Monitoring Spatial Gradients and Temporal Trends of Mercury in Songbirds of New York State, 2013–2017

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Monitoring Spatial Gradients and Temporal Trends of Mercury in Songbirds of New York State, 2013–2017

Final Report

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Abstract

Mercury (Hg) is a global pollutant that impacts New York State songbird populations across many different ecosystems. Currently, songbirds are recognized as critical indicators of mercury in terrestrial ecosystems, where invertivore food webs are able to biomagnify methylmercury (MeHg) to levels that can adversely affect reproductive success in a variety of habitats. To understand the current status of mercury in State songbirds, the Biodiversity Research Institute conducted a five-year study (2013–2017) with the objectives of determining (1) the songbird species, habitats, as well as regions at greatest risk to mercury exposure, (2) how mercury exposure is changing over time in sensitive habitat types, and (3) how mercury is related to habitat, climate, and trophic food webs across the State. Trends of songbird Hg bioavailability were estimated over the entire five-year study period and mercury exposure was stable at most sites sampled, although some sites showed increases—particularly in Long Island. Areas of Hg concern were identified using statewide surveys. Most of these sites were in the core areas of the Adirondacks, Catskills, and Long Island, but new areas of high exposure were observed in the Finger Lakes (e.g., North Montezuma Wildlife Management Area) and New York City regions. Temporal trends in Hg bioavailability were assessed at multiple scales for songbirds. Over the past 100–150 years, Hg exposure increased in many indicator species in the northeastern United States. Mercury in songbird feathers increased from the 1900s to the 1980s, then appears to have stabilized afterward. Mercury exposure was highly variable throughout the State at both regional and site scales. While Long Island, the Catskills, and the Adirondacks had some of the highest Hg concentrations, there was high variability within these regions. Across New York State, wetland area in proximity to the sampling site was an important predictor for songbird Hg exposure, although wetlands in some regions were observed to have a greater effect on songbird concentration levels than others. Long-term climate patterns also influenced Hg exposure concentrations—temperature was a particularly strong effect, as warmer climates tended to have higher songbird Hg. The role of trophic position and diet on Hg exposure was examined using species-level trophic estimates and carbon/nitrogen stable isotope signatures to assess individual-level diet. Species-level information was not a strong predictor of Hg exposure, while individual estimates of trophic level were. The results of this study were also used to provide recommendations for a New York State songbird mercury monitoring plan that can be used to inform future research efforts and assess the bioavailability of mercury across the State.

Keywords

Songbird, Mercury, Bioaccumulation, Methylmercury, Exposure, Risk, Tropic Level, Climate Change Habitat, Foraging Guilds

Acknowledgments

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Summary

Mercury (Hg) is a global pollutant that impacts New York State songbird populations across many different ecosystems. Mercury is transported into an ecosystem from both distant and local sources where it can be converted into methylmercury (MeHg)—a more toxic and environmentally persistent form of Hg. Decreases in Hg deposition rates are expected in the region due to changes to regulations that govern electricity production by the U.S. Environmental Protection Agency, and these policies could lead to less Hg bioavailability in the State. However, MeHg availability is more difficult to manage as it is related to habitat, water quality, climate, and other environmental factors. These complex interactions between Hg deposition and methylation make future Hg bioavailability and the resultant effects on wildlife and humans challenging to curtail and difficult to forecast.

To understand the current status of mercury in New York State songbirds, the Biodiversity Research Institute conducted a five-year study with the objectives of determining (1) the species, habitats, as well as regions at greatest risk to mercury exposure, (2) how mercury exposure is changing over time in sensitive habitats, and (3) how mercury exposure is related to habitat, climate, and trophic food webs across the State. From 2013–2017, 2,425 songbirds have been assessed for Hg exposure in New York State. Blood Hg samples were collected to assess Hg exposure in 104 species across many of the State's regions. The samples were used to (1) evaluate temporal changes in Hg concentrations over the last five years in the core study areas of the Adirondack Mountains, Catskill Mountains, and Long Island and (2) develop predictive models that determine the role of habitat, climate, and trophic level in songbird Hg exposure in a spatially explicit manner. This project focused on the following primary objectives:

1. Conduct annual monitoring at sites in the Adirondack Mountains, Catskill Mountains, and Long Island to both supplement historical Hg songbird samples and to evaluate temporal trends in songbird mercury exposure.
2. Sample sites statewide to identify new areas, species, and habitats with high potential for Hg exposure.
3. Relate mercury exposure with trophic position, diet, and habitat use by utilizing stable isotope signatures of carbon and nitrogen.
4. Use museum specimens of songbirds to quantify trends in Hg exposure over the 20th century.
5. Use data from all Hg sampling to determine (1) the role that habitat and climate play in songbird Hg exposure and (2) how changes to these environmental conditions could affect Hg risk in the future.

Using quantitative techniques that are designed to control for random variation in songbird sampling, analyses were conducted that addressed each of these questions. For Objective 1, trends of songbird Hg bioavailability were estimated over the entire five-year study period. Mercury exposure trends were flat at most sites sampled in the core study areas. Some sites showed increases—particularly in Long Island. To address Objective 2, areas of Hg concern were identified using statewide surveys. Using Hg risk thresholds established in previous studies, the sites had species at moderate risk or greater were selected. Most of these sites were in the core areas of the Adirondacks (Madawaska Flow), Catskills (Sam's Point), and Long Island (North Cinder and Green Sedge Islands), but new areas of high exposure were observed in the Finger Lakes (North Montezuma Wildlife Management Area) and New York City (Sawmill Creek). These sites possess freshwater and estuarine wetlands with many species at risk to reproductive effects of Hg exposure, ranging from saltmarsh sparrows and seaside sparrows in tidal marshes to common yellowthroats, swamp sparrows, warbling vireos, and gray catbirds in palustrine systems.

In Objective 3, the role of trophic position and diet on Hg exposure was assessed using species-level trophic estimates and carbon/nitrogen stable isotope signatures to determine individual-level foraging patterns. Species-level information was not a strong predictor of Hg exposure while individual estimates of trophic level were. Moreover, there were regional differences in the relations between nitrogen stable isotopes and Hg concentrations, which illustrates the associations between trophic level and Hg exposure can be variable across different ecosystems. These data suggest that while species-level behavior patterns provide the potential for examining Hg exposure, individual dietary preferences and local trophic food web complexity are what turns this potential into actual exposure levels.

In addition to quantifying recent trends in Hg bioavailability, Objective 4 provided context for current Hg levels by using museum samples to examine the last 100–150 years of Hg exposure for northeastern songbirds. For most indicator species that were selected for the study, songbird Hg exposure increased from 1900 to 1980, then stabilized for the next 37 years. These increases correspond to a rise in industrialization and Hg emissions in North America. Several species of conservation concern, wood thrush, rusty blackbirds, and saltmarsh sparrows, saw significant increases in feather Hg from the turn of the 19th century, some species showed over an order of magnitude increase.

For Objective 5, the associations of landscape and climate factors with Hg bioavailability were quantified. Wetland areas in proximity to the sampling site w the most important habitat-related predictor for songbird Hg exposure. The importance of wetlands varied around the State; Hg methylation varies due to differences in wetland type, hydrological regimes (e.g., timing of the wet-dry cycle), and water quality. The regional differences were likely a reflection of this variation. Long-term climate patterns also influenced Hg exposure concentrations—temperature was a particularly strong effect as warmer climates tended to correlate with higher songbird Hg. This effect had high-regional variation and could indicate that forecasted changes to the New York State climate could have wide ranging and spatially explicit effects on Hg bioavailability.

To achieve the objectives of this study an extensive and intensive Hg monitoring effort was designed and implemented over the five-year study period. The lessons learned during this multiyear project can be used to create monitoring recommendations to inform future efforts. First, a suite of songbird indicator species was identified for each region of New York State that increase the confidence that Hg bioavailability is detected. Second, we provided a framework for sampling site selection and sample collection that minimizes uncertainty in songbird Hg bioavailability assessments and is robust to a variety of sampling conditions. Third, we suggested additional information that can be collected to help answer specific questions about the causes and consequences of Hg bioavailability.

In conclusion, the dynamics of Hg bioavailability is related to many complex ecological processes across New York State. Mercury exposure varies across species, regions, sites, trophic niches, habitats, and climate regimes. In the future, climate change is expected to directly alter temperature, precipitation, and other weather patterns that in turn will affect songbird communities, habitat, and trophic relations throughout the State. Moreover, while policy changes have reduced emissions, it is unclear how deposition rates will change in the future and the extent to which deposition rates predict Hg bioavailability. National and international policies relating to controlling Hg emissions are currently under development or in flux and this uncertainty emphasizes the importance of continued monitoring of Hg availability in New York State's ecosystems. Taken together with the results of this study, it seems there will be considerable uncertainty in future Hg bioavailability in the State. Continued assessments of Hg bioavailability will be important to track the potential effects of Hg and to inform management decisions. Future research on understanding the small- and large-scale effects of a changing climate on Hg bioavailability across multiple ecosystems will be critical to accurately forecast the effects of Hg on New York State ecosystems and to safeguard ecological and human health in the coming century.

1 Introduction

Mercury (Hg) is a pollutant that is globally distributed, but locally variable in availability for biomagnification and bioaccumulation (Evers and Clair 2005, Driscoll et al. 2013). After being emitted to the atmosphere from natural (e.g., volcanoes) and anthropogenic (e.g., coal-fired power plants, municipal incinerators, etc.) sources, Hg can be globally transported on air currents and deposited on habitats far from the original sources (Vanarsdale et al. 2005, Driscoll et al. 2007). Additionally, Hg can enter habitats from local sources through atmospheric deposition (e.g., municipal incinerators in the Everglades or small-scale artisanal gold mining in the Amazon; Telmer and Veiga 2009, Gibb and O'Leary 2014) or via soil and/or water contamination from industrial activities (e.g., Superfund sites; Amos et al. 2013). Once deposited, microorganisms convert inorganic Hg to methylmercury (MeHg)—a more toxic, environmentally persistent form that has high potential for bioaccumulation and biomagnification in both aquatic and terrestrial ecosystems (Ullrich et al. 2001, Podar et al. 2015).

In vertebrates, and specifically avian communities, numerous neurological, immunological, and physiological effects have been documented as a result of MeHg exposure (Scheuhammer et al. 2007, Hawley et al. 2009, Wada et al. 2009) and these effects can influence life history parameters and alter demographic rates for populations (Brasso and Cristol 2008, Evers et al. 2008, Jackson et al. 2011, Whitney and Cristol 2017). Currently, songbirds are recognized as critical indicators of mercury in terrestrial ecosystems, where invertivore food webs are able to biomagnify methylmercury to levels that can adversely affect reproductive success in a variety of habitats (Cristol et al. 2008, Evers et al. 2012, Jackson et al. 2015). Songbirds species that are generalist invertivores, like many warblers, vireos, wrens, some sparrows, and thrushes, have been utilized in many studies to provide a representation of MeHg levels in various habitat types (Rimmer et al. 2005, Lane et al. 2011, Townsend et al. 2014). Birds are indicative of the amounts of bioavailable MeHg in the associated food chain when other indicators, like fish or amphibians, are absent. Due to the complexity of the various processes related to MeHg exposure in vertebrates and the associated impacts on wildlife and human health, it is particularly important that research efforts better assess and monitor MeHg exposure levels across a variety of ecosystems and taxa in New York State.

Environmental changes are predicted over the next century in New York State, and these changes could potentially affect the bioavailability of Hg to songbirds. Mercury methylation rates are related to water quality (Miskimmin et al. 1992, Sellers et al. 1996), water temperature (Ramlal et al. 1993), and precipitation in wetland environments. All of these environmental variables are likely to be affected by the predicted changes to air temperature and precipitation over the next century (Meehl et al. 2007, Schindler 2001). In arctic ecosystems, changes in climate also could release local stores of Hg in soils and ice, which would create local sources that could further increase MeHg bioavailability in habitats with high Hg methylation rates (Stern et al. 2012). Complicating this process further is the expected effects of climate change on the abundance and distribution of wetland habitat in the northeastern United States (Craft et al. 2009, Kirwan et al. 2010, Kirwan and Megonigal 2013, Mitsch and Hernandez 2013, Schile et al. 2014), which could change the amount and location of Hg methylation throughout the region. Finally, changes to Hg emissions rates over time (Zhang et al. 2016) and weather-dependent deposition rates (Mao et al. 2017) could also impact Hg bioavailability. Ultimately, as the locations where most Hg methylation occurs and the environmental conditions that promote them change, it becomes increasingly difficult to predict the future of Hg bioavailability.

In the face of uncertainty in Hg emissions, deposition, and methylation rates, indicator species become increasingly important to monitor changes in contaminant bioavailability and quantify risk to populations and ecosystems. This project was designed to provide information on spatial and temporal trends of MeHg in New York State by sampling songbirds across the landscape over a five-year period. These data can then be applied to predictive models that will aid regulators and researchers in their efforts to describe and minimize the risk Hg poses to biota. This project builds on previous long-term Hg monitoring studies on songbirds across the Northeast (e.g., Lane et al. 2011, Evers et al. 2012, Lane et al. in review), as well as 14 years of mercury research sponsored by New York State Energy Research and Development Authority (NYSERDA), through Environmental Monitoring, Evaluation, and Protection (EMEP) projects #22258, #25929 and #30388. Over 4,500 blood and 2,200 tail and/or flank feather samples have been collected from songbirds in the State since 2000. From 2013–2017, this project focused on the following primary objectives:

1. Conduct annual monitoring at sites in the Adirondack Mountains, Catskill Mountains, and Long Island to both supplement historical Hg songbird samples and to evaluate temporal trends in songbird mercury exposure.
2. Sample sites statewide to identify new areas, species, and habitats with high potential for Hg exposure.

3. Relate mercury exposure with trophic position, diet, and habitat use by utilizing stable isotope signatures of carbon and nitrogen.
4. Use museum specimens of songbirds to quantify trends in Hg exposure over the 20th century.
5. Use data from all Hg sampling to determine (1) the role that habitat and climate play in songbird Hg exposure and (2) how changes to these environmental conditions could affect Hg risk in the future.

By combining previous Hg monitoring work with an influx of new data using a strong experimental design, knowledge of Hg in songbirds across New York State will be considerably improved. Central to the approach is developing predictive models that can identify areas of concern for Hg availability where long-term monitoring would be most effective and to conduct additional sampling efforts to fill data gaps. Results from this project will assist in the development of long-term strategies for Hg monitoring activities in New York State moving forward.

2 Methods

2.1 Sampling Design and Study Areas

Sampling sites were selected across New York State based on the following criteria: (1) previous Hg sampling efforts for songbirds or other biota, (2) habitat sensitivity to MeHg bioaccumulation, and (3) proximity of Hg emission sources. Two types of sampling sites, core and statewide, were selected using differential weighting of these criteria. Core sites were identified to estimate temporal trends in Hg bioavailability (Objective 1) by sampling songbirds during all five years of the study (Table 1, Figure 1). Four sampling sites were selected in each of three core regions: Adirondack Mountains, Catskill Mountains, and Long Island. Core sites were located in these regions that are known to have high levels of Hg in songbirds and, while they meet the second and third criteria for selection, they were primarily selected due to the large amounts of data previously collected at these sites and strong evidence of consistently elevated tissue Hg levels (Driscoll et al. 2007, Evers et al. 2007). Additionally, the individual regions were selected based on specific Hg exposure and bioavailability issues represented in that region. The primary focus of the Adirondacks core region was to monitor Hg availability in environments where soil acidification complicated Hg methylation. Study sites in the Adirondack Park included high-elevation Sphagnum bog and wetland habitats (Spring Pond Bog, Massawepie Mire) and a mix of deciduous and coniferous upland forests types (Buck Creek, Honnedaga Lake). Mercury monitoring in the Catskills region was designed to assess environmental Hg levels in high risk forested areas near New York City. Sites in this region were representative of large wetland complexes (Bashakill Wildlife Management Areas), upland deciduous forest (Black Rock Forest), and high-altitude, mixed pine-oak forest types (Sam's Point Preserve). Study sites in the Long Island region focused on both freshwater and estuarine wetland habitats (Mashomack Preserve, North Cinder Island) found at coastal locations in the State. Tidal marsh habitat is rare in New York and these sites were focused on monitoring this sensitive habitat type. Each core region also has a nearby Mercury Deposition Network (MDN) atmospheric Hg monitoring station for comparative analysis with Hg levels in biota.

Statewide sites were designed to be visited at least once during the five-year study (although sometimes sites in a statewide region were visited in different years). These sites were used for identifying and mapping new Hg areas of concern and species of concern (Objective 2). For statewide sites, previous information of songbird Hg exposure was not required, but similar to the selection process used for the core sites, the remaining two selection criteria were used for site identification. Data from the Biodiversity Research Institute (BRI) songbird Hg database was also used to inform the selection of sites with little or no prior Hg exposure information. Consequently, five additional regions were identified for statewide sampling: Western New York/Lake Ontario, Northern New York, Tug Hill Plateau, New York City, and the Finger Lakes region. Sites in the Western New York/Lake Ontario region were comprised of mixed forest, forested wetlands, and emergent freshwater wetlands (Bergen Swamp, Tonawanda Wildlife Management Area). Study sites in Northern New York included a mix of alvar grasslands (Chaumont Barrens Preserve), large wetland complexes (Lake Alice Wildlife Management Area) and spruce bog/cedar swamp habitats (Silver Lake Bog). Tug Hill Plateau included sites representing habitat types, such as deciduous upland forests and marsh-beaver meadow complexes (Happy Valley Wildlife Management Area, Cody Brook Club). Study sites in the greater New York City region included entirely estuarine forested and emergent marshes. Finger Lakes study sites were represented by several marsh and large wetland complexes interspersed with forest (North Montezuma and Catherine's Creek Wildlife Management Areas). Within each region, a total of four to six statewide sites were sampled on one occasion to assess exposure levels in songbird blood mercury at each site. Additional blood samples, also concurrently collected by a colleague, were analyzed and included in the analysis from study sites on the Albany Pine Bush Preserve, as designated in the Capital Region (Table 1, Figure 1).

Table 1. Latitude and Longitude of Songbird Sampling Sites

Core regions (Adirondacks, Catskills, and Long Island), statewide regions (Finger Lakes, Northern New York, New York City, Tug Hill Plateau, and Western NY/Lake Ontario) and associated study sites, 2013–2017, New York.

Region	Study Site	Latitude	Longitude
Adirondacks	Arbutus Lake	43.99511	-74.24442
	Bloomingdale Bog	44.3822	-74.14
	Buck Creek	43.74282	-74.71172
	Ferd's Bog	43.78832	-74.75043
	Honnedaga Lake	43.53171	-74.85326
	Madawaska Flow	44.51316	-74.40331
	Massawepie Mire	44.23495	-74.66694
	Rock Lake	43.97143	-74.87717
	Spring Pond Bog	44.37317	-74.50306
Capital Region	Albany Pine Bush Preserve	42.725	-73.875

Table 1 continued

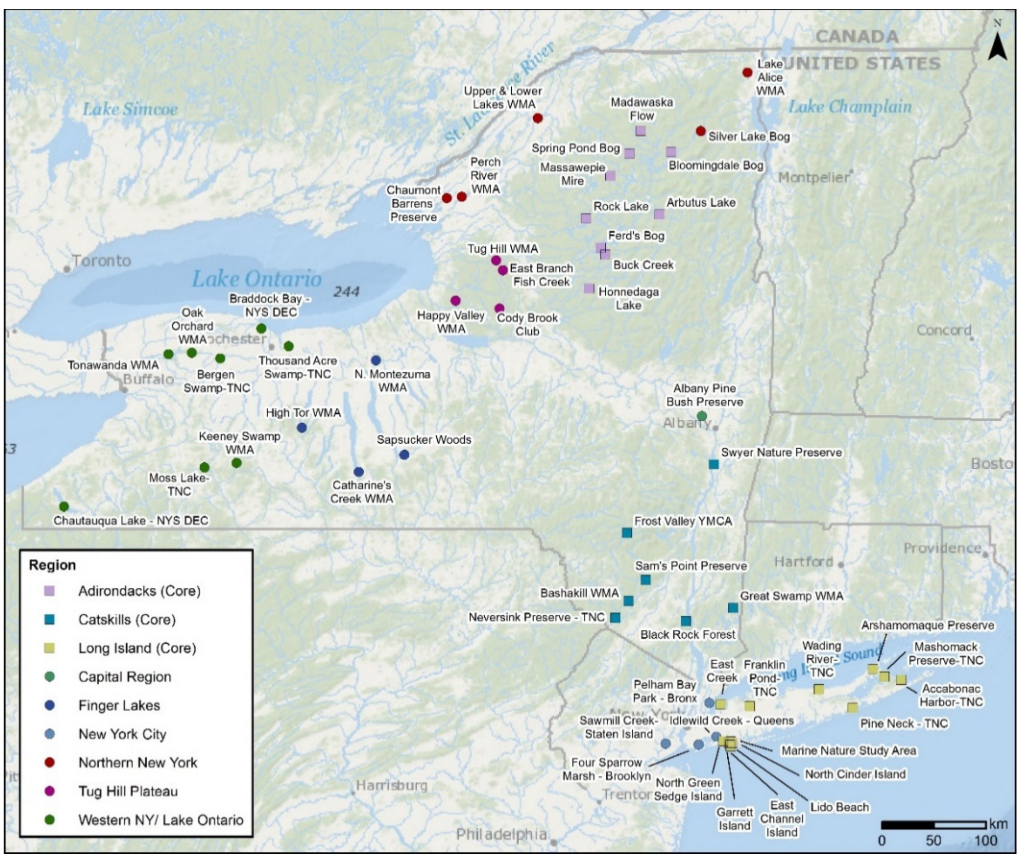
Region	Study Site	Latitude	Longitude
Catskills	Bashakill Wildlife Management Area	41.53693	-74.51047
	Black Rock Forest	41.40575	-74.01349
	Frost Valley YMCA	41.97622	-74.52305
	Great Swamp Wildlife Management Area	41.49204	-73.60403
	Neversink Preserve - The Nature Conservancy	41.42835	-74.62302
	Sam's Point Preserve	41.67217	-74.36057
	Swyer Nature Preserve	42.41623	-73.77046
Finger Lakes	Catharine's Creek Wildlife Management Area	42.36855	-76.84705
	Cornell University - Sapsucker Woods	42.47871	-76.45144
	High Tor Wildlife Management Area	42.65207	-77.34051
	North Montezuma Wildlife Management Area	43.07841	-76.69769
Long Island	Accabonac Harbor- The Nature Conservancy	41.02501	-72.1467
	Arshamomaque Preserve	41.09423	-72.39146
	East Channel Island	40.59885	-73.63123
	East Creek	40.86502	-73.71077
	Franklin Pond-The Nature Conservancy	40.85226	-73.46109
	Garrett Island	40.61063	-73.6383
	North Green Sedge Island	40.62184	-73.68868
	Lido Beach	40.58899	-73.62553
	Marine Nature Study Area	40.62116	-73.6231
	Mashomack Preserve-The Nature Conservancy	41.0456	-72.29373
	North Cinder Island	40.61223	-73.60978
	Pine Neck-The Nature Conservancy	40.84137	-72.56571
	Wading River-The Nature Conservancy	40.96158	-72.85778
Northern New York	Chaumont Barrens Preserve	44.09657	-76.08284
	Lake Alice Wildlife Management Area	44.87149	-73.48108
	Perch River Wildlife Management Area	44.105	-75.95466
	Silver Lake Bog	44.51109	-73.88403
	Upper & Lower Lakes Wildlife Management Area	44.59141	-75.29627
New York City	Four Sparrow Marsh - Brooklyn	40.6003	-73.9039
	Idlewild Creek - Queens	40.6528	-73.7517
	Pelham Bay Park - Bronx	40.87446	-73.81256
	Sawmill Creek - Staten Island	40.6067	-74.1908

Table 1 continued

Region	Study Site	Latitude	Longitude
Tug Hill Plateau	Cody Brook Club	43.40683	-75.62785
	East Branch Fish Creek	43.64675	-75.59986
	Happy Valley Wildlife Management Area	43.45503	-76.00911
	Tug Hill Wildlife Management Area	43.70736	-75.65703
Western NY/ Lake Ontario	Bergen Swamp-The Nature Conservancy	43.09142	-78.0479
	Braddock Bay - NYS DEC	43.28082	-77.69221
	Chautauqua Lake - NYS DEC	42.14691	-79.40166
	Keeney Swamp Wildlife Management Area	42.42569	-77.90788
	Moss Lake-The Nature Conservancy	42.39697	-78.18491
	Oak Orchard Wildlife Management Area	43.12792	-78.29466
	Thousand Acre Swamp-The Nature Conservancy	43.16838	-77.45518
	Tonawanda Wildlife Management Area	43.11752	-78.49653

Figure 1. New York State Songbird Sampling Locations, 2013–2017

Locations where songbirds were captured and sampled for blood and feather mercury. Core regions with sites that were sampled across all five years of the study are labeled.



Almost all sites that were selected were not under active management or any experimental manipulation during the time of the study. One core site, Honnedaga Lake in the Adirondacks, was part of a long-term experimental treatment as part of another study that could affect Hg bioavailability at the site (liming of watersheds). While this study does account for differences in sampling sites, the effects of experimental treatments at the Honnedaga Lake site are not directly addressed.

2.2 Bird Capture and Tissue Sampling

All bird capture and blood and feather sampling was conducted during periods of peak breeding activity in June and July from 2013–2017. Non-lethal, mist-netting techniques used 12-meter (m) nylon, mist nets with a 30-millimeter (mm) mesh. Nets were open for passive capture for at least 2 hours. During this period, a series of recorded conspecific vocalizations were also used to elicit a territorial response from breeding birds and attract them to the net location. This "playback" system was utilized at nets to increase the capture rate of songbirds at the site. While all passerines and near-passerines captured were sampled, territorial songs were used from species that are known to be sensitive to environmental Hg levels (Evers et al. 2012). Thus, our sampling scheme focused on capturing invertivorous species that are known to forage in or near wetlands, but non-target species were captured through chance encounters with the mist net arrays. While this prevents our sampling scheme from being random, it increases the accuracy of patterns of Hg exposure across many sites (see Table 2 for a list of all species captured).

Table 2. Songbird Species Sampled in New York State, 2013–2017

Alpha codes, common names, and scientific names of all species sampled over the course of this study.

Species Code	Common Name	Scientific Name
ACFL	Acadian flycatcher	*Empidonax virescens*
AMGO	American goldfinch	*Spinus tristis*
AMOY	American oystercatcher	*Haematopus palliates*
AMRE	American redstart	*Setophaga ruticilla*
AMRO	American robin	*Turdus migratorius*
BAOR	Baltimore oriole	*Icterus galbula*
BARS	barn swallow	*Hirundo rustica*
BAWW	black-and-white warbler	*Mniotilta varia*
BBCU	black-billed cuckoo	*Coccyzus erythropthalmus*
BCCH	black-capped chickadee	*Poecile atricapillus*
BEKI	belted kingfisher	*Ceryle alcyon*
BGGN	blue-gray gnatcatcher	*Polioptila caerulea*
BHCO	brown-headed cowbird	*Molothrus ater*
BHVI	blue-headed vireo	*Vireo solitarius*
BLBW	Blackburnian warbler	*Setophaga fusca*

Table 2 continued

Species Code	Common Name	Scientific Name
BLJA	blue jay	*Cyanocitta cristata*
BLSK	black skimmer	*Rynchops niger*
BRCR	brown creeper	*Certhia americana*
BRTH	brown thrasher	*Toxostoma rufum*
BTBW	black-throated blue warbler	*Setophaga caerulescens*
BTNW	black-throated green warbler	*Setophaga virens*
BWWA	blue-winged warbler	*Vermivora cyanoptera*
CARW	Carolina wren	*Thryothorus ludovicianus*
CAWA	Canada warbler	*Cardellina canadensis*
CEDW	cedar waxwing	*Bombycilla cedrorum*
CHSP	chipping sparrow	*Spizella passerina*
CLRA	clapper rail	*Rallus crepitans*
COGR	common grackle	*Quiscalus quiscula*
COTE	common tern	*Sterna hirundo*
COYE	common yellowthroat	*Geothlypis trichas*
CSWA	chestnut-sided warbler	*Setophaga pensylvanica*
DOWO	downy woodpecker	*Picoides pubescens*
EABL	eastern bluebird	*Sialia sialis*
EAPH	eastern phoebe	*Sayornis phoebe*
EATO	eastern towhee	*Pipilo erythrophthalmus*
EAWP	eastern wood-pewee	*Contopus virens*
FISP	field sparrow	*Spizella pusilla*
GCFL	great crested flycatcher	*Myiarchus crinitus*
GCKI	golden-crowned kinglet	*Regulus satrapa*
GRCA	gray catbird	*Dumetella carolinensis*
GRSH	great shearwater	*Ardenna gravis*
GWWA	golden-winged warbler	*Vermivora chrysoptera*
HAWO	hairy woodpecker	*Picoides villosus*
HETH	hermit thrush	*Catharus guttatus*
HOFI	house finch	*Haemorhous mexicanus*
HOWR	house wren	*Troglodytes aedon*
INBU	indigo bunting	*Passerina cyanea*
LESA	least sandpiper	*Calidris minutilla*
LISP	Lincoln's sparrow	*Melospiza lincolnii*
LOWA	Louisiana water thrush	*Parkesia motacilla*
MAWA	magnolia warbler	*Setophaga magnolia*
MAWR	marsh wren	*Cistothorus palustris*
MODO	mourning dove	*Zenaida macroura*
MYWA	yellow-rumped warbler	*Setophaga coronata*
NAWA	Nashville warbler	*Oreothylpis ruficapilla*
NOCA	northern cardinal	*Cardinalis cardinalis*

Table 2 continued

Species Code	Common Name	Scientific Name
NOMO	northern mockingbird	*Mimus polyglottos*
NOPA	northern parula	*Setophaga americana*
NOWA	northern water thrush	*Parkesia noveboracensis*
OROR	orchard oriole	*Icterus spurius*
OSPR	osprey	*Pandion haliaetus*
OVEN	ovenbird	*Seiurus aurocapilla*
PIWA	pine warbler	*Setophaga pinus*
PRAW	prairie warbler	*Setophaga discolor*
PUFI	purple finch	*Haemorhous purpureus*
RBGR	rose-breasted grosbeak	*Pheucticus ludovicianus*
RBNU	red-breasted nuthatch	*Sitta canadensis*
REVI	red-eyed vireo	*Vireo olivaceus*
RWBL	red-winged blackbird	*Agelaius phoeniceus*
SALS	saltmarsh sparrow	*Ammodramus caudacutus*
SAVS	savannah sparrow	*Passerculus sandwichensis*
SCJU	slate-colored junco	*Junco hyemalis*
SCTA	scarlet tanager	*Piranga olivacea*
SESA	semipalmated sandpiper	*Calidris pusilla*
SESP	seaside sparrow	*Ammodramus maritimus*
SOSP	song sparrow	*Melospiza melodia*
SSHA	sharp-shinned hawk	*Accipiter striatus*
SWSP	swamp sparrow	*Melospiza georgiana*
SWTH	Swainson's thrush	*Catharus ustulatus*
TRES	tree swallow	*Tachycineta bicolor*
TRFL	traill's flycatcher	*Empidonax traillii*
TUTI	tufted titmouse	*Baeolophus bicolor*
VEER	veery	*Catharus fuscescens*
VIRA	Virginia rail	*Rallus limicola*
WAVI	warbling vireo	*Vireo gilvus*
WBNU	white-breasted nuthatch	*Sitta carolinensis*
WEWA	worm-eating warbler	*Helmitheros vermivorum*
WIFL	willow flycatcher	*Empidonax traillii*
WOTH	wood thrush	*Hylocichla mustelina*
WTSP	white-throated sparrow	*Zonotrichia albicollis*
YBFL	yellow-bellied flycatcher	*Empidonax flaviventris*
YBSA	yellow-bellied sapsucker	*Sphyrapicus varius*
YEWA	yellow warbler	*Setophaga petechia*
YPWA	yellow palm warbler	*Setophaga palmarum*
YTVI	yellow-throated vireo	*Vireo flavifrons*

Once captured, each bird was banded with a uniquely numbered USGS aluminum band. During processing, age, sex, reproductive status, wing chord length, tarsus length, mass and fat score were recorded. Blood samples were collected via venipuncture of the cutaneous ulnar vein with a 27-gauge sterile disposable needle. Fifty to 75 µl of whole blood was collected into heparinized, Mylar-wrapped capillary tubes for Hg and stable isotope analysis. The capillary tubes were sealed with Critocaps® and stored in plastic vacutainers on ice for up to six hours before freezing at -17° Celsius. All birds were released unharmed within 10–25 minutes of capture.

Two tail feathers (R6) were also collected from each bird, and one primary feather (P1) was collected from sparrows on Long Island to connect results from this project to past tidal marsh sparrow monitoring efforts. To support the long-term Hg trend analysis (Objective 4), approximately 5–6 flank feathers were collected from all songbirds for comparison with archived museum feather specimens from the Harvard Museum of Comparative Zoology to evaluate current levels of Hg availability with historical Hg levels from the 19th–20th centuries (Perkins et al. 2019). As Hg concentrations can vary by feather type it is important to use the same feather types for comparative analysis. Due to general sampling restrictions and feather availability for museum specimens, flank feathers were selected and analyzed for both contemporary and historical specimens.

2.3 Laboratory Analysis

2.3.1 Avian Tissues Total Mercury Analysis

All whole blood, body, and flight feather samples were analyzed for total Hg. Mercury concentrations in blood reflect recent dietary uptake. Samples were collected during the breeding period, and thus reflect a bird's Hg exposure at its breeding habitat. Methylmercury was not analyzed because approximately 95% of total Hg in songbird blood and feathers is in the form of MeHg (Rimmer et al. 2005, Edmonds et al. 2010). Blood Hg concentrations are expressed in µg/g, wet weight (ww).

Blood samples were analyzed for total mercury at BRI's Wildlife Mercury Research Laboratory in Portland, Maine, using direct combustion/trapping atomic absorption method on a Milestone DMA 80. This approach has been incorporated by the U.S. Environmental Protection Agency (EPA) in EPA SW-846 Method 7473. Calibration utilized a blank and two standards (CE-464 and DOLT-5), one for each of the two detector cells. Instrument response was evaluated immediately following calibration, after every 20 samples, and at the end of each analytical run by analyzing two certified reference materials and a blank.

2.3.2 Feather Analysis for Methylmercury

Flank feather samples from nine species of birds were collected from archived specimens at the Museum of Comparative Zoology at Harvard University. Flank feather specimens were sampled from the 19th and early 20th centuries to compare with mercury data of modern-day birds using the BRI songbird database. Feathers collected from museum specimens were analyzed for MeHg at the John A. Paulson School of Engineering & Applied Sciences Laboratory at Harvard University, as inorganic Hg was historically used to preserve museum specimens, which would increase total mercury (THg) values and bias results. Therefore, a modified EPA 1630 method, which was established through previous work, was used to analyze MeHg in feathers. Samples were spiked with 1 milliliter (mL) of enriched $Me^{201}Hg$ (2 ng/mL; nanograms per milliliter) and then digested with 5N HNO_3 solution at 70°C overnight prior to MeHg analysis. Two certified reference materials (TORT 3 and DORM 4) were included in each digestion cycle. Acid was neutralized with 8N KOH and buffered with a 2 mega (M) acetate buffer. Aqueous MeHg was ethylated using sodium tetraethylborate ($NaBEt_4$). Ethylated MeHg was purged onto a Tenax packed column and separated by gas chromatography using a Tekran 2700 MeHg autoanalyzer coupled to a Thermo iCAP-Q ICP-MS with Teflon tubing for MeHg detection. Ongoing precision and recovery (OPR) standards were analyzed with different concentrations every 10 samples.

2.3.3 Blood Analysis for Stable Isotopes of Carbon and Nitrogen

A total of 1,018 songbird blood samples were analyzed at the Boston University Stable Isotope Laboratory in Boston, Massachusetts for stable carbon and nitrogen isotope ratios. Isotopic signatures are used to provide an estimate of relative position in the food web (Objective 3).

Bird blood was analyzed using automated continuous-flow isotope ratio mass spectrometry (Michener and Lajtha 2007). Blood was transferred from capillary tubes into pre-weighed tin capsules. Assuming a content of 70% water, approximately 1.3 milligrams (mg) of blood was added to the capsules. All capsules were oven dried at 60˚C for 24 hours and then reweighed for dry mass. The capsules were then folded and compressed prior to analysis. The samples were combusted in a EuroVector Euro EA elemental analyzer. The combustion gases (N_2 and CO_2) were separated on a gas chromatography (GC) column, passed through a reference gas box and introduced into a GV Instruments IsoPrime isotope ratio mass spectrometer; water was removed using a magnesium perchlorate water trap.

2.4 Climate, Habitat, Foraging Niche Data Acquisition

Additional covariates to help explain songbird Hg concentrations were collected from a variety of publicly available databases (Objective 5). To describe patterns of biomagnification, standardized diet composition data for each species were collected from the Wilman et al. (2014) database. The percentage of year-round diet comprised of invertebrates was extracted for each species, which serves as a relative measure of trophic-related mercury exposure risk (Cristol et al. 2008. Jackson et al. 2015).

Land cover data were gathered from the National Land Cover Database 2011 (Homer et al. 2015). Land cover categories were then summarized and assigned from available categories. The three categories of forest habitat (Deciduous Forest, Evergreen Forest, and Mixed Forest) were combined into a single category of titled Forest. Similarly, the two wetland habitat categories (Woody Wetlands and Emergent Herbaceous Wetlands) were combined into a single category of titled Wetlands. Then the area of these aggregated categories was summed within a 100m radius circle around the capture location of each sample (i.e., the capture net).

Climate data were gathered from downscaled BCSD-CMIP5 climate projections.[1] Monthly archival climate data (collected from 1950–2000) and climate projection data for multiple scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) were acquired at the scale one-eighth-degree grid from the hydrology projection set. The capture location of all birds in our database was associated with the 50-year average climatologies of maximum temperature and precipitation from their one-eighth-degree grid cell. Climate variables were averaged across three-month seasonal windows for the entire 50-year period and summer climate data (June–August) was used in this study.

2.5 Statistical Analysis

The mean, standard deviation, and sample size of Hg concentration samples were calculated for species and sites in our data set. Using guidelines established by previous work on Hg in songbirds (Jackson et al. 2011), individuals with blood Hg concentrations higher than 0.7 parts per million (ppm) wet weight (ww) were categorized as having moderate or greater risk of negative effects of Hg to reproductive success.

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[1] https://gdo-dcp.ucllnl.org/downscaled_cmip_projections

This risk threshold is based on data from Carolina wrens and is assumed to be applicable to other songbird species. The locations of these individuals are mapped across New York State to show the spatial distribution of absolute Hg risk and identify locations that could be areas of concern due to chronic Hg availability.

To determine the species that are consistently high in blood Hg concentrations across all sites in a region, a general linear mixed modeling framework was used to test several hypotheses. All general linear mixed models used in this study were evaluated for goodness-of-fit using R-squared (both marginal and conditional), quantile-quantile plots, and fitted versus residual plots. All covariates included in all models were tested for correlations to ensure all model-based inference was unbiased. For these analyses, the data was subset to include only individuals from core and statewide sites that are in the breeding population (i.e., adult birds are the most useful indicator of local Hg availability versus hatch year birds) and that included passerines or near passerines (i.e., excluding incidental captures of raptors, shorebirds, or rails). All recaptures among years are included in the data set, which assumes that each capture is an independent assessment of Hg bioavailability for that year. The response variable used was the log-transformed blood Hg concentration (ppm ww) to conform to assumptions of normality in the response variable for general linear models. Samples without enough Hg to reach the detection limit were given the value of the limit (0.001 Hg ppm ww) to avoid zeroes in the response variable. All analyses were conducted using the R statistical software platform (R Core Team 2018). General linear mixed modeling was conducted using package "lme4" (Bates et al. 2015), whereas data manipulation and figure creation used "dplyr" (Wickham et al. 2018) and ggplot2 (Wickham 2009), respectively.

This particular model parameterization is derived from a priori goals of assessing species while controlling for variance in sampling across sites, regions, years, and sex. Several nested random effects were used to control for regional variance in Hg bioavailability across species and years. Species, a categorical variable, was nested within region, and year, another categorical variable, was nested within each site to account for spatial and temporal variation in Hg bioavailability. Region was included as an additional standalone random effect. Sex was included in the model as the only fixed effect. Parametric bootstrapping (n=250) was used to estimate 95% confidence intervals around parameter estimates and predictions made from the model.

2.5.1 Core Site Annual Trends

Core sites that were visited for all five years were analyzed to determine how Hg bioavailability changed at the sites over the study period. A general linear mixed model that describes annual changes in songbird Hg and accounts for species effects across regions and sex was used. Species was nested within each region as a random variable to account for species variation in Hg over space. An interaction between year (categorical) and site was included as a fixed effect in the model, along with sex. Predictions of annual changes for each site are made using the fixed model and parametric bootstrapping is used to estimate 95% confidence intervals of the model parameters and predictions.

2.5.2 The Role of Habitat and Climate in Mercury Exposure Across New York State

Using data from all sites, the role that habitat and climate played in predicting songbird Hg levels across the State was determined. Only one model was tested, which is a specific hypothesis about the importance of regional variation in the role that climate and wetland habitat have on songbird Hg bioavailability. To do this, a general linear mixed model that can account for variability in the Hg response to habitat across different regions was used.

To make this habitat/climate model, a nested random effects, fixed effects, and fixed effects with random components was used. First, in random effects, a species nested within year, nested within region term was used to account for variation in species composition, temporal trends, and spatial variation across all the sites as well as a random effect for a site with no nesting or interactions. For pure fixed effects, sex and the amount of upland forest found near the site (which is assumed to have limited region variation) was used. To understand the effects of foraging niche, habitat, and climate, the species-level percentage of invertebrates in the diet, the amount of wetland habitat (both emergent and woody wetlands combined), the 50-year average summer maximum temperature, and the 50-year average summer rainfall were included as fixed effects with random components. Fixed parameter estimates were allowed to change among regions using a nested random variable structure. This specification is similar to using an interaction between these effects and region but reduces the number of degrees of freedom needed in the model and allows more variance in information quality (i.e., uncertainty) among regions.

2.5.3 The Role of Individual Variation in Trophic Position and Foraging Behavior in Mercury Exposure

This analysis uses results from the previous habitat/climate model and additional modeling work with the stable isotope data. Using the invertebrate-diet information from the previous model, how effectively Hg moves through the food web from region to region can be estimated. Species-level diet information can be used to represent broad estimates related to foraging and dietary selection but does not describe individual variation in diet. To address this, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes in blood were used to refine our understanding of the role of wetland diet (as estimated by $\delta^{13}C$) and trophic level (as estimated by $\delta^{15}N$) to the individual scale. Using a similar general linear model structure as above (including testing a single, complex model), a single stable isotope model that includes nested random effects, fixed effects, and fixed and random mixtures was utilized. The nested random effects of species within region and year were used as described in the previous model. The standalone effect of site is included to control for additional site-to-site variance with region. Sex is included as a pure fixed effect, and stable carbon and nitrogen isotopes are included as fixed effects with random components nested in region. As above, this allows the model to estimate an overall effect of these covariates across all regions and then allows for variation in Hg availability between regions.

3 Results and Discussion

3.1 Avian Mercury Exposure Summary

Mercury concentrations varied widely among sites and species in the blood and feather samples analyzed from 2013–2017 (appendix A). The blood Hg concentrations (n=2243) ranged from a low of below the instrument detection limit in an American goldfinch at Neversink Preserve to a high of 4.1 ppm ww in a swamp sparrow from North Montezuma Wildlife Management Area. Tail feather Hg (n=1869) ranged from below the detection limit in a seaside sparrow on North Cinder Island to 29.2 ppm fresh weight (fw) in a blue-gray gnatcatcher from Mashomack Preserve on Long Island. Mercury in first primary (P1) feathers (n=38) ranged from 0.5 ppm fw in a song sparrow in Accabonac Harbor to 18.6 ppm in a saltmarsh sparrow from North Cinder Island. First primary feathers were only collected from the seaside and saltmarsh sparrows as these feathers are grown at the end of the previous breeding season and thus Hg concentrations reflect local nesting locations. The highest mean blood Hg levels were identified in Long Island tidal marshes at 1.4 ppm ww. Songbirds on Long Island and New York City had the highest average blood Hg concentrations, followed by the Finger Lakes, Adirondacks, and Catskills regions (Table 3).

Table 3. Mean Blood Mercury Concentrations, Standard Deviation (SD) and Sample Size (n) for Regions Sampled from 2013–2017

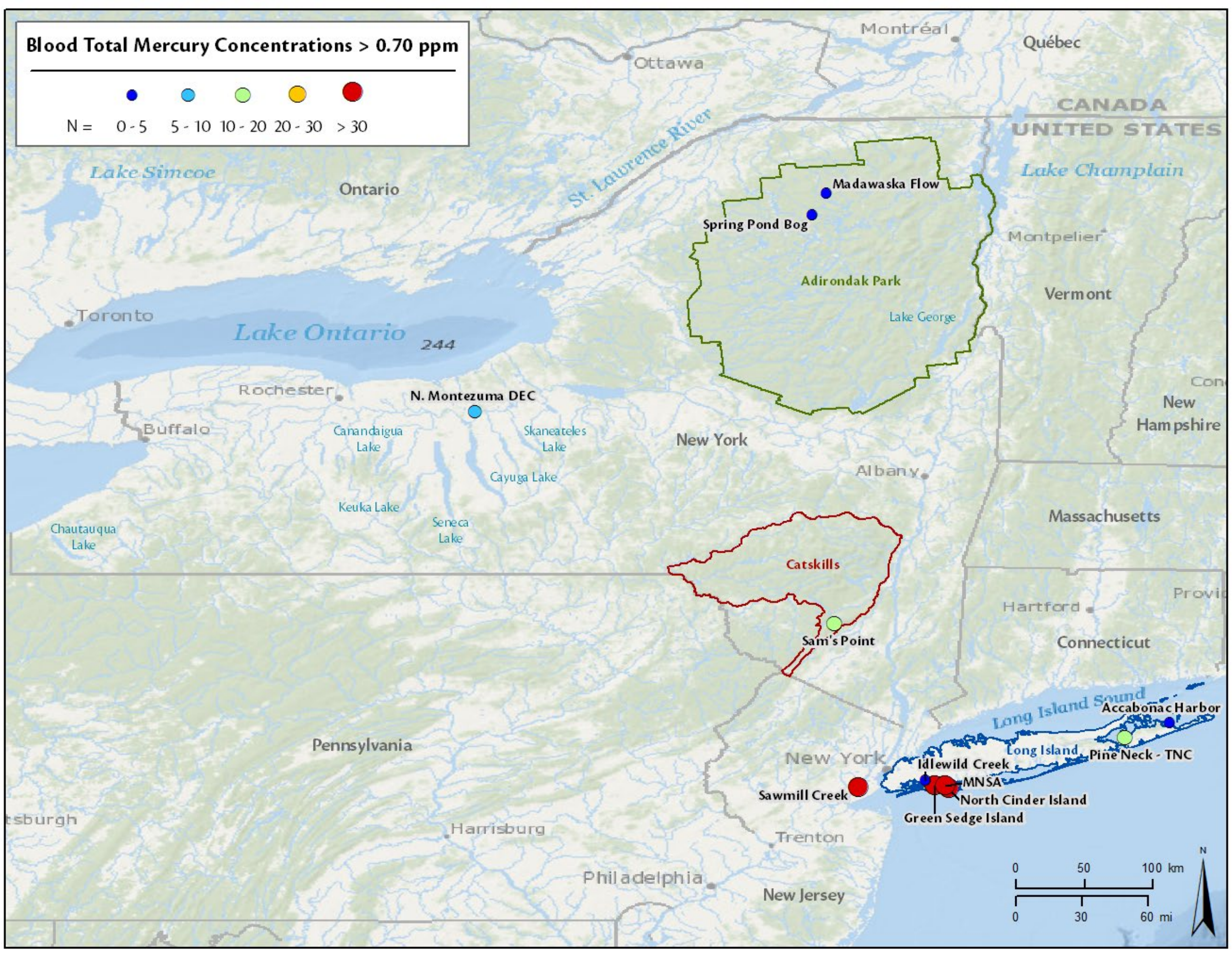
Summary statistics for all songbirds sampled in each region for each year. Blood mercury concentrations measured in ppm.

Region	Year														
	2013			2014			2015			2016			2017		
	Mean	***SD***	***n***	***Mean***	***SD***	***n***	***Mean***	***SD***	***n***	***Mean***	***SD***	***n***	***Mean***	***SD***	***n***
Adirondacks	0.18	0.16	68	0.18	0.17	101	0.18	0.13	110	0.18	0.14	167	0.23	0.17	90
Capital Region							0.05	0.04	56						
Catskills	0.12	0.10	139	0.13	0.20	105	0.12	0.14	93	0.19	0.24	90	0.15	0.16	82
Finger Lakes							0.37	0.20	17	0.35	0.54	84			
Long Island	0.52	0.41	126	0.45	0.44	176	0.72	0.65	73	0.65	0.49	132	0.61	0.57	96
Northern New York							0.10	0.10	55	0.20	0.14	33			
New York City	0.41	0.33	75	0.49	0.51	107	0.53	0.57	62	0.50	0.55	64			
Tug Hill				0.10	0.07	38	0.17	0.13	41						
Western NY/Lake Ontario							0.14	0.11	46				0.12	0.08	98

Individuals with high blood Hg tended to be spatially clustered (Figure 2). Tidal marsh sites across Long Island, like North Green Sedge Island and Cinder Island, had consistently high levels of mercury in marsh-obligate species. This mostly occurred in saltmarsh sparrows, but other sparrow species and flycatchers using habitat adjacent to the tidal marshes were also found to be high in blood Hg. Sawmill Creek, in the nearby New York City region, also had a large proportion of high-risk individuals. The Catskills region had many moderate or greater risk individuals at Sam's Point Preserve; the Finger Lakes region had many high-risk individuals at Montezuma National Wildlife Refuge; and Sphagnum bog sites at Spring Pond Bog and Madawaska Flow in the Adirondacks also had high-risk individuals. Other Regions of New York State had lower proportions of individuals > 0.7 blood Hg ppm ww (see appendix B for a list of all species > 0.7 ppm blood Hg).

Figure 2. Spatial Distribution of Songbirds at Moderate Risk of Mercury Effects

Map of potential hotspots based on blood THg concentrations in songbirds sampled in New York State in 2013–2017 (the size and color of the circle represents the number of individual birds above moderate risk). Moderate risk is defined as > 0.7 ppm ww blood Hg as defined using Jackson et al. (2011).



Generally, the sites with elevated Hg levels are located in wetland habitats with high Hg deposition or potential local Hg sources (e.g., Long Island). Outside of the expansive tidal marsh of Long Island, songbird blood Hg concentrations varied significantly among sites in each region. This variability is likely due to discrete wetlands having differing Hg bioavailability due to local or site-specific differences in wetland soils, habitat type, or Hg deposition rates. Thus, the identification of additional sites with at-risk songbirds would require a spatially extensive sampling plan.

3.2 Overall Model Fit for All Analyses

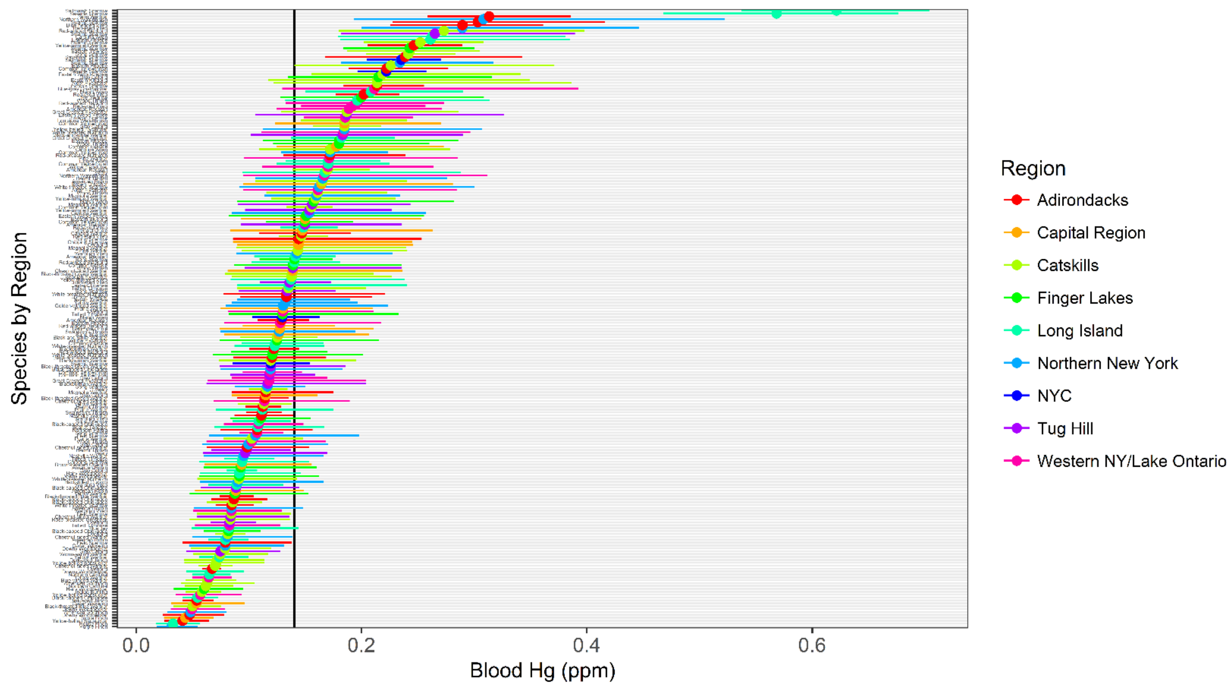
Each of the three general linear mixed models used for this project showed strong goodness-of-fit. All models showed high overall goodness-of-fit (R^2 ranged from 0.80 to 0.87) and there appeared to be no signs of heteroscedasticity or other examples of poor fit based on the use of a normal distribution to describe the log-transformed blood Hg dependent variable. The complex random effects structure used in this effort consistently explained more of the variance than the fixed effects in all the models. Some models only had a few fixed effects parameterized (e.g., the model for Objective 1), but even models that included more fixed effects did not explain large amounts of variance. While this can complicate model-based inference, this pattern does not influence model appropriateness or fit.

3.3 Identifying Indicator Species

The large number of sites and generalist sampling approach of this project provides an opportunity to evaluate many species in their role as indicators of Hg bioavailability. Using the general linear mixed model that is focused on variation in blood Hg across species, sites, and regions, the average blood Hg for each species in the regions they were captured was estimated (Figure 3). In this analysis, 62% of the total variation in the blood Hg data is explained by variation in species over different regions. This is a large portion of the total variance in the data set, and these variables are critical to predictive effectiveness of the model. Changes in songbird Hg in sites and across years represented about 18% of the total variation and showed that these variables are also important, which are discussed in further detail in the following temporal trends section. For this objective, the differences in Hg exposure across site and year were controlled to identify indicator species that were high in blood Hg across multiple years and sites in a region. Long Island saltmarsh and seaside sparrows were the highest species/region combinations, while purple and house finches in Northern New York and Long Island were the lowest.

Figure 3. Model Estimated Mean and Variance of Blood Mercury Concentrations for All Species in All Regions They Occupied

Model estimated blood Hg concentrations for all species in each region. The black vertical line is the global blood Hg average across all species and regions. The color of each species shows the region that the species was found in and the horizontal line around each point is the 95% confidence interval of the estimate. Species are ranked from highest to lowest average Hg values and can appear multiple times in the graph if they appear in multiple regions.



By examining the top five Hg species per region, the most consistently observed Hg sensitive species can be identified for each region (Figure 4). These species are often significantly greater than the average blood Hg concentrations for the region. Even in these top five species, there can be significant differences in average Hg levels that could be dependent on habitat-use or amounts of bioavailable Hg. The Adirondacks, Catskills, Long Island, and Northern New York regions had many different indicator species with consistently high blood Hg concentrations in regions, while the blood Hg concentrations were lower in indicator species found in the Capital and Western New York/Lake Ontario regions (Table 4). These differences are likely to due to variation in MeHg bioavailability in sites throughout these regions.

Figure 4. Model Estimated Mean and Variance of Blood Mercury Concentrations for the Five Highest Species in Each Region

Top five species by blood mercury for each region. The error bars represent the 95% confidence interval of the regional blood Hg concentration estimate for each species. The solid black line is the overall average blood Hg concentration across all sites and regions.

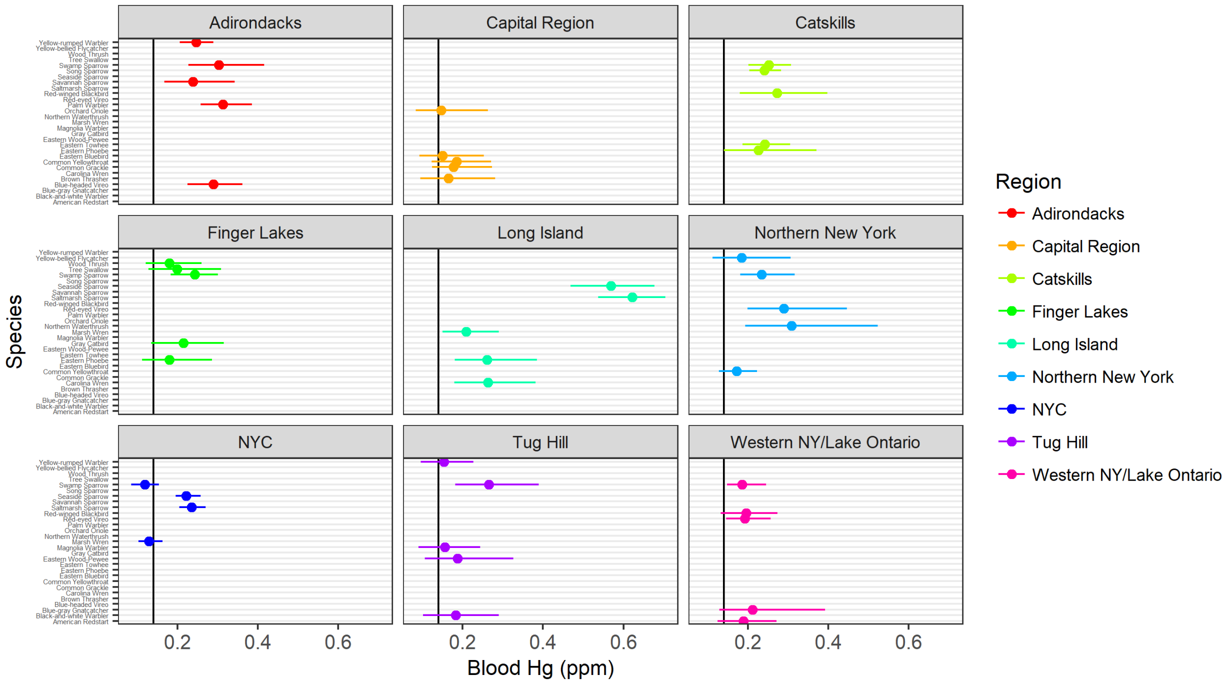


Table 4. Songbird Indicator Species for Mercury Organized by Region and Habitat Type

Species include regional top five songbird indicator species (highest blood Hg by region) and additional suggested species to target for Hg monitoring by regions and habitat type in New York State. *Habitat type designations adapted from Cornell Lab of Ornithology, All About Birds website.

Region	Habitat Type	Regional Top Five High Hg Songbirds	Suggested Additional Target Species
Adirondacks	Forests	blue-headed vireo; yellow-rumped warbler	red-eyed vireo; Canada warbler; Swainson’s thrush; Bicknell’s thrush; rusty blackbird; northern water thrush; American redstart; eastern wood-pewee
	Grasslands	savannah sparrow	
	Marshes	swamp sparrow	red-winged blackbird
	Open Woodlands		song sparrow; hermit thrush; olive-sided flycatcher; eastern phoebe
	Scrub		common yellowthroat; Lincoln’s sparrow
	Sphagnum Bogs; Wetlands	yellow palm warbler	
Capital Region	Forests		red-eyed vireo; American redstart; eastern wood-pewee
	Grasslands	eastern bluebird	
	Open Woodlands	common grackle; orchard oriole	song sparrow; eastern phoebe
	Scrub	common yellowthroat; brown thrasher	

Table 4 continued

Region	Habitat Type	Regional Top Five High Hg Songbirds	Suggested Additional Target Species
Catskills	Forests		red-eyed vireo; American redstart; eastern wood-pewee; wood thrush; Swainson's thrush; Bicknell's thrush; northern water thrush
	Marshes	red-winged blackbird; swamp sparrow	
	Open Woodlands	song sparrow; eastern phoebe	gray catbird; Carolina wren; hermit thrush; olive-sided flycatcher
	Rivers and Streams		Louisiana water thrush
	Scrub	eastern towhee	common yellowthroat
Finger Lakes	Forests	wood thrush	northern water thrush; American redstart
	Lakes and Ponds	tree swallow	
	Marshes	swamp sparrow	marsh wren; red-winged blackbird
	Open Woodlands	gray catbird; eastern phoebe	song sparrow; olive-sided flycatcher
	Rivers and Streams		Louisiana water thrush
	Scrub		common yellowthroat

Table 4 continued

Region	Habitat Type	Regional Top Five High Hg Songbirds	Suggested Additional Target Species
Long Island	Forests		red-eyed vireo; wood thrush; American redstart; northern water thrush; eastern wood-pewee
	Marshes	saltmarsh sparrow; seaside sparrow; marsh wren	red-winged blackbird
	Open Woodlands	eastern phoebe; Carolina wren	house wren; gray catbird
New York City	Marshes	saltmarsh sparrow; seaside sparrow; marsh wren; swamp sparrow	red-winged blackbird
	Open Woodlands		song sparrow
Northern New York	Forests	northern water thrush; yellow-bellied flycatcher; red-eyed vireo	magnolia warbler; Swainson's thrush; Canada warbler; American redstart; eastern wood-pewee
	Marshes	swamp sparrow	red-winged blackbird
	Open Woodlands		hermit thrush; song sparrow; gray catbird; olive-sided flycatcher; eastern phoebe
	Scrub	common yellowthroat	
Tug Hill Plateau	Forests	eastern wood-pewee; black-and-white warbler; magnolia warbler; yellow-rumped warbler	red-eyed vireo; northern water thrush; American redstart
	Marshes	swamp sparrow	red-winged blackbird
	Open Woodlands		song sparrow; hermit thrush; olive-sided flycatcher; eastern phoebe
	Rivers and Streams		Louisiana water thrush
	Scrub		common yellowthroat

Table 4 continued

Region	Habitat Type	Regional Top Five High Hg Songbirds	Suggested Additional Target Species
Western New York/Lake Ontario	Forests	blue-gray gnatcatcher; red-eyed vireo; American redstart	eastern wood-pewee
	Marshes	red-winged blackbird; swamp sparrow	willow flycatcher
	Open Woodlands		song sparrow; eastern phoebe
	Rivers and Streams		Louisiana water thrush
	Scrub		common yellowthroat

Many of the high-exposure risk species documented in this study have also been identified in previous songbird Hg monitoring efforts. As an example, previous studies in the Northeast have also suggested that saltmarsh sparrow, common yellowthroat, swamp sparrow, and red-eyed vireo were useful indicators of habitat Hg levels (Evers et al. 2012). Additionally, other indicator species identified as part of this research have been used to assess environmental Hg bioavailability in other studies, including tree swallows (Longcore et al. 2007) and Northern water thrush (Adams et al. in review). These species often use mesic forests or wetlands as breeding habitat, so high blood Hg concentrations appear consistent with the increased rates of Hg methylation in these habitats. The results of this study and similar work provides a foundation for identifying relevant Hg-songbird indicator species and allows for strong monitoring recommendations relating to species selection when designing future studies.

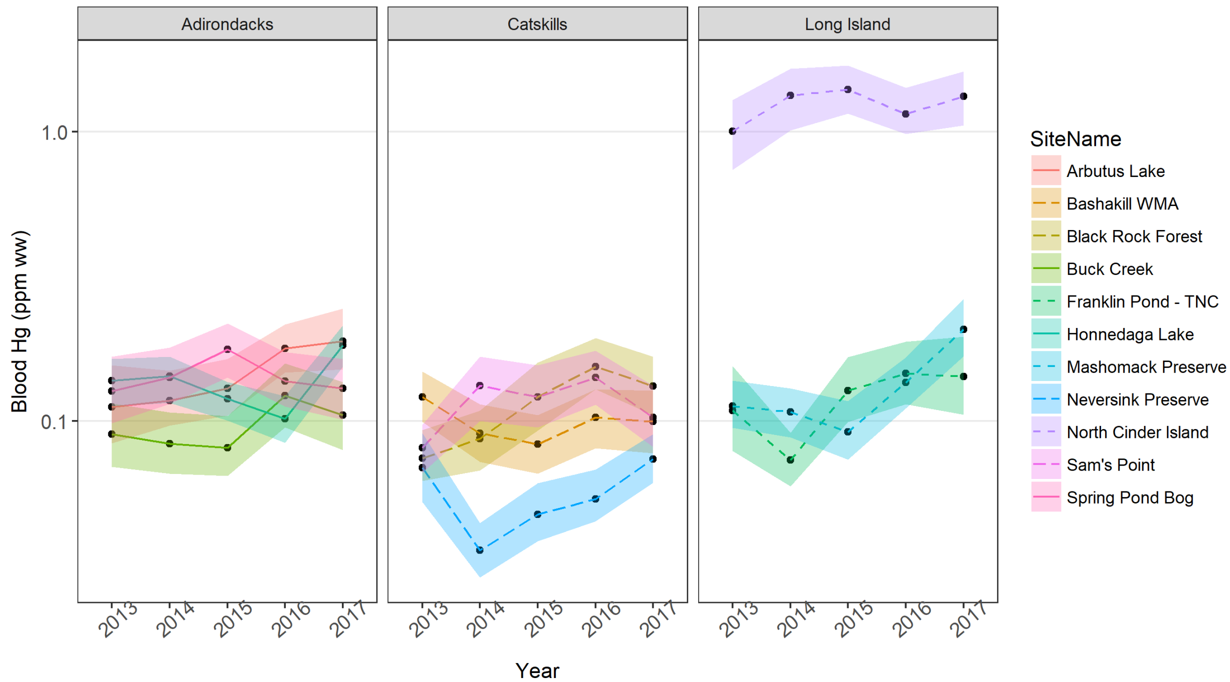
Differences in songbird blood Hg concentrations among regions likely have many potential origins. Some sites, particularly in Long Island, may be close to local industrial sources and other sites may have high songbird Hg concentrations due to higher local deposition rates. But habitat-specific Hg methylation rates also can cause significant differences among sites that likely have similar Hg deposition rates. The Capital Region was found to have very low Hg concentrations across all levels of the food web, as there is limited bioavailable Hg for uptake into associated food webs. All data from this region comes from the Albany Pine Bush Reserve which sits upon sandy soils that likely to do not facilitate Hg methylation. On the other hand, the Catskills and the Adirondacks have wetland habitats with high Hg methylation rates and have bioavailable Hg in multiple components of the terrestrial/aquatic food web.

3.4 Temporal Trends in Mercury Bioavailability

The fixed effects component of the temporal trends general linear mixed model explained 46% of the total variation in the blood Hg data, and the interaction between site and year was an extremely important effect (F-test with Satterthwaite approximation: $F_{54,677} = 6.96$, $p < 0.001$). While most core sites sampled in all five years have similar levels of songbird blood Hg over time, some sites had more annual variation (Figure 5). All Long Island sites showed increases over time, though Franklin Pond and Mashomack Preserve showed the greatest increase. The Catskills showed the greatest diversity in trends among their sites. Most sites stayed close to their five-year average, while Neversink Preserve showed a significant decrease in the middle years only to increase back to 2013 levels by 2017. All Adirondack sites showed slight increases that appeared to be within the 95% confidence intervals for each estimate.

Figure 5. Modeled Trends in Songbird Mercury Levels at Core Sites, 2013–2017

Average annual blood Hg concentrations in songbirds at core sites in Adirondacks, Catskills and Long Island regions, 2013–2017. These estimates are plotted on a log-transformed scale for visual clarity. Each annual estimate for a site is for the average bird across all sites and all regions in the study. Absolute levels of blood Hg concentration can vary among sites depending on the species captured each year.



Changes to emissions standards in the United States and around the globe have contributed to significant decreases in Hg emissions over the past 10 years (Zhang et al. 2016). Wide-ranging marine species have been shown to be reflective of patterns in global Hg emissions (Lee et al. 2016), but similar results are not found here. Temporal lags in Hg methylation caused by legacy or local Hg sources (Amos et al. 2013), and Hg cycling (Demers et al. 2007) potentially contribute to this lack of connection. Mercury deposition varies significantly over space and time in New York State (Mao et al. 2017) and accurate estimates of deposition rates are difficult to obtain for each site. Deposition data collected from sites in the National Atmospheric Deposition Program's Mercury Deposition Network (MDN) located in the Adirondacks, Catskills, and Long Island suggest stable to decreasing trends. While these data show songbirds to have a similar stability over time, it is difficult to say if these indicator species are correlated with regional and global patterns of emissions and deposition. However, songbirds do clearly elucidate the complexities of Hg cycling in wetland/terrestrial ecotones at smaller spatial scales and these patterns are dependent on Hg inputs. The connections between deposited Hg and bioavailable MeHg are complex are more research on temporal changes in these patterns are needed such that more useful models describing these patterns can be specified.

This analysis is most useful for comparing relative in-site changes in songbird Hg bioavailability over time, as compared to examining absolute differences in songbird blood Hg among sites over time. Average annual blood concentrations are measured after species composition is controlled for, and species composition of a site can strongly influence the blood Hg concentrations measured. See section 3.1 for a further exploration of what species and what locations have Hg blood concentrations that are potentially causing negative effects on populations.

3.5 Spatial Variation in the Role of Habitat and Climate on Mercury Bioavailability

Using the habitat and climate general linear mixed model, random effects explained approximately 80% of the total variation in songbird blood Hg, while fixed effects explained about 8%. Because the model specification includes fixed effects with random components this is a complex type of model to describe, but essentially most of the data are explained by the random effects and the random components of the fixed effects. Of the random effects, the nested term of year, region, and species explains 24% of the total variation and the random component that explains the regional variation of the 50-year average summer maximum temperatures explains 44% of the variation. Site explains 8% of the variation and all other random components explained < 5% of the total variation. Of the fixed effects, the amount of wetland in the sampling area was the only fixed effect that showed a statistically significant effect ($\beta = 0.17$, 95% Confidence Interval: 0.03 – 0.32). The 50-year average summer rainfall was borderline statistically significant ($\beta = 0.23$, 95% CI: -0.04 – 0.49) and all the other covariates were of minimal importance.

However, these fixed effects have important random components that make some covariates more important in some regions. In terms of wetland area, as it increases, songbird blood Hg increases in almost all sites. The positive effect of wetlands on blood Hg is particularly important in the New York City and Catskills regions (and marginally less important in Long Island), while there is more uncertainty in the estimates for other regions (Figure 6). Average summer temperatures have a more complex effect. Western New York/Lake Ontario, New York City, and the Finger Lakes regions show a positive relation between temperature and blood Hg, while Northern New York has a negative relation (Figure 7). Here, even though the fixed effect was not statistically significant for all regions, average temperatures are important to blood Hg concentrations in many regions. While the effect of rainfall was consistently positive on blood Hg, there was limited variation among regions (Figure 8).

Figure 6. The Effect of Wetland Habitat on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of wetland habitat acreage on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.

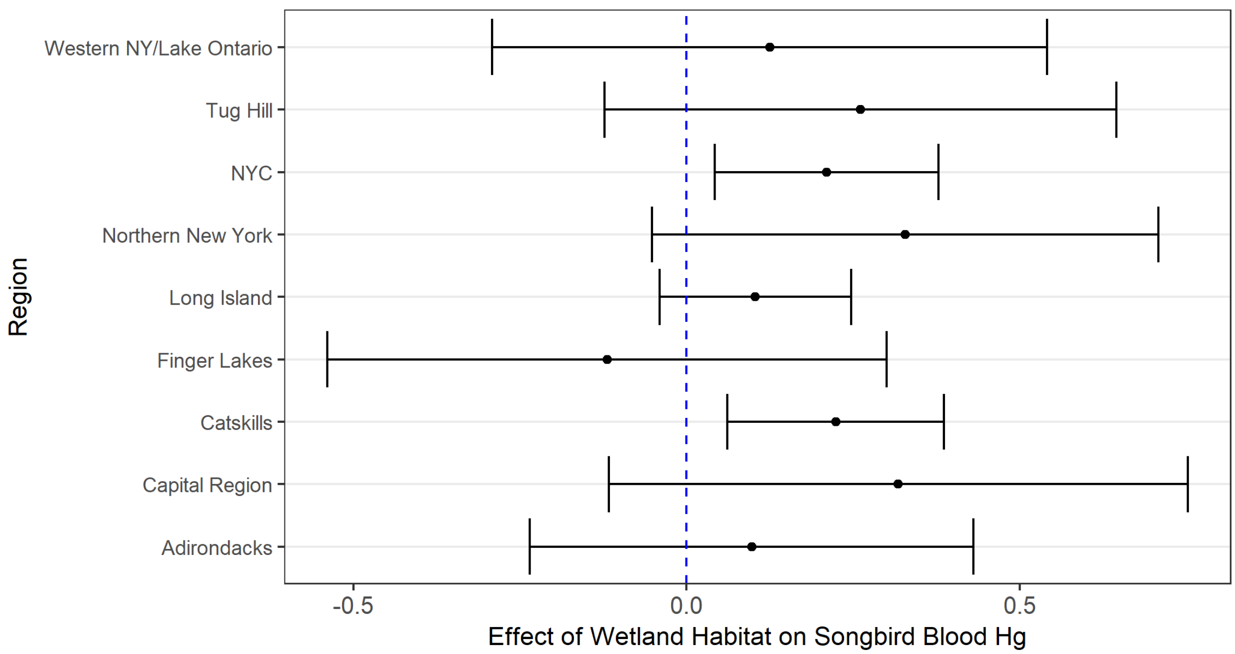


Figure 7. The Effect of Summer Maximum Temperatures on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of 50-year average summer maximum temperatures on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.

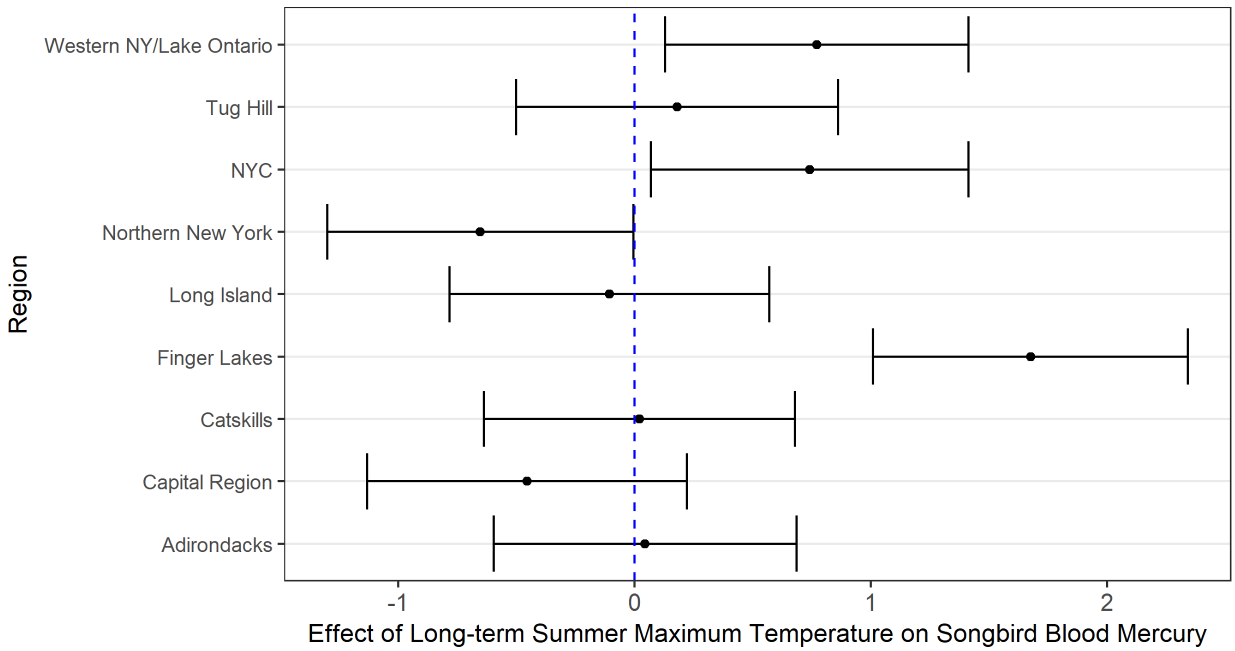
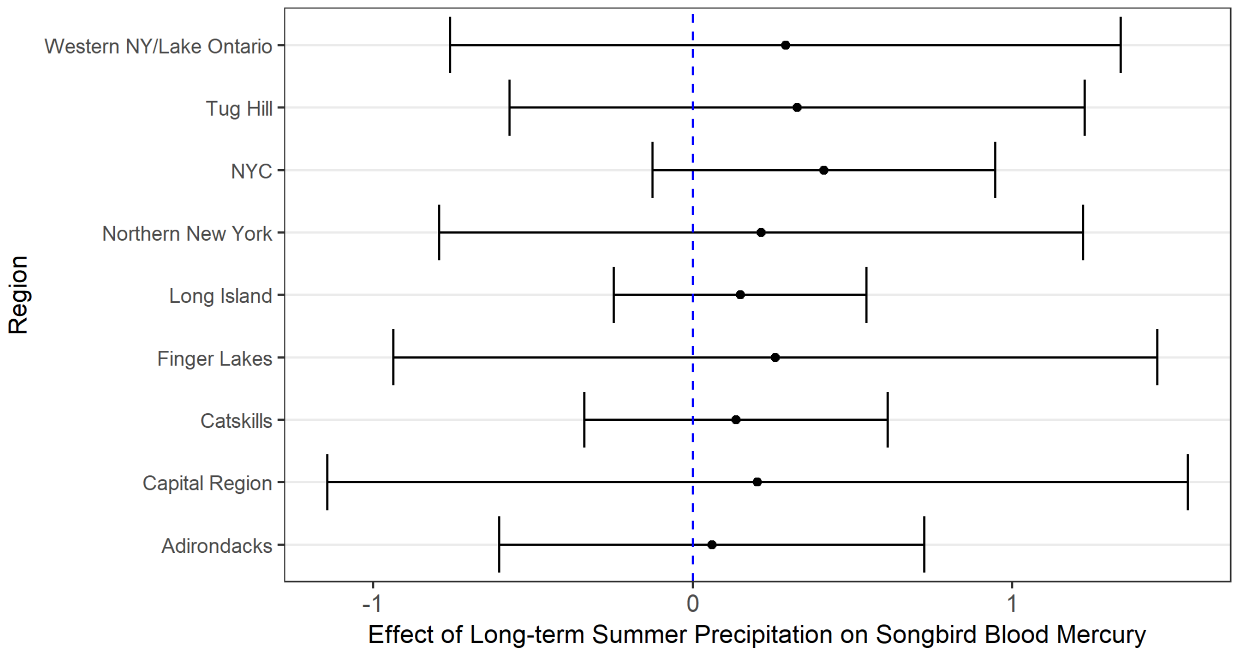


Figure 8. The Effect of Summer Precipitation on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of 50-year average summer precipitation on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.



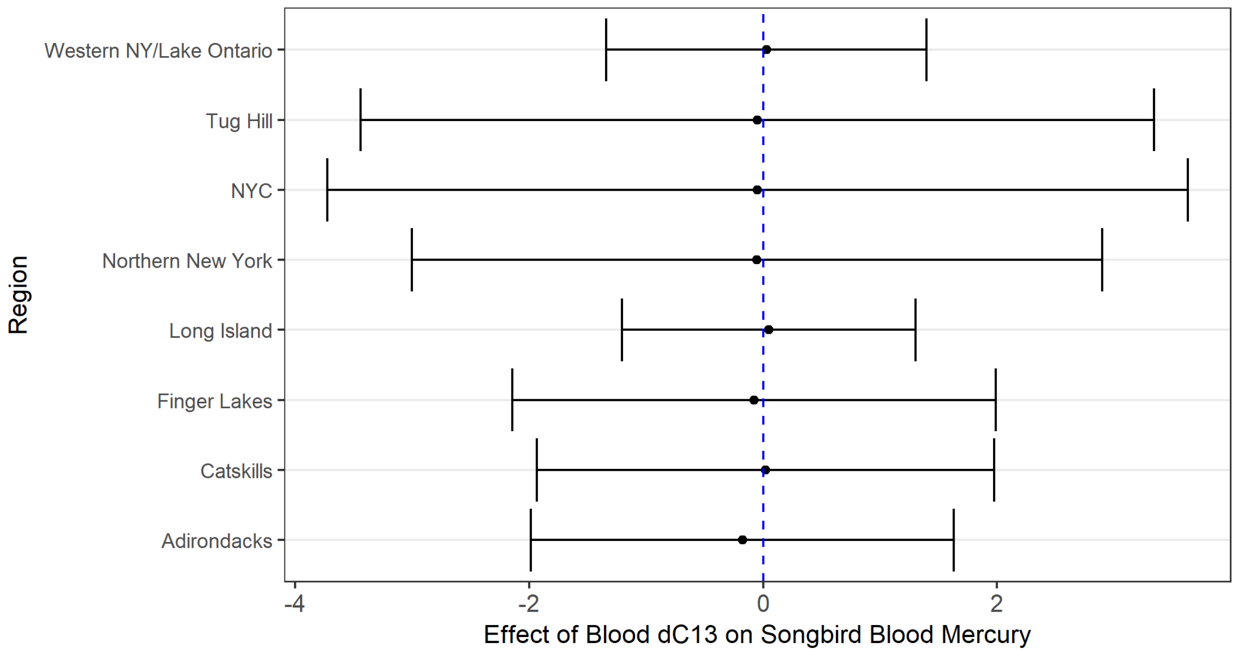
The impact of these results is potentially far reaching. Both habitat and climate are expected to change over this century in New York State. If the conditions that created these patterns of Hg bioavailability continue, then it seems likely that changes to the amounts of wetland habitat and temperature will have strong, regional components. Habitat change can be difficult to project into the future and wetland habitat, in particular can be challenging to build models for in estuarine (Craft et al. 2009, Kirwan et al. 2010, Kirwan and Megonigal 2013, Schile et al. 2014) and palustrine (Schindler 2001, Mitsch and Hernandez 2013) wetlands. Wetlands habitats have declined globally (Zedler and Kercher 2005, Kirwan and Megonigal 2013), but only have been slightly declining in the northeastern United States recently (USDA 2015, Dahl 2006). While overall numbers remain recently stable, man-made wetlands are being created to counteract the destruction of natural wetlands (Dahl 2006), and it is unclear what effect this may have on Hg bioavailability. Additionally, climate change is expected to increase both temperature and precipitation in the northeastern United States (Hayhoe et al. 2007, Hayhoe et al. 2008), and there is evidence that these conditions could results in higher Hg bioavailability in some regions of the State. This study is based on 50-year climate averages and is correlational, so it is difficult to say how incremental changes in climate will influence Hg bioavailability. More evidence is needed to better understand the mechanisms behind this potential process and the effects it would have on songbird Hg exposure, but changes in these patterns could directly affect Hg methylation (Ramlal et al. 1993) or potentially alter wetting and drying patterns that influence this process (St. Louis et al. 2004, Windham-Myers et al. 2014). Finally, changes to climate in New York also could influence the amount of statewide wetland habitat, both in estuarine (Warren and Niering 1993) and palustrine systems (Hayhoe et al. 2007, Brooks 2009). Thus, habitat and climate are likely to influence future Hg bioavailability both independently and synergistically; these interactions between variables could make the future of Hg bioavailability difficult to project.

3.6 Relations between Blood Mercury and the Food Web

Using the habitat/climate general linear mixed model, the effect of a species-level invertebrate diet on the amount of Hg found in an individual's blood could be analyzed. Generally, this was a weak effect that showed no consistent pattern across all regions (Figure 9). This model was expected to explain broad differences in trophic levels among species, but species level changes across regions appeared to be a more important factor. This result suggests that these processes are operating at a trophic scale smaller than the species level. Partly, this is because invertivorous diets are a generalized estimate of trophic position, but it is also due to significant site-scale and individual variation in diet and trophic position within species. Additionally, not all invertebrates are equal in terms of Hg concentrations. Low trophic-level aquatic invertebrates tend to be a part of food webs that include more Hg biomagnification (Boening 2000) and higher trophic-level invertebrate predators consuming these species can biomagnify and transport Hg into the surrounding terrestrial environments (Cristol et al. 2008). Thus, more detailed foraging information could be helpful in refining this aspect of the model.

Figure 9. The Effect of Species-Level Diet on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of species-level invertivorous diet (%) on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.



Using the stable isotope general linear mixed model (n=1018), the effects of individual-level $\delta^{13}C$ and $\delta^{15}N$ on blood mercury levels were quantified. In this model, the random effects represent 72% of the total variance in songbird blood Hg and the fixed effects only 8%. The most important random effect was region, which explained most of the variance in the data. The nest term of year/region/species and site term both explained much smaller portions. In terms of fixed effects, there was a marginal negative effect of $\delta^{13}C$ on blood mercury levels (β = -0.04, 95% CI: -0.11 – 0.04) that was invariable among regions (Figure 10). Depleted $\delta^{13}C$ values indicate that the animal's food is coming from wetter habitats that have higher Hg bioavailability potential, but there is high site-to-site variance in this process that likely represents variation in the types of mesic habitat the $\delta^{13}C$ -depleted diet is linked to. The effect of $\delta^{15}N$ was strongly positive overall (β = 0.11, 95% CI: -0.04 – 0.2), and variable by region (Figure 11). As enriched $\delta^{15}N$ values indicate an individual foraging from a higher trophic position, higher trophic level was strongly positively correlated with blood Hg. The effect was strongest in the Adirondacks, Catskills, New York City, Northern New York, and Long Island, and was the weakest in Western New York/Lake Ontario. The effect of sex on blood Hg concentration was negligible.

Figure 10. The Effect of Stable Carbon Isotopes on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of blood $\delta^{13}C$ (per mil) on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.

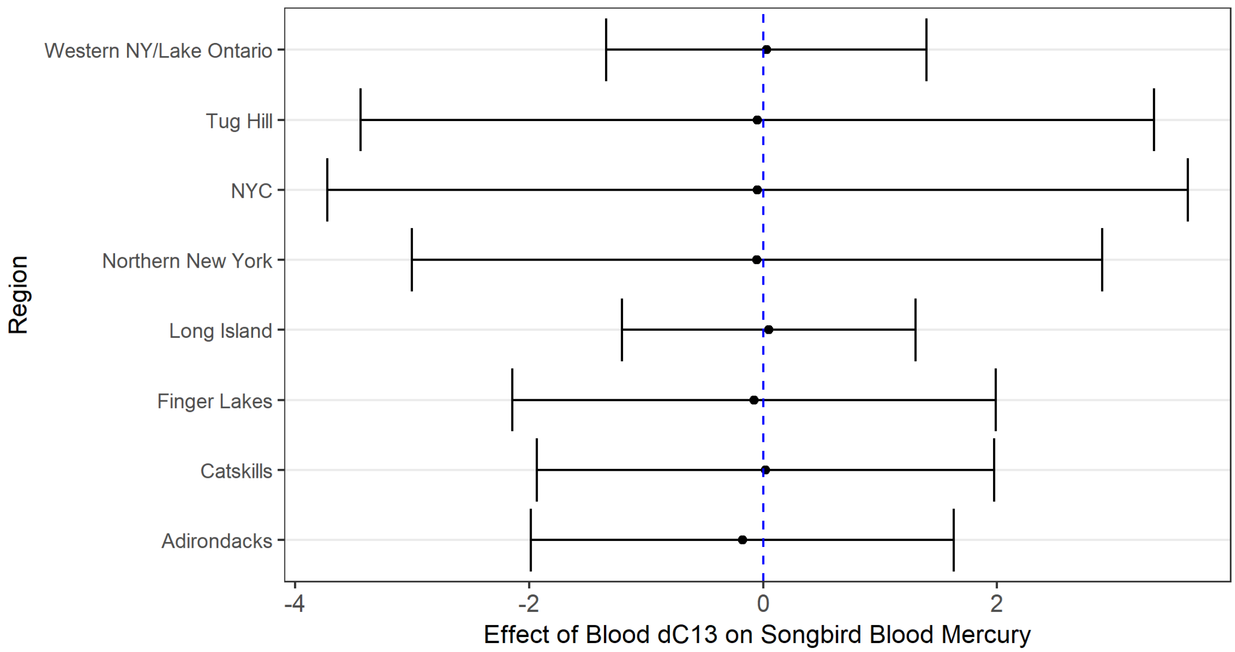
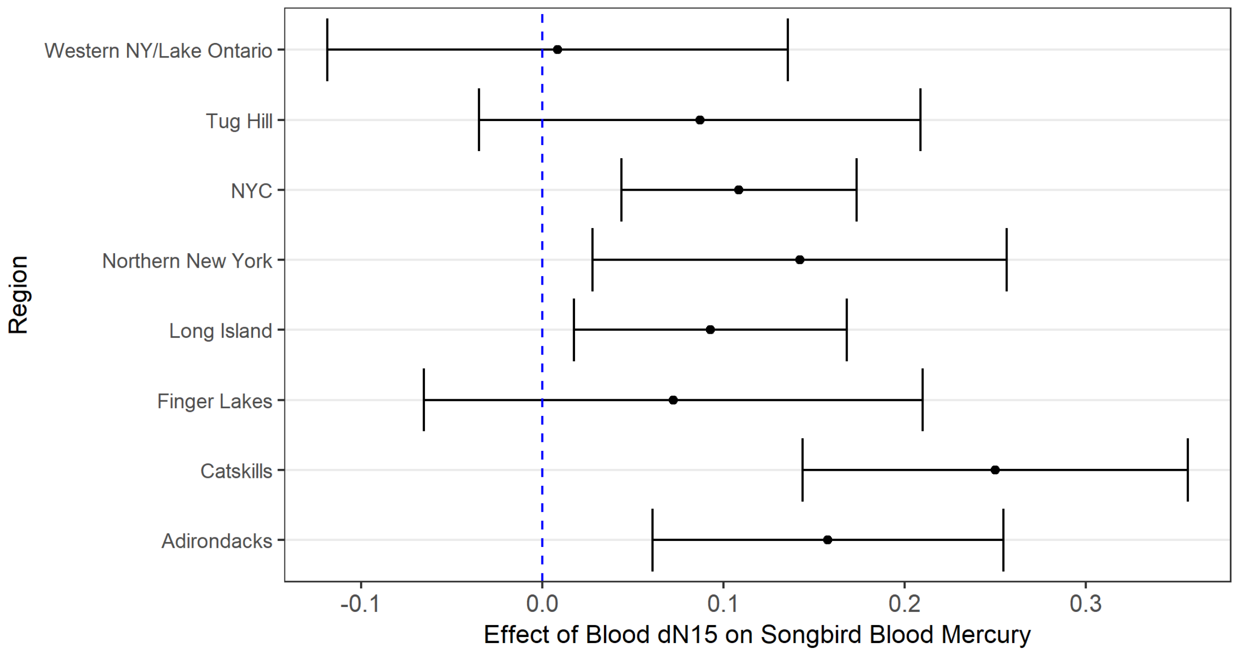


Figure 11. The Effect of Stable Nitrogen Isotopes on Songbird Blood Mercury Across Regions

Regional estimates of the beta parameter describing the effect of blood $\delta^{15}N$ (per mil) on songbird blood Hg concentrations. Point estimates are a combination of the overall fixed beta estimate combined with the random effect estimate for each region. The error bar represents two times the standard deviation of the combined estimate and the dotted blue line is at zero. If the error bar overlaps zero, then it is likely that the effect is not strong in that region. The standard deviation is estimated by combining the variance of the fixed and random effects using the delta method.



Thus, trophic level at the individual scale (as inferred by blood $\delta^{15}N$) is a strong predictor of blood Hg concentrations, while species-level trophic level (as inferred by percent of diet as invertebrates) is a fairly weak predictor. Individual trophic level has been found to be an important predictor of Hg in studies in many ecosystems (Kidd et al. 1995, Cizdziel et al. 2002, Becker et al. 2002). While species-level traits can be useful in considering some aspects of Hg exposure risk, it can be difficult to predict how many individuals will utilize the portions of the food web where Hg availability is the highest and how these patterns will change at the site- and region-scales. Site-level food web complexity, food chain length, and/or location of Hg contamination all appear to influence Hg biomagnification and Hg exposure risk to songbirds and C or N stable isotopes can continue to be a tool to describe these patterns and better predict Hg exposure risk in vertebrates. Further work is needed to identify additional species- or population-level factors that help describe these relations and increase the precision that songbirds can indicate Hg bioavailability at a given site.

3.7 Changes in Mercury Bioavailability Over the Past 100–150 Years

Bioavailability of Hg to songbirds has been increasing for most of the 20th century and the levels currently observed appear to be a maximum for many species (Perkins et al. 2019). Overall, species-corrected feather Hg concentrations increased from 1900 to 1980 with levels steadying past 1980. In terms of individual species, wood thrush, rusty blackbirds, and saltmarsh sparrows saw significant increases in feather Hg from the turn of 19th century until more recent times. Sometimes these differences could be on the scale of over an order of magnitude (e.g., rusty blackbird). Many of these species (e.g., saltmarsh sparrows and rusty blackbirds) are of significant conservation concern. It is unclear what role Hg exposure has played in some of these large population declines, but it is certainly a mechanism that warrants consideration and an issue that should be considered when developing conservation plans.

3.8 Recommendations for Future New York State Songbird Mercury Monitoring

When conducting a monitoring project there are three general roles that the project can play in decision-making: (1) an assessment of status or trends in status, (2) evaluation of a management action, and (3) learning about the system to facilitate future decision-making (Lyons et al. 2008). To optimally design a Hg monitoring program, first the decision(s) and decision-maker(s) must be identified. In this section, three types of decisions are explored concerning Hg biomonitoring to inform habitat or energy management decisions.

If the goal of a monitoring project was to periodically assess the status of a site (first role in decision making) to determine if further action was needed, sampling efforts could occur once every three to five years at a site. Instead of focusing on intensive sampling, status assessments should focus on extensive sampling, whereas many sites and regions are visited in a multiyear period. Most sites sampled in this study had high-temporal autocorrelation and repeated visits had minimal impact on the overall site mean or variance estimates. A few sites showed stronger temporal patterns that could be missed without annual sampling effort that have the potential to confound less frequent sampling efforts. When evaluating management actions (second role) or learning about the system (third role), annual trends can be more important. Habitat changes could have temporal lag effects, or the system could be responding to annual changes in climate. Addressing these sorts of monitoring questions require intensive effort in Hg monitoring where consistent effort to monitoring Hg bioavailability in specific habitats, trophic niches, and climate regimes could be needed. Additional data focusing on micro-climates, habitats, and habitat change (among many other potential covariates) are often needed in these cases to learn about how these factors affect bioavailability.

As the management decisions and research questions about songbird Hg become clearer, a more focused monitoring plan can be developed and enacted. In the absence of this, there are several recommendations about species selection, site selection, and sampling effort that are based on the present study and other Hg research and monitoring projects in the northeastern United States.

3.8.1 Species Selection

Songbird indicator species should be selected that have the potential to efficiently bioaccumulate Hg in proximity to their breeding territory and are, therefore, reflective of mercury concentrations in the associated habitat type. Ideally, target species should be comprised primarily of invertivores, particularly those that consume high-trophic level spiders or aquatic emergent species (Cristol et al. 2008), species that forage in wetlands or terrestrial/wetland ecotones (Edmonds et al. 2010, Lane et al. 2011), and those that are abundant for purposes of comparative analysis across study sites. While target species serve as a foundation for directing capture efforts, it is also important to sample a wide range of non-target species to cover as much of the local food web as possible, and to provide valuable supplemental data on Hg exposure in various habitat types.

The following represent the highest Hg songbird species identified from each core and statewide region and are, therefore, recommended as ideal indicator songbird species for future monitoring strategies across New York State (Table 4, Figure 5):

- Forests: American redstart; black-and-white warbler; blue-gray gnatcatcher; blue-headed vireo; eastern wood-pewee; magnolia warbler; yellow-rumped warbler; northern water thrush; red-eyed vireo; wood thrush; yellow-bellied flycatcher
- Grasslands: eastern bluebird; savannah sparrow
- Lakes and Ponds: tree swallow
- Marshes: marsh wren; red-winged blackbird; saltmarsh sparrow; seaside sparrow;* swamp sparrow
- Open Woodlands: Carolina wren; common grackle; eastern phoebe; gray catbird; song sparrow; orchard oriole
- Scrub: brown thrasher; common yellowthroat; eastern towhee
- Sphagnum Bog/Wetlands: yellow palm warbler

    * The seaside sparrow is currently listed in New York State as a Species of Special Concern (SC), a high-priority (Y-H) Species of Greatest Conservation Need (SGCN) and has breeding populations that are either imperiled (S2) or uncommon (S3) [Schlesinger, 2017].

While these recommended species have been identified as useful indicators based on the current research, this does not preclude other species from being considered as strong indicators in describing local Hg bioavailability. Additional target species that have been established as environmental indicator species based on previous Hg songbird exposure studies (Louisiana water thrush, red-eyed vireo) and those that are experiencing declining population numbers (rusty blackbird, olive-sided flycatcher) are suggested in Table 4 for possible inclusion in monitoring plans.

3.8.2 Study Site Selection

Study sites should be ideally located in habitat types that facilitate the methylation of Hg and the subsequent uptake and biomagnification into associated aquatic or terrestrial food webs (e.g., sphagnum bogs, freshwater wetlands, estuaries, river floodplains, and reservoirs). Study results documented elevated blood mercury concentrations at several tidal saltmarsh and wetland research sites in Long Island, New York City and the Adirondacks. Continued regional monitoring in high-priority locations (i.e., Adirondacks, Catskills and Long Island) with known elevated biotic Hg levels would provide valuable long-term Hg trends assessments and further documentation of Hg exposure levels in these sensitive habitats.

Conducting future Hg research efforts at established long-term sampling locations would also serve to maximize assessment of Hg concentrations across various ecosystem components, which encompasses both abiotic and biotic sampling (e.g., developing long-term, intensive Hg monitoring study sites at several locations in New York State, potentially paired with MDN sites). Additionally, continued and future biotic sampling efforts to assess the status of Hg levels in designated wildlife sanctuaries, such as National Wildlife Refuges (NWR), Important Bird Areas (IBA), Wildlife Management Areas (WMA), and Bird Conservation Areas (BCA) would contribute valuable data on Hg levels in wildlife and natural resource conservation areas in the State.

3.8.3 Sample Collection

All study sites should be sampled during periods of peak breeding activity to increase capture rate and ensure habitat use in the sampling area. Avoid capturing birds near the beginning or end of the breeding season to minimize the possibility of Hg carry-over from wintering and migratory stopover sites. Similar to the methodologies utilized for this project (see Methods-Bird Capture and Tissue Sampling), sample collection for each individual should include blood samples (50-75 µl for Hg and stable isotope analysis) and two tail feathers (R6) for Hg analysis. Blood samples are preferred as the data are easiest to interpret and they originate from a known breeding location and time. Tail feather samples are useful in that they minimize disturbance to the bird, but the Hg concentrations reflect the time period when the feathers were grown, which is ideally (but not always) the previous breeding location. Additionally, 5–6 flank feathers should be collected if study objectives will include any historical comparisons with archived museum specimens. A sample size of at least 20 individuals per site will minimize statistical uncertainty and allow for a site-specific Hg assessment. This number will vary depending on the sensitivity of the species to Hg bioavailability and the variance in Hg across food webs at the sampling site. Additional information about individual energetic condition, trophic level, diet, foraging habitat, and age can all be useful when trying to understand the location of trophic hotspots, the outcomes of habitat management or learning about specific Hg bioavailability processes.

4 Conclusions

From 2013–2017, the Hg exposure risk to many songbird species and sites in New York State was assessed. For areas of Hg concern, trends of songbird Hg bioavailability were estimated over the entire five-year study period. Mercury exposure was stable at most sites sampled in this survey area though some sites showed increases—particularly in Long Island. New areas of Hg concern (e.g., North Montezuma Wildlife Management Area) were identified using statewide surveys in under-sampled locations. Overall, areas of Hg risk were in core regions with known issues, but new areas of high exposure were observed in the Finger Lakes and New York City.

Invertivores songbird species that forage in and around wetlands are often considered to be optimal indicators of Hg in terrestrial ecosystems; this study provided an extensive survey of the most sensitive songbird species across the State. Some were habitat specialists only found in certain habitats, like saltmarsh sparrows in Long Island tidal marshes or yellow palm warblers in high-elevation Adirondack bogs. Others were more ubiquitous like song sparrows or eastern phoebes. Not all individuals designated as an indicator species must have high Hg levels to be useful for Hg assessments, but if Hg is bioavailable for uptake in terrestrial food webs, these species should have a high probability of reflecting similar patterns. The species evaluated in the study will be useful for establishing refined assessment plans for the many regions of New York State and will provide valuable direction for future monitoring efforts.

Temporal trends in Hg bioavailability were assessed at multiple scales for songbirds. Over the past 100–150 years, Hg exposure increased in many indicator species in the northeastern United States. Mercury in songbird feathers increased from the 1900s to the 1980s, then appears to have stabilized afterward. This increase corresponds with a rise in industrialization and Hg emissions in North America during this time period. Over the 2013–2017 study period, patterns of Hg availability were mostly stable at sites across New York. Changes to Hg emissions regulations in the United States was likely decreasing Hg depositions across the State, but this pattern was not observed in songbirds. The lack of connection between recent changes in Hg emissions and songbird Hg exposure could be related to temporal lags between Hg deposition and subsequent bioavailability, atmospheric deposition not being the primary limiting factor in songbird Hg exposure, or Hg inputs to sites from local sources.

Mercury exposure was highly variable throughout New York State at both regional and site scales. While Long Island, New York City, the Catskills, and the Adirondacks had some of the highest Hg concentrations, there was high variability within these regions. Across the State, wetland area in proximity to the sampling site was an important predictor for songbird Hg exposure, though wetlands in some regions were observed to have a greater effect on songbird concentration levels than others. More expansive wetlands in the sampling area lead to increasing levels of Hg exposure when compared to smaller wetlands. Since methylation varies due to differences in wetland type, the regional differences were likely a reflection of these site-specific differences in wetland habitat type. Long-term climate patterns also influenced Hg exposure concentrations—temperature was a particularly strong effect as higher songbird Hg concentrations tended to be observed in warmer climates. Higher temperatures can influence Hg methylation rates in wetlands, so this observation may be describing regional patterns in methylation rates or climate-related wetland microhabitat differences. While the causality is unclear, these results suggest that future increases in temperature could result in increased songbird Hg exposure; while such patterns have been theorized, this study presents evidence for their importance.

In many ecosystems, trophic position can be a strong predictor of Hg exposure. In this study, species-level estimates were not a useful predictor of songbird Hg exposure. Rather, individual-level trophic position estimates through stable nitrogen isotope signatures proved to be strongly correlated with blood Hg concentrations. These data suggest that while species-level behavior patterns provide the potential for examining Hg exposure, individual dietary preferences and local trophic food web complexity are what turns this potential into actual exposure. Many songbird species are generalist invertivores that forage on a wide variety of species that are available in their local habitat, therefore, even small differences in foraging location and associated prey items could lead to significant changes in individual trophic level. These results suggest that when evaluating a site for Hg exposure risk to songbirds, the selection of ideal indicator species during the study design process is useful for providing a partial Hg assessment; however, establishing trophic positions of individuals is critical to determining the potential for Hg biomagnification of each individual, and thus effectively evaluating the absolute Hg exposure risk of the site.

The methods employed in this study were effective in assessing the status and trends of Hg exposure in songbirds, while also addressing questions about the origins of these patterns across New York State. For future monitoring efforts, a similar approach—focusing on songbird species sensitive to Hg bioavailability in conjunction with research locations that have a potential for high Hg methylation—is expected to be useful. A sample size of 20 individuals per site balances minimizing uncertainty while maximizing efficiency. The type of monitoring questions that need to be answered should dictate the remainder of the study design decision-making. Studies that are focused on statewide status assessment should maximize spatial coverage and attempt to describe trophic niches of each songbird sampled, while research projects linking patterns of Hg bioavailability to songbird Hg exposure might focus on intensive studies using repeated measures designs.

There are many questions that remain about the causes and patterns of Hg exposure in New York State songbird species. But this project has described the locations that merit further monitoring, habitat and climate conditions that create high Hg exposure conditions, as well as the role that trophic relationships play in determining Hg sensitivity. Climate change is a source of great uncertainty in forecasting the future of many species; the effects of Hg is another in a long list of potential effects that are not well understood. Species distributions will be altered, food webs will be reorganized, current habitats will migrate, and no-analog communities will be created with changing climate regimes (Williams and Jackson 2007). Mercury emissions, deposition, and methylation will likely change, and this study suggests at some of the first indications as to what songbird Hg exposure will look like in 50–100 years. Future research on understanding the small- and large-scale effects of a changing climate on Hg bioavailability across multiple ecosystems will help reduce such uncertainty and inform conservation decision-making from emissions regulations to species listing and delisting.

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Appendix A. Blood and Tail Feather Mercury Concentrations Parts per Million in New York State Songbirds, June–July 2013-2017

[submitted *in* nyserda_songbird_hg_monitoring.csv]

Appendix B. Blood and Feather Mercury Concentrations of Adult Birds with Blood Hg > 0.7 Parts per Million, Wet Weight (at Moderate or Greater Risk to Reproductive Effects)

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
Adirondacks	2016	Madawaska Flow	SWSP	M	1.112		0.59	
	2017	Spring Pond Bog	SAVS	M	0.98		0.21	
Catskills	2017	Sam's Point	GRCA	M	0.717		0.37	
	2013	Sam's Point	SOSP	M	0.743		0.58	
	2017	Sam's Point	EATO	F	0.745		0.48	
	2017	Sam's Point	SOSP	M	0.78		1.32	
	2016	Sam's Point	SOSP	M	0.826		1.36	
	2016	Sam's Point	EATO	F	0.937		0.68	
	2016	Sam's Point	EATO	F	0.981		0.96	
	2016	Sam's Point	SOSP	M	1.107		0.52	
	2015	Sam's Point	SOSP	F	1.162		5.04	
	2016	Sam's Point	SOSP	M	1.249		0.66	
	2014	Sam's Point	SOSP	M	1.809			
Finger Lakes	2016	N. Montezuma DEC	SWSP	F	0.715		2.06	
	2016	N. Montezuma DEC	WAVI	M	0.727		13.56	
	2015	N. Montezuma DEC	SWSP	M	0.791		1.93	3.17
	2016	N. Montezuma DEC	COYE	M	0.814		13.45	
	2016	N. Montezuma DEC	VIRA	U	0.873			3.79
	2016	N. Montezuma DEC	SOSP	M	1.216		4.41	
	2016	N. Montezuma DEC	SWSP	M	1.299		6.67	
	2016	N. Montezuma DEC	COYE	M	1.931		1.93	
	2016	N. Montezuma DEC	SWSP	M	4.425			
Long Island	2013	Accabonac Harbor	SALS	M	0.76	2.5	1.05	

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2013	Accabonac Harbor	SALS	M	0.8	12.58	1.7	
	2013	Accabonac Harbor	SALS	M	0.809	13.01	1.62	
	2016	Green Sedge Island	SESP	F	0.721			
	2016	Green Sedge Island	SALS	M	0.725		2.55	3.64
	2014	Green Sedge Island	SALS	F	0.733			
	2013	Green Sedge Island	SESP	M	0.734			
	2016	Green Sedge Island	SALS	F	0.734		1.59	2.01
	2017	Green Sedge Island	SALS	M	0.742	5.44	1.44	1.92
	2017	Green Sedge Island	SALS	F	0.773	2.84	0.91	2.19
	2016	Green Sedge Island	SESP	F	0.774		1.84	
	2016	Green Sedge Island	SESP	M	0.774		2.53	
	2013	Green Sedge Island	SALS	M	0.791			
	2016	Green Sedge Island	SESP	M	0.81		2.08	
	2014	Green Sedge Island	SALS	M	0.813	7.83	3.39	
	2014	Green Sedge Island	SALS	M	0.821	14.21	1.6	
	2016	Green Sedge Island	SALS	M	0.821		1.56	2.48
	2014	Green Sedge Island	SALS	F	0.826	27.04		
	2016	Green Sedge Island	SALS	M	0.826		3.64	2.77
	2017	Green Sedge Island	SESP	F	0.835		0.54	
	2013	Green Sedge Island	SESP	F	0.857		1.78	
	2017	Green Sedge Island	SESP	M	0.901	2.03	0.42	
	2017	Green Sedge Island	SALS	M	0.904	2.72	2.69	3.65
	2017	Green Sedge Island	SESP	M	0.906	2.06	0.96	
	2013	Green Sedge Island	SESP	F	0.918		1.27	

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2017	Green Sedge Island	SALS	M	0.959	2.38	0.78	1.54
	2014	Green Sedge Island	SESP	F	0.96	17.73	1.16	
	2016	Green Sedge Island	SALS	F	0.963		1.91	5.24
	2017	Green Sedge Island	SESP	F	0.963		1.06	
	2016	Green Sedge Island	SALS	M	0.978		1.96	4.19
	2014	Green Sedge Island	SALS	F	0.982	5.13	1.82	
	2016	Green Sedge Island	SALS	F	0.983			3.72
	2017	Green Sedge Island	SESP	M	0.986	2.31	1.34	
	2013	Green Sedge Island	SALS	M	0.988		2.48	
	2013	Green Sedge Island	SALS	F	0.989		1.45	
	2013	Green Sedge Island	SALS	F	0.995			
	2014	Green Sedge Island	SESP	M	0.995	14.38	1.24	
	2014	Green Sedge Island	SESP	M	1.012	17.73	1.61	
	2014	Green Sedge Island	SALS	M	1.013	21.73	0.64	
	2017	Green Sedge Island	SALS	F	1.017	4.4	1.29	2.75
	2017	Green Sedge Island	SESP	M	1.018	2.14	1.05	
	2017	Green Sedge Island	SESP	M	1.02	1.15	0.48	
	2014	Green Sedge Island	SESP	M	1.027	22.7	1.46	
	2016	Green Sedge Island	SALS	F	1.037		2.92	10.01
	2013	Green Sedge Island	SESP	M	1.039		3.1	
	2013	Green Sedge Island	SALS	M	1.066		2.95	
	2014	Green Sedge Island	SALS	M	1.069	27.99	2.75	
	2016	Green Sedge Island	SESP	M	1.107		1.92	
	2017	Green Sedge Island	SESP	F	1.121	2.08	0.29	

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2014	Green Sedge Island	SESP	F	1.141	1.24	1.87	
	2017	Green Sedge Island	SALS	F	1.143	3.31	0.69	1.11
	2016	Green Sedge Island	SESP	F	1.144		1.95	
	2017	Green Sedge Island	SALS	M	1.144	5	0.36	0.91
	2016	Green Sedge Island	SESP	F	1.151		1.04	
	2016	Green Sedge Island	SALS	M	1.158		1.58	1.96
	2014	Green Sedge Island	SALS	F	1.199	22.57	2.26	
	2016	Green Sedge Island	SALS	M	1.207		1.75	2.36
	2016	Green Sedge Island	SALS	M	1.276		2.71	2.65
	2013	Green Sedge Island	SALS	F	1.312		10.33	
	2013	Green Sedge Island	SALS	M	1.334		2.27	
	2016	Green Sedge Island	SALS	F	1.34		1.45	2.41
	2013	Green Sedge Island	SALS	F	1.388		1.18	
	2013	Green Sedge Island	SESP	F	1.499		0.71	
	2016	Green Sedge Island	SALS	F	1.514			3.35
	2016	North Cinder Island	SESP	M	0.744		1.84	
	2013	North Cinder Island	SESP	F	0.77			
	2015	North Cinder Island	SESP	M	0.77	11.05	1.22	1.51
	2013	North Cinder Island	SESP	F	0.778		1.18	
	2013	North Cinder Island	SESP	F	0.792		2.9	
	2013	North Cinder Island	SALS	F	0.865		4.19	
	2016	North Cinder Island	SESP	F	0.928		2.14	
	2013	North Cinder Island	SALS	F	0.941			
	2016	North Cinder Island	SALS	F	0.952		1.71	2.9

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2017	North Cinder Island	SALS	M	0.953	3.48		3.72
	2013	North Cinder Island	SESP	M	0.988		1.99	
	2015	North Cinder Island	SESP	F	0.988	17.01	2.06	4.05
	2014	North Cinder Island	SESP	M	1.002	7.03	1.06	
	2015	North Cinder Island	SESP	F	1.017	3.26	1.17	1.7
	2014	North Cinder Island	SALS	M	1.041	5.05	1.1	
	2013	North Cinder Island	SESP	M	1.045		1.25	
	2016	North Cinder Island	SESP	F	1.083		1.21	
	2016	North Cinder Island	SESP	M	1.084		1.59	
	2016	North Cinder Island	SALS	F	1.087		7.2	17
	2014	North Cinder Island	SALS	M	1.093	21.54	4.21	
	2016	North Cinder Island	SALS	M	1.093		1.77	2.78
	2015	North Cinder Island	SESP	M	1.1	7.34	3.11	6.06
	2016	North Cinder Island	SALS	F	1.121		2.72	3.69
	2017	North Cinder Island	SESP	M	1.124	1.77	0.8	
	2015	North Cinder Island	SALS	F	1.131	5.93	1.34	2.83
	2014	North Cinder Island	SESP	M	1.134	17.15	3	
	2016	North Cinder Island	SESP	M	1.164		2.35	
	2014	North Cinder Island	SESP	F	1.176	3.67	1.18	
	2017	North Cinder Island	SALS	F	1.187	4.35	4.5	8.24
	2014	North Cinder Island	SALS	M	1.189	2.72	2.58	
	2015	North Cinder Island	SESP	F	1.189	2.52	0.76	3.1
	2017	North Cinder Island	SALS	F	1.19	3.25	0.88	2.04
	2014	North Cinder Island	SALS	M	1.195	3.24	3.6	

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2016	North Cinder Island	SALS	M	1.211		6.66	9.03
	2015	North Cinder Island	SESP	M	1.213	15.71	2.33	3.57
	2016	North Cinder Island	SALS	M	1.213		1.78	2.33
	2013	North Cinder Island	SALS	F	1.219		3.68	
	2016	North Cinder Island	SALS	F	1.225			2.24
	2015	North Cinder Island	SESP	M	1.227	7.58	1.7	3.25
	2017	North Cinder Island	SALS	M	1.227	4.2	1.04	1.57
	2015	North Cinder Island	SESP	F	1.235	5.26		2.64
	2013	North Cinder Island	SALS	F	1.239		1.23	
	2014	North Cinder Island	SALS	M	1.246	25.88	2.92	
	2013	North Cinder Island	SALS	F	1.252			
	2014	North Cinder Island	SALS	M	1.255	2.53	11.54	
	2017	North Cinder Island	SALS	M	1.257	3.11	0.91	2.13
	2016	North Cinder Island	SALS	F	1.266			3.67
	2013	North Cinder Island	SALS	F	1.268		2.67	
	2017	North Cinder Island	SALS	F	1.272	2.8	0.47	0.9
	2016	North Cinder Island	SALS	F	1.277			3.75
	2017	North Cinder Island	SESP	F	1.293	1.55	0.77	
	2017	North Cinder Island	SALS	M	1.311	6.92	3.36	6.85
	2016	North Cinder Island	SALS	M	1.319		4.79	7.78
	2013	North Cinder Island	SALS	F	1.32			
	2015	North Cinder Island	SESP	M	1.324	15.75	2.19	3.68
	2017	North Cinder Island	SALS	M	1.332		1.49	2.41
	2017	North Cinder Island	SALS	M	1.375	3.74	2.98	4.14

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2016	North Cinder Island	SALS	F	1.404		1.97	2.71
	2016	North Cinder Island	SALS	M	1.417		3	4.82
	2016	North Cinder Island	SESP	M	1.428		5	
	2015	North Cinder Island	SESP	M	1.443	15.35	1.15	5.06
	2016	North Cinder Island	SALS	F	1.454		2.3	4.11
	2016	North Cinder Island	SALS	M	1.474		1.8	2.04
	2017	North Cinder Island	SALS	F	1.475	6.4	0.87	1.57
	2013	North Cinder Island	SALS	M	1.494		2.07	
	2015	North Cinder Island	SALS	F	1.5	23.71	2.2	5.32
	2017	North Cinder Island	SALS	M	1.51	10.78	0.87	1.63
	2017	North Cinder Island	SALS	M	1.543	18.65	3.14	1.37
	2017	North Cinder Island	SALS	M	1.546	9.35	1.46	2.54
	2016	North Cinder Island	SALS	M	1.55		1.17	1.82
	2015	North Cinder Island	SALS	M	1.561	4.3	2.1	4.05
	2014	North Cinder Island	SALS	M	1.568	2.46	2.69	
	2017	North Cinder Island	SALS	F	1.569	6.66	2.04	3.38
	2017	North Cinder Island	SALS	M	1.576	4.66	2.55	5.54
	2015	North Cinder Island	SESP	F	1.578	19.27		4.57
	2016	North Cinder Island	SALS	F	1.589		2.2	2.97
	2016	North Cinder Island	SALS	M	1.59		1.74	2.46
	2013	North Cinder Island	SALS	F	1.592		1.16	
	2015	North Cinder Island	SALS	M	1.602	22.52	3.38	3.28
	2017	North Cinder Island	SALS	M	1.625	6.77	0.86	1.92
	2015	North Cinder Island	SALS	M	1.636	5.22	1.91	2.72

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2014	North Cinder Island	SESP	F	1.641	7.26	1.17	
	2016	North Cinder Island	SALS	F	1.647		2.24	1.89
	2014	North Cinder Island	SALS	F	1.691	3.71	0.95	
	2014	North Cinder Island	SESP	M	1.714	2.21	1.05	
	2015	North Cinder Island	SALS	M	1.761	21.78	1.26	2.55
	2015	North Cinder Island	SESP	M	1.78	3.21	0.7	1.07
	2016	North Cinder Island	SALS	F	1.796		1.33	
	2014	North Cinder Island	SESP	M	1.849	2.83	0.44	
	2017	North Cinder Island	SALS	M	1.864	3.51	1.84	3.33
	2015	North Cinder Island	SALS	M	1.996	23.31	1.2	2.2
	2017	North Cinder Island	SESP	M	2.143	4.57	0.93	
	2015	North Cinder Island	SALS	F	2.145		1.31	3.21
	2014	North Cinder Island	SALS	F	2.258	42.86	3.64	
	2015	North Cinder Island	SALS	F	2.369	4.7	1.33	2.54
	2017	North Cinder Island	SALS	M	2.521	3.32	0.77	1.49
	2013	Oceanside-MNSA	SALS	F	0.707			
	2014	Oceanside-MNSA	SALS	F	0.713			
	2014	Oceanside-MNSA	SALS	M	0.719			
	2016	Oceanside-MNSA	SALS	F	0.745			
	2013	Oceanside-MNSA	SALS	M	0.753			
	2014	Oceanside-MNSA	SALS	F	0.754			
	2014	Oceanside-MNSA	SALS	M	0.757			
	2015	Oceanside-MNSA	SESP	U	0.763			
	2013	Oceanside-MNSA	SALS	M	0.764			

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2013	Oceanside-MNSA	SALS	F	0.765			
	2013	Oceanside-MNSA	SALS	M	0.777			
	2014	Oceanside-MNSA	SALS	M	0.796			
	2016	Oceanside-MNSA	SALS	F	0.799			
	2015	Oceanside-MNSA	SALS	M	0.812			
	2016	Oceanside-MNSA	SALS	F	0.814			
	2014	Oceanside-MNSA	SALS	M	0.835			
	2016	Oceanside-MNSA	SALS	M	0.841			
	2013	Oceanside-MNSA	SALS	M	0.853			
	2016	Oceanside-MNSA	SALS	M	0.862			
	2016	Oceanside-MNSA	SALS	M	0.869			
	2014	Oceanside-MNSA	SALS	M	0.892			
	2016	Oceanside-MNSA	SALS	M	0.923			
	2014	Oceanside-MNSA	SALS	M	0.924			
	2015	Oceanside-MNSA	SALS	F	0.93			24.35
	2016	Oceanside-MNSA	SALS	M	0.944			
	2015	Oceanside-MNSA	SALS	F	0.967	3.02		1.9
	2014	Oceanside-MNSA	SALS	M	1.02			
	2013	Oceanside-MNSA	SALS	M	1.051			
	2015	Oceanside-MNSA	SALS	M	1.201			
	2014	Oceanside-MNSA	SALS	M	1.276			
	2015	Oceanside-MNSA	SALS	M	1.284	12.68		2.56
	2015	Oceanside-MNSA	SALS	F	1.305	1.55		3.88
	2016	Oceanside-MNSA	SALS	M	1.414			

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2016	Oceanside-MNSA	SALS	M	1.47			
	2015	Oceanside-MNSA	SESP	F	1.932	21.93		
	2014	Oceanside-MNSA	SALS	F	1.978			
	2013	Pine Neck Preserve	SALS	F	0.705	3.39	1.39	
	2014	Pine Neck Preserve	SALS	F	0.708	3.29	1.42	
	2015	Pine Neck Preserve	SALS	F	0.725	2.59	1.58	3.07
	2014	Pine Neck Preserve	SALS	M	0.727	19.65	0.59	
	2013	Pine Neck Preserve	SALS	F	0.729	12.12	2.61	
	2014	Pine Neck Preserve	SALS	M	0.761	4.19	1.74	
	2013	Pine Neck Preserve	SALS	M	0.844	14.37	2.21	
	2013	Pine Neck Preserve	SALS	F	0.953	2.95	2.64	
	2014	Pine Neck Preserve	SALS	F	0.958	16.68	1.93	
	2015	Pine Neck Preserve	SALS	M	1.003	1.57	1.45	2.51
	2013	Pine Neck Preserve	SALS	F	1.024	3.21	1.56	
	2015	Pine Neck Preserve	SALS	F	1.031	2.29	1.24	1.73
	2015	Pine Neck Preserve	SALS	M	1.055		2.63	2.02
	2015	Pine Neck Preserve	SALS	F	1.137	13.27	3.34	3.14
	2015	Pine Neck Preserve	SALS	M	1.2	2.69	1.21	1.89
	2015	Pine Neck Preserve	SALS	F	1.315	2.29	1.59	2.45
New York City	2014	Idlewild Creek	SESP	M	0.718			
	2015	Idlewild Creek	SALS	F	1.046	2.83		3.41
	2013	Sawmill Creek	SESP	F	0.703			
	2015	Sawmill Creek	SALS	F	0.723	3.63		
	2016	Sawmill Creek	SESP	M	0.733			
	2014	Sawmill Creek	SALS	F	0.758			
	2013	Sawmill Creek	SALS	F	0.762			
	2013	Sawmill Creek	SALS	F	0.768			
	2014	Sawmill Creek	SESP	F	0.813			

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2013	Sawmill Creek	SESP	M	0.842			
	2014	Sawmill Creek	SALS	M	0.862			
	2014	Sawmill Creek	SALS	M	0.869			
	2013	Sawmill Creek	SALS	M	0.938			
	2013	Sawmill Creek	SALS	F	0.986			
	2013	Sawmill Creek	SALS	M	1.013			
	2014	Sawmill Creek	SALS	M	1.029			
	2013	Sawmill Creek	SALS	M	1.04			
	2013	Sawmill Creek	SALS	F	1.057			
	2014	Sawmill Creek	SALS	M	1.059			
	2016	Sawmill Creek	SESP	F	1.065			
	2014	Sawmill Creek	SALS	M	1.115			
	2014	Sawmill Creek	SALS	M	1.115			
	2013	Sawmill Creek	SALS	M	1.118			
	2016	Sawmill Creek	SALS	F	1.119			
	2014	Sawmill Creek	SALS	F	1.124			
	2014	Sawmill Creek	SESP	F	1.179			
	2014	Sawmill Creek	SESP	M	1.217			
	2014	Sawmill Creek	SALS	M	1.247			
	2013	Sawmill Creek	SALS	M	1.254			
	2014	Sawmill Creek	SALS	M	1.254			
	2014	Sawmill Creek	SALS	M	1.269			
	2015	Sawmill Creek	SALS	M	1.324	16		4.54
	2016	Sawmill Creek	SALS	M	1.372			
	2015	Sawmill Creek	SALS	F	1.381	3.31		
	2013	Sawmill Creek	SALS	F	1.386			
	2014	Sawmill Creek	SALS	F	1.405			
	2014	Sawmill Creek	SALS	M	1.408			
	2016	Sawmill Creek	SALS	M	1.415			
	2016	Sawmill Creek	SALS	F	1.456			
	2014	Sawmill Creek	SALS	F	1.587			
	2013	Sawmill Creek	SALS	M	1.627			
	2014	Sawmill Creek	SALS	M	1.74			
	2015	Sawmill Creek	SALS	M	1.775	27.92		
	2015	Sawmill Creek	SALS	F	1.777	24.62		3.56
	2016	Sawmill Creek	SALS	M	1.785			
	2014	Sawmill Creek	SESP	M	1.804			
	2016	Sawmill Creek	SALS	M	1.844			
	2014	Sawmill Creek	SALS	M	1.881			
	2015	Sawmill Creek	SESP	F	1.894	15.94		
	2016	Sawmill Creek	SALS	M	1.9			

Region	Year	Site	Species	Sex	Blood Hg	P1 Hg	Tail Hg	Flank Hg
	2015	Sawmill Creek	SALS	M	1.934	18.92		
	2014	Sawmill Creek	SALS	M	1.986			
	2015	Sawmill Creek	SESP	F	1.999	2.66		
	2015	Sawmill Creek	SESP	M	2.09	36.97		
	2016	Sawmill Creek	SESP	M	2.172			
	2016	Sawmill Creek	SESP	M	2.231			
	2015	Sawmill Creek	SALS	M	2.288	20.49		5.27
	2014	Sawmill Creek	SALS	M	2.747			

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