 0.020 - 0.189 | | | |
| | 9 | Madawaska Flow | 0.415 ± 0.212 | 0.037 - 0.678 | | | |
| | 22 | Massawepie Mire | 0.236 ± 0.115 | 0.080 - 0.486 | | | |
| | 15 | Spring Pond Bog | 0.319 ± 0.188 | 0.136 - 0.821 | | | |
| Nashville Warbler | 23 | All | 0.106 ± 0.069 | 0.028 - 0.254 | Parulidae | Insectivore | Lower Canopy |
| | 4 | Bloomingdale Bog | 0.035 ± 0.009 | 0.028 - 0.048 | | | |
| | 7 | Madawaska Flow | 0.126 ± 0.052 | 0.090 - 0.232 | | | |
| | 4 | Massawepie Mire | 0.066 ± 0.027 | 0.049 - 0.107 | | | |
| | 8 | Spring Pond Bog | 0.145 ± 0.079 | 0.046 - 0.254 | | | |
| Swamp Sparrow | 1 | Madawaska Flow | 0.56 | | Emberizidae | Omnivore | Ground |
| Yellow Palm Warbler | 42 | All | 0.617 ± 0.477 | 0.131 - 2.815 | Parulidae | Insectivore | Ground |
| | 9 | Bloomingdale Bog | 0.285 ± 0.084 | 0.131 - 0.376 | | | |
| | 13 | Madawaska Flow | 0.616 ± 0.181 | 0.345 - 0.878 | | | |
| | 6 | Massawepie Mire | 0.975 ± 0.94 | 0.371 - 2.815 | | | |
| | 14 | Spring Pond Bog | 0.679 ± 0.453 | 0.253 - 1.862 | | | |

**Table C-1 continued**

| Species | Number of Individuals | Site | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| **Forest** | **158** | **Forest** | **0.167 ± 0.162** | **0.020 - 1.313** | | | |
| American Redstart | 1 | Spring Pond Bog | 0.112 | | Parulidae | Insectivore | Lower Canopy |
| American Robin | 1 | Bloomingdale Bog | 0.053 | | Turdidae | Vermivore | Ground |
| Blue-headed Vireo | 1 | Madawaska Flow | 0.404 | | Vireonidae | Insectivore | Lower Canopy |
| Canada Warbler | 1 | Spring Pond Bog | 0.106 | | Parulidae | Insectivore | Lower Canopy |
| Hairy Woodpecker | 1 | Massawepie Mire | 0.079 | | Picidae | Insectivore | Bark |
| Hermit Thrush | 63 | All | 0.132 ± 0.086 | 0.020 - 0.536 | Turdidae | Insectivore | Ground |
| | 14 | Bloomingdale Bog | 0.106 ± 0.072 | 0.028 - 0.272 | | | |
| | 12 | Madawaska Flow | 0.096 ± 0.037 | 0.044 - 0.158 | | | |
| | 16 | Massawepie Mire | 0.131 ± 0.071 | 0.051 - 0.354 | | | |
| | 21 | Spring Pond Bog | 0.17 ± 0.112 | 0.020 - 0.536 | | | |
| Magnolia Warbler | 1 | Bloomingdale Bog | 0.064 | | Parulidae | Insectivore | Lower Canopy |
| Ovenbird | 29 | All | 0.077 ± 0.026 | 0.022 - 0.124 | Parulidae | Insectivore | Ground |
| | 12 | Bloomingdale Bog | 0.077 ± 0.031 | 0.022 - 0.124 | | | |
| | 7 | Madawaska Flow | 0.089 ± 0.026 | 0.052 - 0.113 | | | |
| | 8 | Massawepie Mire | 0.069 ± 0.019 | 0.033 - 0.101 | | | |
| | 2 | Spring Pond Bog | 0.068 ± 0.003 | 0.066 - 0.070 | | | |
| Red-eyed Vireo | 42 | All | 0.313 ± 0.226 | 0.054 - 1.313 | Vireonidae | Insectivore | Upper Canopy |
| | 8 | Bloomingdale Bog | 0.274 ± 0.122 | 0.057 - 0.466 | | | |
| | 13 | Madawaska Flow | 0.318 ± 0.206 | 0.054 - 0.699 | | | |
| | 16 | Massawepie Mire | 0.35 ± 0.306 | 0.121 - 1.313 | | | |
| | 5 | Spring Pond Bog | 0.239 ± 0.057 | 0.150 - 0.305 | | | |
| Scarlet Tanager | 1 | Massawepie Mire | 0.061 | | Cardinalidae | Insectivore | Upper Canopy |

**Table C-1 continued**

| Species | Number of Individuals | Site | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| Swainson's Thrush | 2 | All | 0.08 ± 0.035 | 0.055 - 0.105 | Turdidae | Omnivore | Ground |
| | 1 | Bloomingdale Bog | 0.105 | | | | |
| | 1 | Spring Pond Bog | 0.055 | | | | |
| Veery | 1 | Bloomingdale Bog | 0.069 | | Turdidae | Omnivore | Ground |
| White-throated Sparrow | 10 | All | 0.074 ± 0.048 | 0.023 - 0.161 | Emberizidae | Omnivore | Ground |
| | 3 | Bloomingdale Bog | 0.036 ± 0.014 | 0.023 - 0.051 | | | |
| | 4 | Madawaska Flow | 0.055 ± 0.025 | 0.034 - 0.084 | | | |
| | 1 | Massawepie Mire | 0.161 | | | | |
| | 2 | Spring Pond Bog | 0.126 ± 0.008 | 0.120 - 0.131 | | | |
| Yellow-bellied Sapsucker | 1 | Bloomingdale Bog | 0.034 | | Picidae | Omnivore | Bark |
| Yellow-rumped Warbler | 3 | All | 0.292 ± 0.163 | 0.122 - 0.446 | Parulidae | Insectivore | Lower Canopy |
| | 1 | Bloomingdale Bog | 0.122 | | | | |
| | 2 | Madawaska Flow | 0.377 ± 0.097 | 0.309 - 0.446 | | | |

**Table C-2. Individuals Excluded from Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog Analysis (48 Juveniles)**

| Species | Number of Individuals | Site | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| **Bog** | **19** | | **0.136 ± 0.071** | **0.024 - 0.319** | | | |
| Common Yellowthroat | 1 | Madawaska Flow | 0.121 | | Parulidae | Insectivore | Lower Canopy |
| Lincoln's Sparrow | 4 | All | 0.103 ± 0.084 | 0.024 - 0.190 | Emberizidae | Omnivore | Ground |
| | 1 | Bloomingdale Bog | 0.024 | | | | |
| | 2 | Massawepie Mire | 0.114 ± 0.107 | 0.038 - 0.190 | | | |
| | 1 | Spring Pond Bog | 0.159 | | | | |
| Nashville Warbler | 1 | Bloomingdale Bog | 0.026 | | Parulidae | Insectivore | Lower Canopy |
| Song Sparrow | 1 | Spring Pond Bog | 0.099 | | Emberizidae | Omnivore | Ground |
| Yellow Palm Warbler | 12 | All | 0.160 ± 0.064 | 0.097 - 0.319 | Parulidae | Insectivore | Ground |
| | 6 | Bloomingdale Bog | 0.173 ± 0.083 | 0.103 - 0.319 | | | |
| | 6 | Madawaska Flow | 0.148 ± 0.040 | 0.097 - 0.183 | | | |
| **Forest** | **29** | | **0.034 ± 0.033** | **0.008 - 0.168** | | | |
| Hermit Thrush | 15 | All | 0.040 ± 0.039 | 0.008 - 0.168 | Turdidae | Insectivore | Ground |
| | 5 | Bloomingdale Bog | 0.056 ± 0.064 | 0.017 - 0.168 | | | |
| | 7 | Madawaska Flow | 0.028 ± 0.016 | 0.008 - 0.059 | | | |
| | 1 | Massawepie Mire | 0.068 | | | | |
| | 2 | Spring Pond Bog | 0.023 ± 0.009 | 0.017 - 0.030 | | | |
| Magnolia Warbler | 1 | Bloomingdale Bog | 0.109 | | Parulidae | Insectivore | Lower Canopy |
| Ovenbird | 8 | All | 0.025 ± 0.008 | 0.013 - 0.038 | Parulidae | Insectivore | Ground |
| | 4 | Madawaska Flow | 0.029 ± 0.008 | 0.019 - 0.038 | | | |
| | 4 | Massawepie Mire | 0.021 ± 0.006 | 0.013 - 0.027 | | | |
| Dark-eyed Junco | 1 | Spring Pond Bog | 0.012 | | Emberizidae | Omnivore | Ground |
| Swainson's Thrush | 1 | Bloomingdale Bog | 0.01 | | Turdidae _ | Omnivore | Ground |
| White-throated Sparrow | 3 | Madawaska Flow | 0.023 ± 0.004 | 0.020 - 0.028 | Emberizidae | Omnivore | Ground |

# Appendix D

**Table D-1. Mean Total Mercury Concentrations (ng/g, dw) for Invertebrates Sampled at Bloomingdale Bog, Madawaska Flow, Massawepie Mire and Spring Pond Bog: 2008, 2009, 2011**

| Order | Number of Individuals | Community Type | Mean Hg ± SD (ng/g) | Range Hg (ng/g) |
|---|---|---|---|---|
| **Araneae** | **434** | **All** | 323.2 ± 198.6 | 39.4 - 1286.9 |
| | 274 | Bog | 363.3 ± 217.5 | 111.4 - 1286.9 |
| | 160 | Forest | 246.2 ± 125.2 | 39.4 - 896.9 |
| **Coleoptera** | **523** | **All** | 118.6 ± 173.2 | 11.5 - 1436.3 |
| | 184 | Bog | 222.5 ± 282.3 | 21.1 - 1436.3 |
| | 339 | Forest | 77.2 ± 66.7 | 11.5 - 514.9 |
| **Diptera** | **354** | **All** | 203.8 ± 414.5 | 8.2 - 4581.3 |
| | 158 | Bog | 239.5 ± 559.9 | 29.1 - 4581.3 |
| | 196 | Forest | 169.6 ± 189.9 | 8.2 - 1500.0 |
| **Haplotaxida** | **7** | Forest | 179.6 ± 89.3 | 96.6 - 291.1 |
| **Hemiptera** | **87** | **All** | 63.2 ± 57.4 | 14.0 - 188.5 |
| | 20 | Bog | 59.5 ± 53.9 | 16.3 - 187.6 |
| | 67 | Forest | 69.2 ± 64.6 | 14.0 - 188.5 |
| **Hymenoptera** | **237** | **All** | 91.6 ± 78.2 | 10.9 - 331.7 |
| | 211 | Bog | 100.9 ± 86.3 | 10.9 - 331.7 |
| | 26 | Forest | 72.4 ± 56.0 | 11.4 - 201.8 |
| **Julida** | **38** | Forest | 68.8 ± 23.8 | 32.4 - 130.1 |
| **Lepidoptera** | **228** | **All** | 29.5 ± 24.5 | 8.2 - 123.2 |
| | 195 | Bog | 23.6 ± 16.7 | 8.3 - 105.9 |
| | 33 | Forest | 42.5 ± 32.9 | 8.2 - 123.2 |
| **Lithobiomorpha** | **1** | Forest | 151.5 | 151.5 - 151.5 |
| **Mecoptera** | **4** | Forest | 100.5 ± 68.8 | 36.5 - 196.5 |
| **Odonata** | **9** | **All** | 244.9 ± 92.8 | 135.5 - 400.6 |
| | 7 | Bog | 261.9 ± 95.5 | 136.8 - 400.6 |
| | 2 | Forest | 185.6 ± 70.9 | 135.5 - 235.7 |
| **Opiliones** | **3** | Forest | 111.2 ± 35.6 | 82.1 - 150.9 |
| **Orthoptera** | **64** | **All** | 37.4 ± 30.3 | 7.2 - 166.8 |
| | 35 | Bog | 35.1 ± 35.5 | 7.2 - 166.8 |
| | 29 | Forest | 41.2 ± 19.5 | 13.8 - 90.8 |
| **Polydesmida** | **95** | **All** | 37.1 ± 13.3 | 18.9 - 93.5 |
| | 30 | Bog | 37.4 ± 10.2 | 24.2 - 59.6 |
| | 65 | Forest | 37.0 ± 14.5 | 18.9 - 93.5 |
| **Pulmonata** | **13** | **All** | 116.4 ± 97.3 | 23.4 - 359.4 |
| | 1 | Bog | 129.6 | 129.6 - 129.6 |
| | 12 | Forest | 115.0 ± 103.1 | 23.4 - 359.4 |
| **Stylommatophora** | **1** | Forest | 34.2 | 34.2 - 34.2 |

# Appendix E

**Table E-1. Stable Isotope Values ($\delta^{13}C$, $\delta^{15}N$) and Total Mercury Concentrations (ng/g) for Songbird and Invertebrate Species Sampled in *Sphagnum* Bog at Madawaska Flow: 2009**

| | Number of Individuals | Mean $\delta^{13}C$ ± SD | Mean $\delta^{15}N$ ± SD | Mean Blood Mercury (ng/g) ± SD |
|---|---|---|---|---|
| **Songbirds** | | **-25.99 ± 1.21** | **3.88 ± 1.07** | **434.39 ± 323.33** |
| Lincoln's Sparrow | 3 | -26.11 ± 1.57 | 3.70 ± 1.72 | 318.22 ± 325.17 |
| Nashville Warbler | 3 | -24.57 ± 0.26 | 2.92 ± 0.40 | 116.61 ± 32.31 |
| Yellow Palm Warbler | 5 | -26.78 ± 0.35 | 4.55 ± 0.20 | 694.77 ± 193.28 |
| **Invertebrates** | | | | |
| **Herbivores** | **17** | **-26.32 ± 1.23** | **-0.93 ± 2.52** | **16.27 ± 12.94** |
| Aquatic Leaf Beetle | 10 | -25.91 | 2.37 | 21.61 |
| Chain-dotted Geometer | 1 | -27.08 | -0.74 | 13.09 |
| Leafhopper | 2 | -24.78 | -1.64 | 0.002 |
| Marsh Beetle | 4 | -27.51 | -3.69 | 30.38 |
| **Omnivores** | **69** | **-27.04 ± 0.23** | **2.66 ± 0.47** | **147.07 ± 67.35** |
| Ant | 61 | -26.91 ± 0.11 | 2.57 ± 0.63 | 112.76 ± 44.80 |
| Soldier Beetle | 8 | -27.29 | 2.85 | 215.7 |
| **Predators** | **77** | **-27.97 ± 1.79** | **4.71 ± 2.10** | **395.71 ± 404.38** |
| Deer Fly | 20 | -27.71 ± 1.33 | 5.94 ± 0.36 | 54.67 ± 15.11 |
| Ground Beetle | 30 | -27.78 ± 0.74 | 3.62 ± 0.54 | 180.55 ± 49.15 |
| Oodes amaroides | 5 | -31.76 ± 1.24 | 5.82 ± 1.33 | 1181.84 ± 359.81 |
| Predacious Stink Bugs | 1 | -26.37 | 0.66 | 31.5 |
| Spider | 17 | -27.19 ± 0.93 | 4.43 ± 2.46 | 405.06 ± 177.81 |
| Wolf Spider | 4 | -27.21 | 7.49 | 809.53 |
| **Scavengers** | | | | |
| American Carrion Beetle | 1 | -24.57 | 5.52 | 337.34 |

# Appendix F

**Table F-1. Stable Isotope Values ($\delta^{13}C$, $\delta^{15}N$) and Total Mercury Concentrations (ng/g) for Songbird and Invertebrate Species Sampled in Northern Hardwood Forest at Madawaska Flow: 2009**

| | Number of Individuals | Mean $\delta^{13}C$ ± SD | Mean $\delta^{15}N$ ± SD | Mean Blood Mercury (ng/g) ± SD |
|---|---|---|---|---|
| **Songbirds** | | **-25.29 ± 0.44** | **5.12 ± 0.41** | **130.12 ± 88.03** |
| Hermit Thrush | 8 | -25.27 ± 0.53 | 5.34 ± 0.16 | 90.77 ± 38.55 |
| Ovenbird | 1 | -25.01 | 4.34 | 107.09 |
| Red-eyed Vireo | 3 | -25.45 ± 0.03 | 4.81 ± 0.42 | 242.74 ± 109.26 |
| **Invertebrates** | | | | |
| **Detritivores** | **20** | **-24.72 ± 0.75** | **0.28 ± 1.34** | **41.98 ± 24.69** |
| Flat-backed Millipede | 17 | -24.67 ± 0.90 | -0.33 ± 0.71 | 29.64 ± 0.76 |
| Slug | 3 | -24.89 | 2.08 | 79.01 |
| **Herbivores** | **11** | **-27.19 ± 1.88** | **2.69 ± 1.79** | **93.16 ± 91.23** |
| Click Beetle | 4 | -24.96 | 5.49 | 87.62 |
| Leafhopper | 1 | -26.82 | 3.08 | 32.04 |
| Moth | 1 | -28.12 | 2.85 | 0.002 |
| Sawfly Larvae | 2 | -30.17 | 0.8 | 29.36 |
| Shining Leaf Chafers | 3 | -26.53 ± 1.40 | 1.97 ± 1.86 | 204.98 ± 9.61 |
| **Omnivores** | **13** | **-26.06 ± 1.78** | **3.34 ± 0.36** | **63.51 ± 29.64** |
| Camel cricket | 11 | -25.46 ± 0.40 | 3.47 ± 0.31 | 58.07 ± 28.48 |
| Daddy Long Legs | 1 | -29.15 | 2.83 | 100.57 |
| Firefly | 1 | -24.75 | 3.49 | 42.75 |
| **Predators** | **68** | **-27.72 ± 3.05** | **5.52 ± 1.45** | **236.06 ± 409.32** |
| Damselfly | 1 | -34.62 | 5.64 | 235.69 |
| Deer Fly | 5 | -29.25 ± 2.16 | 6.29 ± 0.43 | 754.10 ± 1054.83 |
| Ground Beetle | 32 | -25.64 ± 1.21 | 4.88 ± 0.99 | 49.98 ± 20.86 |
| Mosquito | 6 | -31.16 | 4.35 | 207.42 |
| Oodes amaroides | 1 | -24.72 | 9.31 | 27.16 |
| Spider | 23 | -27.01 ± 0.89 | 4.97 ± 0.45 | 218.09 ± 64.42 |
| **Scavengers** | | | | |
| American Carrion Beetle Larvae | 1 | -27.8 | 6.83 | 216.1 |

# Appendix G

**Table G-1. Stable Isotope Values ($\delta^{13}C$, $\delta^{15}N$) and Total Mercury Concentrations (ng/g) for Songbird and Invertebrate Species Sampled in *Sphagnum* Bog at Bloomingdale Bog: 2009**

| | Number of Individuals | Mean $\delta^{13}C$ ± SD | Mean $\delta^{15}N$ ± SD | Mean Blood Mercury (ng/g) ± SD |
|---|---|---|---|---|
| **Songbirds** | | **-26.48 ± 1.46** | **2.74 ± 1.03** | **169.33 ± 107.62** |
| Yellow Palm Warbler | 2 | -27.03 ± 1.9 | 2.4 ± 0.7 | 252.60 ± 171 |
| Lincoln's Sparrow | 4 | -26.2 ± 1.4 | 2.8 ± 1.2 | 127.68 ± 50 |
| **Invertebrates** | | | | |
| **Detritivores** | **17** | **-25.09 ± 0.09** | **-2.02 ± 0.34** | **66.39 ± 54.78** |
| Flat-backed Millipede | 16 | -25.10 ± 0.12 | -1.92 ± 0.4 | 34.75 ± 0.66 |
| Slug | 1 | -25.08 | -2.21 | 129.64 |
| **Herbivores** | **34** | **-26.38 ± 0.87** | **-3.28 ± 3.69** | **27.01 ± 20.21** |
| Bee | 1 | -24.64 | 1.42 | 14.00 |
| Butterfly | 1 | -26.41 | -2.65 | 44.59 |
| Caterpillar | 1 | -27.43 | -8.27 | 25.20 |
| Chain-dotted Geometer | 15 | -26.65 ± 1.17 | -4.42 ± 0.02 | 12.41 ± 5 |
| Click Beetle | 4 | -26.16 | -1.84 | 63.61 |
| Grasshopper | 2 | -26.50 ± 0.36 | -0.44 ± 6.3 | 36.69 ± 21 |
| Leafhopper | 3 | -25.75 | -5.65 | 0.001 |
| Marsh Beetle | 7 | -27.09 | -6.08 | 24.44 |
| **Omnivores** | | | | |
| Ant | 75 | -25.70 ± 0.16 | -0.86 ± 1.02 | 66.12 ± 13 |
| **Predators** | **32** | **-29.05 ± 8.72** | **2.86 ± 2.38** | **288.33 ± 241.46** |
| Deer Fly | 2 | -54.54 | -1.24 | 305.87 |
| Ground Beetle | 5 | -25.63 ± 0.72 | 2.40 ± 1.5 | 62.77 ± 23 |
| Oodes amaroides | 1 | -32.79 | 7.20 | 761.40 |
| Spider | 24 | -25.92 ± 0.11 | 3.1 ± 1.8 | 370.64 ± 173 |
| **Scavengers** | **5** | **-25.03 ± 1.09** | **9.17 ± 4.94** | **628.18 ± 520.50** |
| American Carrion Beetle | 1 | -24.91 | 11.57 | 1221.83 |
| Burying Beetle | 4 | -25.08 ± 1.5 | 7.9 ± 6.3 | 331.34 ± 114 |

# Appendix H

**Table H-1. Stable Isotope Values ($\delta^{13}C$, $\delta^{15}N$) and Total Mercury Concentrations (ng/g) for Songbird and Invertebrate Species Sampled in Northern Hardwood Forest at Bloomingdale Bog: 2009**

| | Number of Individuals | Mean $\delta^{13}C$ ± SD | Mean $\delta^{15}N$ ± SD | Mean Blood Mercury (ng/g) ± SD |
|---|---|---|---|---|
| **Songbirds** | | **-24.61 ± 0.72** | **5.13 ± 0.67** | **152.36 ± 118.25** |
| Hermit Thrush | 9 | -24.78 ± 0.94 | 4.88 ± 0.73 | 104.6 ± 59 |
| Ovenbird | 4 | -24.25 ± 0.25 | 5.21 ± 0.39 | 86.3 ± 20 |
| Red-eyed Vireo | 4 | -24.56 ± 0.26 | 5.57 ± 0.57 | 325.8 ± 109 |
| **Invertebrates** | | | | |
| **Detritivores** | **8** | **-24.76 ± 0.61** | **1.07 ± 2.98** | **129.07 ± 155.91** |
| Flat-backed Millipede | 6 | -25.26 ± 0.15 | -0.38 ± 0.65 | 33.91 ± 11.7 |
| Little Brown (Julida) Millipede | 1 | -24.08 | -0.47 | 89.01 |
| Slug | 1 | -24.42 | 5.51 | 359.44 |
| **Herbivores** | **92** | **-27.66 ± 1.79** | **1.99 ± 1.87** | **19.48 ± 8.83** |
| Caterpillar | 2 | -25.63 | 0.23 | 29.90 |
| Sawfly Larvae | 3 | -29.72 | 0.43 | 12.80 |
| Weevil | 41 | -26.80 ± 0.34 | 3.579 ± 1.8 | 19.85 ± 11 |
| Leafhopper | 46 | -29.36 | 2.13 | 15.00 |
| **Omnivores** | | | | |
| Camel cricket | 2 | -25.06 ± 0.05 | 3.03 ± 0.97 | 43.22 ± 9.3 |
| **Predators** | **56** | **-25.09 ± 2.15** | **4.36 ± 2.18** | **86.63 ± 59.17** |
| Deer Fly | 2 | -26.28 | 6.58 | 78.59 |
| Ground Beetle | 33 | -25.31 ± 0.75 | 4.64 ± 0.99 | 39.88 ± 3.3 |
| Searcher Beetle | 3 | -24.69 | 5.72 | 35.89 |
| Spider | 18 | -24.60 ± 3.7 | 2.88 ± 2.97 | 152.96 ± 32 |
| **Scavengers** | **2** | **-25.28 ± 0.61** | **7.56 ± 5.47** | **88.02 ± 32.07** |
| Burying Beetle | 1 | -24.85 | 11.44 | 110.69 |
| Margined Carrion Beetle | 1 | -25.71 | 3.69 | 65.34 |
| **Unknown** | | | | |
| Beetle Larvae | 2 | -24.69 ± 1.05 | 4.56 ± 2.04 | 83.3 ± 7.5 |

# Appendix I

**Table I-1. Blood Mercury Concentrations (µg/g, ww) for Songbird Species Sampled on Whiteface Mountain: 2009-2010**

| Species | Number of Individuals | Community Type | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| American Robin | 1 | Spruce-Fir Forest | 0.053 | | Turdidae | Vermivore | Ground |
| Bicknell's Thrush | 23 | All | 0.092 ± 0.031 | 0.051 - 0.180 | Turdidae | Omnivore | Ground |
| | 18 | Spruce-Fir Forest | 0.094 ± 0.030 | 0.054 - 0.180 | | | |
| | 5 | Alpine Zone | 0.084 ± 0.037 | 0.051 - 0.145 | | | |
| Black and White Warbler | 3 | All | 0.065 ± 0.014 | 0.053 - 0.080 | Parulidae | Insectivore | Bark |
| | 2 | Northern Hardwood | 0.071 ± 0.012 | 0.062 - 0.080 | | | |
| | 1 | Spruce-Fir Forest | 0.053 | | | | |
| Blackpoll Warbler | 3 | All | 0.059 ± 0.015 | 0.044 - 0.074 | Parulidae | Insectivore | Upper Canopy |
| | 1 | Spruce-Fir Forest | 0.044 | | | | |
| | 2 | Alpine Zone | 0.066 ± 0.012 | 0.058 - 0.074 | | | |
| Black-throated Blue Warbler | 1 | Northern Hardwood | 0.033 | | Parulidae | Insectivore | Lower Canopy |
| Black-throated Green Warbler | 1 | Northern Hardwood | 0.043 | | Parulidae | Insectivore | Upper Canopy |
| Blue-headed Vireo | 2 | Northern Hardwood | 0.135 ± 0.032 | 0.112 - 0.157 | Vireonidae | Insectivore | Lower Canopy |
| Hermit Thrush | 31 | All | 0.064 ± 0.026 | 0.025 - 0.119 | Turdidae | Insectivore | Ground |
| | 30 | Northern Hardwood | 0.063 ± 0.025 | 0.025 - 0.119 | | | |
| | 1 | Spruce-Fir Forest | 0.108 | | | | |
| Nashville Warbler | 2 | All | 0.040 ± 0.022 | 0.024 - 0.056 | Parulidae | Insectivore | Lower Canopy |
| | 1 | Northern Hardwood | 0.024 | | | | |
| | 1 | Spruce-Fir Forest | 0.056 | | | | |
| Ovenbird | 34 | All | 0.055 ± 0.019 | 0.018 - 0.096 | Parulidae | Insectivore | Ground |
| Red-eyed Vireo | 22 | All | 0.115 ± 0.048 | 0.062 - 0.266 | Vireonidae | Insectivore | Upper Canopy |
| Dark-eyed Junco | 35 | All | 0.052 ± 0.022 | 0.027 - 0.151 | Emberizidae | Omnivore | Ground |

**Table I-1 continued**

| Species | Number of Individuals | Community Type | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| | 5 | Northern Hardwood | 0.070 ± 0.049 | 0.031 - 0.151 | | | |
| | 22 | Spruce-Fir Forest | 0.053 ± 0.012 | 0.034 - 0.077 | | | |
| | 8 | Alpine Zone | 0.037 ± 0.007 | 0.027 - 0.046 | | | |
| Swainson's Thrush | 42 | All | 0.095 ± 0.041 | 0.019 - 0.233 | Turdidae | Omnivore | Ground |
| | 13 | Northern Hardwood | 0.081 ± 0.051 | 0.019 - 0.233 | | | |
| | 27 | Spruce-Fir Forest | 0.102 ± 0.037 | 0.037 - 0.184 | | | |
| | 2 | Alpine Zone | 0.082 ± 0.013 | 0.072 - 0.092 | | | |
| White-throated Sparrow | 31 | All | 0.043 ± 0.024 | 0.023 - 0.153 | Emberizidae | Omnivore | Ground |
| | 1 | Northern Hardwood | 0.030 | | | | |
| | 16 | Spruce-Fir Forest | 0.052 ± 0.030 | 0.027 - 0.153 | | | |
| | 14 | Alpine Zone | 0.035 ± 0.009 | 0.023 - 0.053 | | | |
| Yellow-rumped Warbler | 2 | Spruce-Fir Forest | 0.088 ± 0.009 | 0.081 - 0.094 | Parulidae | Insectivore | Lower Canopy |

**Table I-2. Individuals Excluded from Whiteface Analysis (12 Juveniles, 2 Sharp-shinned Hawks, 1 Winter Wren of Unknown Age)**

| Species | Number of Individuals | Community Type | Mean Hg ± SD (µg/g) | Range Hg (µg/g) | Family | Foraging Guild | Foraging Layer |
|---|---|---|---|---|---|---|---|
| Hairy Woodpecker | 2 | Northern Hardwood | 0.022 ± 0.003 | 0.020 - 0.043 | Picidae | Insectivore | Bark |
| Dark-eyed Junco | 8 | All | 0.077 ± 0.041 | 0.039 - 0.620 | Emberizidae | Omnivore | Ground |
| | 1 | Alpine Zone | 0.039 | | | | |
| | 7 | Spruce-Fir Forest | 0.083 ± 0.041 | 0.060 - 0.581 | | | |
| White-throated Sparrow | 1 | Alpine Zone | 0.031 | | Emberizidae | Omnivore | Ground |
| Winter Wren | 1 | Spruce-Fir Forest | 0.071 | | Troglodytidae | Insectivore | Ground |
| Sharp-shinned Hawk | 1 | Northern Hardwood | 1.723 | | Accipitridae | Carnivore | Air |
| Sharp-shinned Hawk | 1 | Spruce-Fir Forest | 1.122 | | Accipitridae | Carnivore | Air |
| Winter Wren (unknown age) | 1 | Spruce-Fir Forest | 0.101 | | Troglodytidae | Insectivore | Ground |

# Appendix J

**Table J-1. Mean Total Mercury Concentrations (ng/g, dw) for Invertebrates Sampled at Whiteface Mountain: 2009-2010**

| Order | Number of Individuals | Mean Hg ± SD (ng/g) | Range Hg (ng/g) |
|---|---|---|---|
| Araneae | 105 | 211.4 ± 107.3 | 63.1 - 682.5 |
| Coleoptera | 457 | 73.9 ± 53.7 | 13.6 - 505.6 |
| Diptera | 131 | 127.4 ± 65.2 | 11.3 - 312.2 |
| Haplotaxida | 3 | 152.8 | 152.8 - 152.8 |
| Hemiptera | 11 | 65.5 ± 63.5 | 10.9 - 187.4 |
| Hymenoptera | 60 | 72.4 ± 54.4 | 14.7 - 303.6 |
| Julida | 63 | 84.5 ± 52.0 | 33.6 - 333.0 |
| Lepidoptera | 33 | 82.7 ± 133.4 | 15.7 - 705.3 |
| Lithobiomorpha | 4 | 197.6 ± 45.2 | 146.8 - 233.4 |
| Mecoptera | 11 | 216.3 ± 310.8 | 75.9 - 1148.9 |
| Odonata | 1 | 166.4 | 166.4 - 166.4 |
| Opiliones | 3 | 74.7 ± 13.6 | 60.1 - 87.1 |
| Orthoptera | 19 | 43.2 ± 25.3 | 15.8 - 114.5 |
| Polydesmida | 47 | 60.3 ± 116.6 | 21.5 - 772.8 |
| Pulmonata | 42 | 187.7 ± 134.1 | 29.7 - 659.7 |
| Spirobolida | 4 | 390.1 ± 176.2 | 170.4 - 598.5 |
| Stylommatophora | 2 | 156.2 ± 171.5 | 34.9 - 277.4 |

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