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The effects of climate, habitat, and trophic position on methylmercury bioavailability for breeding New York songbirds

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Abstract

Mercury (Hg) is a global pollutant that affects songbird populations across a variety of ecosystems following conversion to methylmercury (MeHg)—a form of Hg with high potential for bioaccumulation and bioavailability. The amount of bioavailable MeHg in an ecosystem is a function of the amount of total Hg present as well as Hg methylation rates, which vary across the landscape in space and time, and trophic transfer. Using songbirds as an indicator of MeHg bioavailability in terrestrial ecosystems, we evaluated the role of habitat, climate, and trophic level in dictating MeHg exposure risk across a variety of ecosystems. To achieve this objective, 2243 blood Hg samples were collected from 81 passerine and near-passerine species in New York State, USA, spanning 10 different sampling regions from Long Island to western New York. Using a general linear mixed modeling framework that accounted for regional variation in sampling species composition, we found that wetland habitat area within 100 m of capture location, 50-year average of summer maximum temperatures, and trophic position inferred using stable isotope analysis were all correlated with songbird blood Hg concentrations statewide. Moreover, these patterns had a large degree of spatial variability suggesting that the drivers of MeHg bioavailability differed significantly across the state. Mercury deposition, land cover, and climate are all expected to change throughout the northeastern United States in the coming decades. Terrestrial MeHg bioavailability will likely respond to these changes. Focused research and monitoring efforts will be critical to understand how exposure risk responds to global environmental change across the landscape.

Keywords Mercury · Methylmercury · Songbirds · Stable isotopes · Climate · Wetlands

Introduction

Mercury (Hg) is a pollutant that is globally distributed, but locally variable in its 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 sources (e.g., coal-fired power plants, municipal incinerators), Hg can be transported globally and deposited in 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., Evers et al. 2007) or via soil and/or water contamination from human activities (e.g., artisanal gold mining Telmer and Veiga 2009; Gibb and O'Leary 2014; industrial sites; Reis et al. 2009; Davis et al. 2012; Amos et al. 2013). Micro-organisms convert inorganic Hg to methylmercury (MeHg)—a form of Hg that has high potential for bioaccumulation and biomagnification (Boening 2000; Ullrich et al. 2001; Podar et al. 2015). In terrestrial habitats Hg methylation can occur in upland soils (Demers et al. 2007; Rodenhouse et al. 2019) and particularly wetland soils (St. Louis et al. 1994; Kramar et al. 2005).

Songbirds are recognized as critical indicators of MeHg in terrestrial ecosystems, where MeHg can biomagnify in food webs to concentrations that can adversely affect bird populations (Cristol et al. 2008; Jackson 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). These effects can influence population demography (Brasso and Cristol 2008; Evers et al. 2008; Jackson et al. 2011; Whitney and Cristol 2017). In particular, invertivores

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like many warblers, vireos, wrens, and some sparrows and thrushes, have been utilized in studies to provide a representation of MeHg concentrations in a variety of ecosystems (Rimmer et al. 2005; Lane et al. 2011; Edmonds et al. 2012; Townsend et al. 2014). However, songbirds can use a variety of habitats in a survey area resulting in individual variation in diet and trophic position resulting in pairing stable isotope with songbird MeHg studies to gain clarity on the causes of the results (Kidd et al. 1995; Cizdziel et al. 2002; Becker et al. 2002; Tsui et al. 2017). When species are habitat generalists, information on individual foraging ecology helps maximize accuracy and precision of monitoring efforts.

Global environmental changes are predicted over this century (Schindler 2001; Meehl et al. 2007), many of which will likely affect MeHg bioavailability in terrestrial food chains and songbirds. Methylmercury production has been shown to vary with Hg inputs, meteorological and hydrological conditions, redox status and land cover (Miskimmin et al. 1992; Ramlal et al. 1993; Sellers et al. 1996; Taylor et al. 2019; Eagles-Smith et al. 2018). In addition to the direct effects of climate on Hg methylation, climate and habitat change will likely alter the location and timing of hotspots of Hg methylation by influencing the abundance and distribution of wetland soils and the frequency and duration of wetting and drying cycles (Craft et al. 2009; Kirwan et al. 2010; Kirwan and Megonigal 2013; Mitsch and Hernandez 2013; Schile et al. 2014). Influx of Hg into ecosystems will change with Hg emissions (Zhang et al. 2016) and the influence of weather on Hg deposition (Mao et al. 2017a, 2017b; Ye et al. 2019). Finally, climate changes can remobilize local stores of Hg in soils and ice, which further increases MeHg bioavailability in habitats with high Hg methylation rates (Stern et al. 2012). Ultimately, as global environmental change alters spatial and temporal patterns of Hg deposition and methylation on the landscape, the future of MeHg bioavailability becomes increasingly uncertain.

In the face of anticipated changes in Hg emissions, deposition, and methylation rates, research on MeHg bioaccumulation in New York State, USA has used passerine and near-passerine communities to explain current patterns of terrestrial Hg biomagnification and bioaccumulation. A single indicator species is rarely present in terrestrial habitats statewide. As a result, sampling multiple species from a broader community is necessary to allow for more cost-effective and geographically comprehensive assessments. This research builds on 14 previous years of Hg research in New York State as well as other long-term Hg monitoring studies on songbirds across the northeastern United States (e.g., Sauer et al. 2019; Lane et al. 2011, 2019) to inform future MeHg monitoring efforts.

Songbird blood Hg concentrations collected in New York State from 2013–2017 were used to better understand the environmental variables that affect MeHg bioavailability in terrestrial ecosystems. As both abiotic and biotic conditions are known affect Hg methylation rates, we hypothesize that both climate and habitat at the sampling location combine to influence Hg concentrations in songbird blood. Moreover, we hypothesize that individual foraging patterns and diet influence blood Hg concentrations in songbirds. To describe patterns of Hg concentrations in songbird blood in New York and address these hypotheses we determined: (1) the species with the highest blood Hg concentrations in each sampling region; (2) the effects of habitat and climate on songbird blood Hg concentrations across all the sampling sites; and (3) the importance of individual diet on Hg blood concentrations using stable carbon and nitrogen isotope analysis. Further, we assess regional variation in the importance of climate, habitat, and individual diet to songbird blood Hg.

Methods

Sampling design and study areas

Songbird Hg sampling took place throughout New York State. Sites were selected in a based on the following criteria: (1) previous Hg sampling efforts for songbirds or other biota, (2) habitat sensitivity to MeHg bioaccumulation, and (3) proximity to Hg emission sources. Four 'core' sampling sites were selected in each of three regions known to have consistent elevated Hg concentrations capable of causing adverse effects in biota: the Adirondack Mountains, Catskill Mountains, and Long Island (Driscoll et al. 2007; Evers et al. 2007; Fig. 1). Core sites were visited each year to robustly sample each community and estimate interannual variation in Hg exposure (Table 1). Study sites within the Adirondack Park included boreal *Sphagnum* bog and wetland habitats and a mix of deciduous and coniferous upland forests types. Sites within the Catskills were representative of large wetland complexes, upland deciduous forest, and high-elevation mixed pine-oak forest. Long Island sites were primarily composed of tidal marsh and riparian forest.

In addition to these 12 core sites an additional 40 sampling sites were visited once during the five-year study. These sites were selected to increase the spatial scope and habitat diversity of the sampling effort. Previous information on songbird Hg exposure was not a prerequisite for site selection, but the remaining two selection criteria from the core site study design were used. Consequently, five additional regions were identified for statewide sampling: Western New York, Northern New York, Tug Hill Plateau, New York City, the Capital Region and the Finger Lakes (Fig. 1). Sites within the Western New York region were

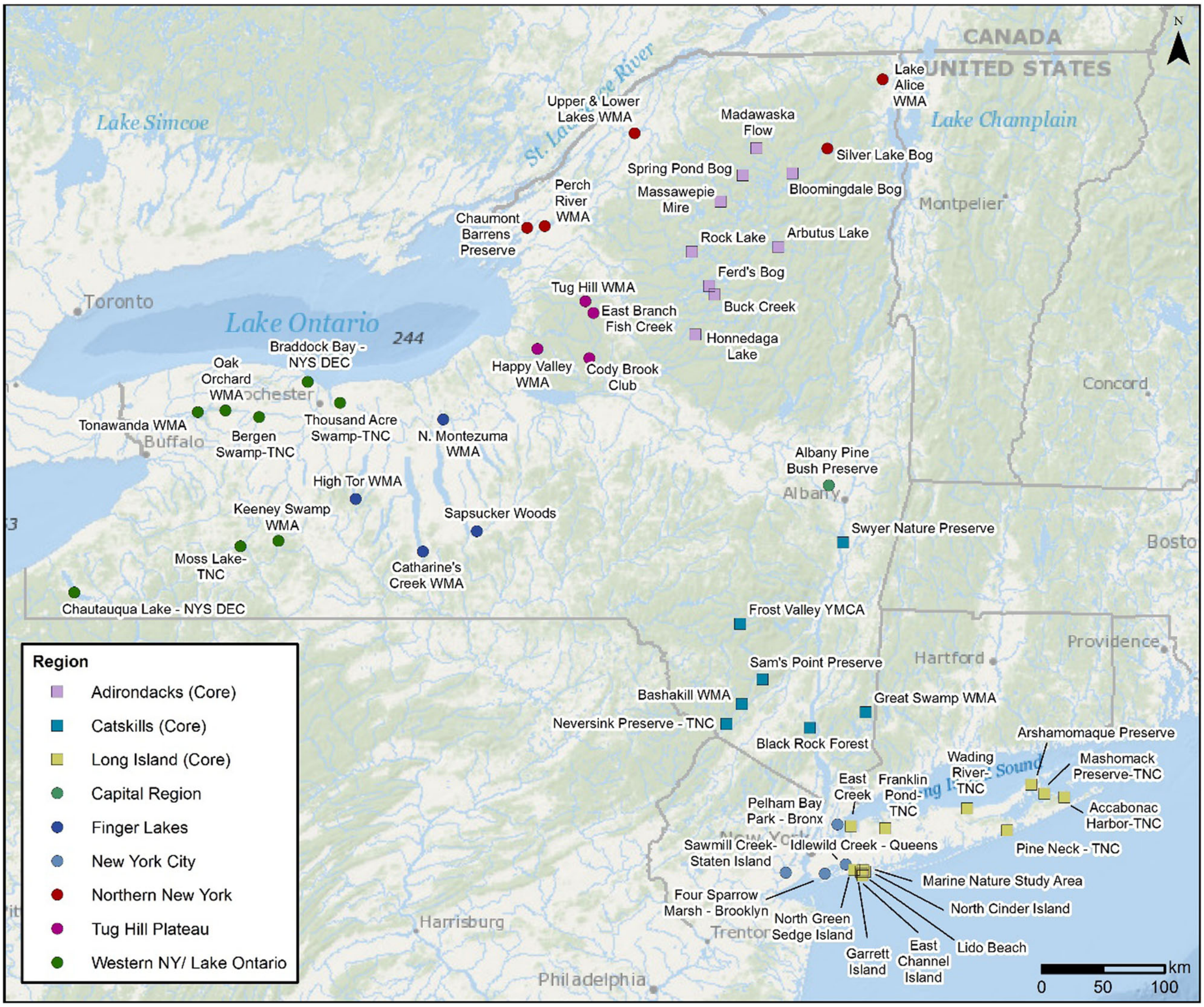

Fig. 1 Sampling locations for songbird blood Hg monitoring in New York, 2013–2017. Core regions are sites that were sampled in all five years of the study

Table 1 Mean of songbird blood Hg concentration (ppm ww) with standard deviation (SD) and sample size (n) of data by region and year in New York, USA (2013–2017)

Region	Year																	
	2013			2014			2015			2016			2017			All		
	Mean	SD	*n*	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	0.19	0.15	536
Capital region							0.05	0.04	56							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	0.14	0.16	509
Finger Lakes							0.37	0.20	17	0.35	0.54	84				0.35	0.48	101
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	0.57	0.49	603
Northern New York							0.10	0.10	55	0.20	0.14	33				0.14	0.12	88
New York City	0.41	0.33	75	0.49	0.51	107	0.53	0.57	62	0.50	0.55	64				0.48	0.49	308
Tug Hill				0.10	0.07	38	0.17	0.13	41							0.14	0.10	79
Western NY							0.14	0.11	46				0.12	0.08	98	0.13	0.09	144

comprised of mixed forest, forested wetlands, and emergent freshwater wetlands. Study sites in Northern New York and the Capital Region included a mix of alvar grasslands, large wetland complexes, and spruce bog/cedar swamp habitats. Tug Hill Plateau included sites representing deciduous upland forests and marsh-beaver meadow. Study sites within the greater New York City region included estuarine emergent marsh and coastal scrub. Finger Lakes sites were represented by several marsh and large wetland complexes interspersed with forest. Within each region, four to six sites were sampled. Generally, all sites in a given region were sampled in the same year, though there were a few exceptions for logistical reasons.

Bird capture and tissue sampling

All bird capture and tissue sampling was conducted from 2013–2017 during periods of peak breeding activity in June and July. Birds were captured by opening 6 m- and 12 m-long, 30–36 mm mesh mist nets for a minimum of 2 h. During this period, capture effort was augmented with conspecific vocalization playback for up to 30 min to attract birds to each net. Vocalizations from species known to be sensitive to Hg bioaccumulation were used in the audio playback to increase capture rate and bias the sample toward these species (Jackson et al. 2015).

Once captured, each bird was banded with a uniquely-numbered USGS aluminum band and sampled. Age, sex, and reproductive status were assessed using plumage and presence of cloacal protuberances/brood patches, and morphometric measures like wing chord length 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. Not all samples were large enough for both Hg and stable isotope analysis, so Hg determination was prioritized. The capillary tubes were sealed with Critocaps® and stored in plastic vacutainers on ice for up to 6 h before freezing at −17° Celsius. All birds were released unharmed within 10–25 min of capture.

Laboratory analysis

Blood samples were analyzed for total Hg at BRI's Wildlife Mercury Research Laboratory in Portland, Maine. Mercury concentration was determined via thermal decomposition coupled with atomic absorption spectroscopy using a Milestone DMA 80, following Environmental Protection Agency SW-846 Method 7473. Prior to analysis, the equipment was calibrated using NIST-certified standard solutions, and accuracy and precision were evaluated within each analytical batch through continued calibration verifications and the inclusion of certified reference materials, duplicates, blanks, and matrix spikes (approximately ten out of every 40 measurements). Quality control methods, including the use of one of the DOLT-certified reference materials (DOLT 4, DOLT 5) and BCR 463 or CE 464 were used to ensure consistent analytical precision and accuracy. Calibration utilized a blank and two standards, one for each of the two detector cells. Percent recovery of certified reference materials was >90% and relative percent difference (RPD) of duplicates were within 10%. The instrument detection limit was 0.001 μg/g, and all blood Hg concentrations were reported in μg/g wet weight (ww). Methylmercury was not analyzed because approximately 95% of total Hg in songbird blood is in the form of MeHg (Rimmer et al. 2005, Edmonds et al. 2010) and we assume this relationship is consistent across all songbird species.

A total of 1018 songbird blood samples were analyzed at the Boston University Stable Isotope Laboratory in Boston, Massachusetts for stable carbon and nitrogen isotope ratios. 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 70% water content, approximately 1.3 mg of blood was added to the capsules. All capsules were oven dried at 60 °C for 24 h 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.

Climate, habitat, and trophic position data integration

Independent variables were gathered from publicly available data sources to explain songbird blood Hg concentrations. To describe patterns of biomagnification, standardized diet composition data for each species was 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 position for most invertivores and can correlate with MeHg exposure risk (Cristol et al. 2008; Jackson et al. 2015). As stable isotope data was only available for a subset of the samples, the Wilman et al. (2014) data were used to infer species-level dietary differences for all sampled individuals.

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

Climate data were gathered from downscaled BCSD-CMIP5 climate projections (https://gdo-dcp.ucllnl.org/downscaled_cmip_projections). Monthly climate analysis results, used to train climate projection models from a common 20C3M simulation, were acquired at the 1/8-degree grid size scale from the Hydrology projection set. These data were used to describe the 50-year averages of maximum temperature and precipitation at the monthly time scale from 1950–1999. These data are not themselves assuming a climate projection scenario, but rather are modeled climate baseline data used to describe the climate of New York. The capture locations of all birds in our database were associated with the climate averages from a 1/8-degree grid cell. Some capture locations were just outside of the closest grid cell (e.g., tidal marsh sites on Long Island) so the climate averages from the nearest available cell were used as a reasonable approximation. Climate variables were averaged across a three-month seasonal window that matches the songbird breeding season for most species (June-August).

Statistical analysis

The mean, standard deviation, and sample size of Hg samples were used to describe overall patterns of Hg exposure for each region. To determine how differing factors influenced Hg bioavailability across sites, however, it was necessary to control for random variation in species and site sampling frequency. Blood Hg concentrations varied considerably across species, primarily due to differences in foraging habitat and diet, and the sampled songbird community varied significantly among sites, which was necessary to achieve unbiased estimates of site-level MeHg bioavailability.

To make comparisons among large numbers of species, this analysis controls for species-level and site-level variance and explains relative differences in species across habitat, climate, and trophic level. To achieve this goal, we parameterized three different general linear mixed models to answer three different questions; all models had a similar overall structure. The response variable used for the models was $\log_e$-transformed blood Hg concentrations. Goodness-of-fit was evaluated using R^2 (both marginal and conditional), quantile-quantile plots, and fitted versus residual plots. Samples without enough Hg to reach the detection limit were given the value of the analytical detection limit (0.001 Hg ppm ww) to avoid zeroes in the untransformed response variable. All independent covariates were tested for multicollinearity before inclusion. Continuous covariates were scaled by subtracting the mean then dividing by the standard deviation to improve maximum likelihood optimization. Not all individuals sampled were included in the analysis; only breeding birds (i.e., adults) and passerines or near-passerines (i.e., including woodpeckers but excluding incidental captures of raptors, shorebirds, and rails) were included in analysis ($n = 2243$). Recaptures within years were not included in the analysis, though the small number of recaptures among years were included.

The first model was designed to assess regional variation in species-level blood Hg concentrations and identify species with significant Hg bioaccumulation potential in each region. We used a general linear model with multiple nested random effects; this model parameterization allowed the average Hg blood concentration to be estimated independently for each species/region combination. The species variable was nested within region, and year (a categorical variable) was nested within 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 from this model (and the following models).

The second model was designed to assess the importance of climate and habitat in influencing terrestrial MeHg bioavailability (as estimated via songbird blood Hg). Nested random effects, fixed effects, and fixed effects with random components were all used to parameterize this model. Random effects were both nested and standalone; species nested within year and region was used to estimate annual means for each species in each region sampled. Site was also included as a random effect with no nesting or interactions to account for spatial variation in sampling within each region. Fixed effects included individual and environmental covariates that were thought to influence blood Hg levels: sex (male/female/unknown), the amount of forest/wetland habitat area around the capture area, the 50-year averages of maximum summer temperatures and total rainfall for the capture area, and the species-level percentage of invertebrates in the diet. For the wetland, temperature, rainfall, and diet covariates we added a random effect that allowed for regional variation in the main fixed effect, as these variables had the potential to have significant spatial variation in their effects.

The third model included the subset of Hg samples for which stable isotope analysis was conducted ($n = 1018$) and was constructed in a similar manner to the second model. Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes in blood were used to refine our understanding of the habitat origins of food source (as estimated by $\delta^{13}C$) and trophic level (as estimated by $\delta^{15}N$) in determining blood Hg at the individual scale. Using a similar general linear model structure to that described above, we parameterized a single model that included nested random effects, fixed effects, and fixed and random mixtures. Regional variation the relationship between $\delta^{13}C$ and $\delta^{15}N$ was allowed to account for differences in isotope composition among biomes (Hobson 1999). Sex was included as a fixed effect, and stable carbon and nitrogen isotopes were included as fixed effects with random components nested within region. As above, parameters that combined fixed and random effects estimated an overall effect of these covariates across all regions and then allowed for variation in Hg availability between regions.

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). Data manipulation and figure creation used 'dplyr' (Wickham et al. 2018) and 'ggplot2' (Wickham 2009), respectively.

Results

Mercury concentrations varied widely among sites and species. The blood Hg concentrations ranged from a low of <0.001 ppm ww (i.e., below the instrument detection limit) in an American Goldfinch at Neversink Preserve (Catskills) to a high of 4.1 ppm ww in a Swamp Sparrow from Northern Montezuma Wildlife Management Area (Finger Lakes). 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 1). Among the core regions, Long Island showed the highest overall interannual variation in Hg concentrations (Table 1).

Overall model fit

All three general linear mixed models showed strong 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 dependent variable (log-transformed blood Hg). The complex random effects structure used in this effort consistently explained more of the response variance than the fixed effects in all the models. Overall, this shows the importance of controlling for the species and location (site and region) random effects, particularly when using these data to make inference about broader patterns of MeHg availability.

Regional variation in species Hg concentrations

The large number of sites and multi-species sampling approach of this project provided an opportunity to evaluate the blood Hg concentration of many species. A summary of all species/region combinations can be found in supplemental materials (Appendix). Sixty-two percent of the total variation in the blood Hg data was explained by the species nested within region parameters. Changes in songbird Hg within sites and across years represented about 18% of the total variation. The five species with the highest Hg concentrations in each region included a wide range of invertivorous passerines (Fig. 2). Blood Hg concentrations in species varied significantly by region, thus the highest species in some regions were not significantly higher than the overall study average (e.g., the Capital Region) while other regions had many species that were significantly higher than the overall average (e.g., Long Island, the Adirondacks, and the Catskills). Seaside and Saltmarsh Sparrows had much higher average blood Hg concentrations than the other species but were only found in two regions. While Swamp Sparrows were identified as having elevated Hg concentrations relative to the other species sampled in seven different regions. Most species were only observed with elevated blood Hg concentrations in a single region. Sex was not an important predictor of blood Hg concentrations across this sampled community.

The effects of climate and habitat on Hg bioavailability

In the generalized linear mixed model with habitat and climate variables, random effects explained approximately 80% of the total variation in songbird blood Hg. Fixed effects explained 8%. Of the random effects, the nested parameters of year, region and species explained 24% of the total variation, and the regional variation in 50-year average summer maximum temperatures explained 44% of the total variation. Site explained 8% of the variation and all other random components explained <5% of the total variation. Of the fixed effects, the amount of wetland habitat in the sampling area was the only parameter that showed a statistically significant effect ($\beta = 0.17$, 95% Confidence Interval: 0.03–0.32; Fig. 3). The 50-year average summer rainfall was marginally statistically significant ($\beta = 0.23$, 95% CI: −0.04–0.49; Fig. 3). Species-level diet and forest habitat were not important to explaining patterns of Hg concentrations.

There was significant regional variance in the effects of wetlands and climate on songbird blood Hg concentrations. Overall, songbird blood Hg concentrations increased with increasing amounts of wetland habitat within 100 m of the sampling site; the positive effect of wetlands on blood Hg was particularly important in the New York City and Catskills regions (Fig. 4a). Summer maximum temperature had a more variable effect across regions. Western New York, New York City, and the Finger Lakes regions showed a strong positive relationship between temperature and blood Hg, while Northern New York had a negative

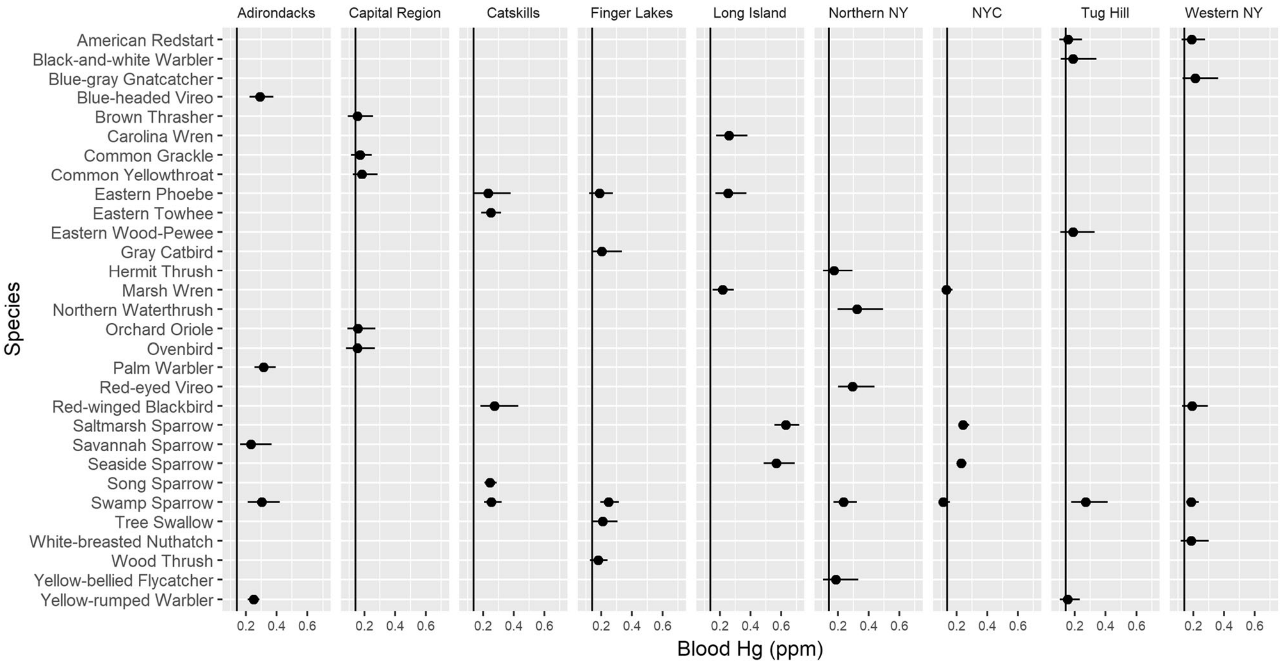

Fig. 2 Model estimated mean and variance of blood Hg concentrations (ppm ww) for the five highest species in each region. Estimates were obtained from a general linear mixed model that nested species within region and were calculated for males of each species. Error bars represent bootstrapped 95% confidence intervals of the mean. The vertical black line represents the study-wide average blood Hg concentration (0.14 ppm ww)

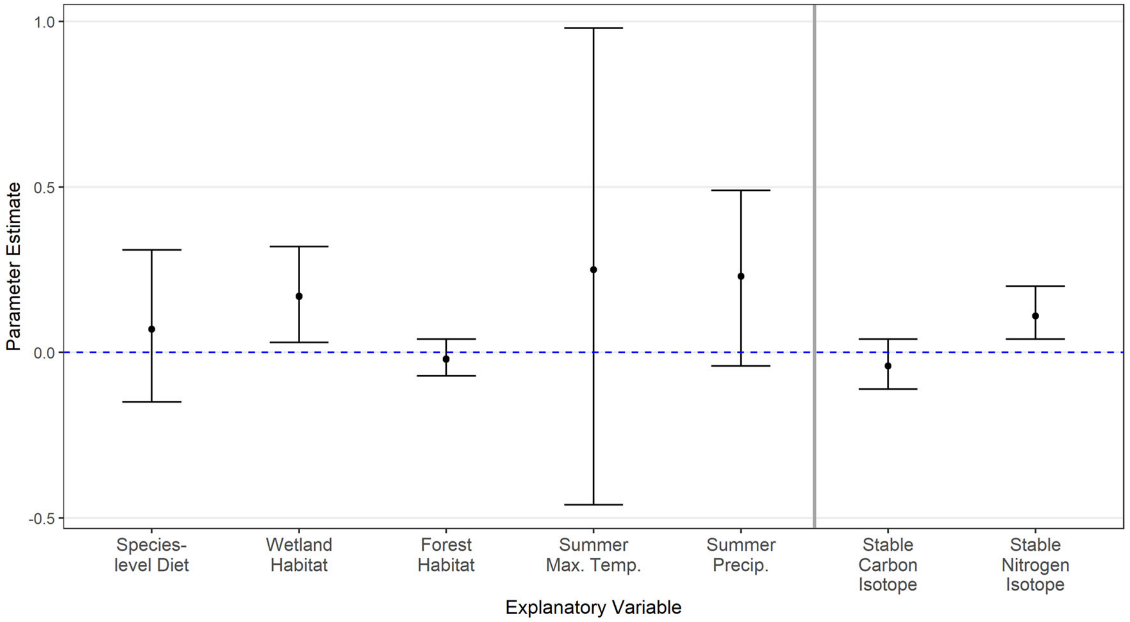

Fig. 3 Parameter estimates for fixed effects from two separate general linear mixed models that explained patterns in songbird blood Hg concentrations (ppm ww). All covariates were scaled before analysis so covariate magnitude is an accurate reflection of importance. Stable carbon and nitrogen estimates represent a subset of the total database and come from a different model than the rest of the estimates. Points represent maximum likelihood estimates of beta parameters and error bars are bootstrapped 95% confidence intervals

relationship (Fig. 4b). Here, even though the effect was not statistically significant for all regions, average temperatures were important to blood Hg concentrations in many regions and was one of the most important variables for explaining songbird blood Hg concentrations overall. Summer rainfall had a borderline important positive effect on blood Hg overall, but there was minimal regional variation in the effect.

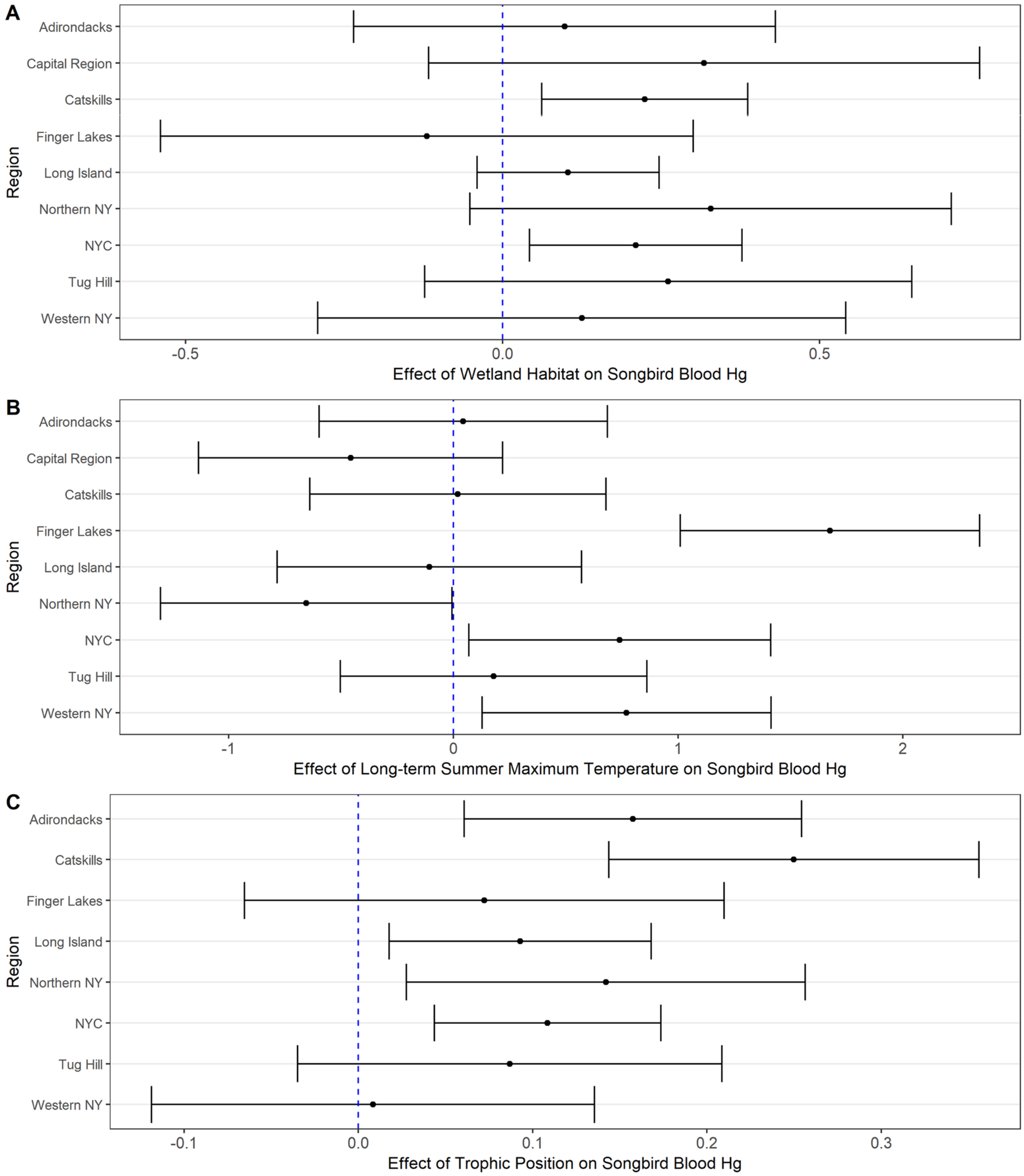

Fig. 4 Regional variation in the effect of wetland habitat area (**a**), summer maximum temperatures (**b**), and trophic position (**c**) on songbird blood Hg (ppm ww). The x-axis represents the slope of the relationship between the covariate and the response variable from a general linear mixed effects model. Regional means are a combination of the overall fixed effect beta estimate and random regional variation in the effect. 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

The effect of trophic position on Hg exposure risk

Using the stable isotope general linear mixed model, we were able to quantify the effects of individual-level $\delta^{13}C$ and $\delta^{15}N$ on songbird blood Hg levels. In this model, the random effects represented 72% of the total variance in songbird blood Hg and the fixed effects 8%. The most important random effect was region, which explained the vast majority of the variance in the data. Species nested within region and year parameters as well as the site parameters both explained much smaller portions of the total variance. In terms of fixed effects, there was a marginal negative effect of $\delta^{13}C$ on blood Hg levels that was consistent among regions ($\beta = -0.04$, 95% CI: −0.11–0.04; Fig. 3). Depleted (i.e., more negative) $\delta^{13}C$ values would indicate that the animal's food was coming from more mesic habitats, but we find no evidence of this effect. We lacked the data to understand site to site variation in stable carbon isotope signatures, and this likely reduced our power to assess this effect on Hg bioavailability. The effect of $\delta^{15}N$ was strongly positive overall ($\beta = 0.11$, 95% CI: 0.04–0.2, Fig. 3), and also variable by region (Fig. 4c). 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 unimportant only in Western NY, Tug Hill, and the Finger Lakes. The effect of sex on blood Hg concentration was negligible in this model, as it was in the previous analyses.

Discussion

From 2013–2017, blood Hg concentrations across the New York songbird community were affected by habitat, climate, and trophic level. The highest blood Hg concentrations were found in areas of historical Hg monitoring activity: Long Island, the Adirondack Mountains, and the Catskill Mountains. Saltmarsh Sparrows and Seaside Sparrows in the Long Island tidal marshes had elevated blood Hg concentrations that were similar to those found in past studies in the northeastern United States (Warner et al. 2010; Lane et al. 2011, 2019). At inland sites, wetland-dependent species like Palm Warblers also had elevated blood Hg levels that were similar to past studies (Sauer et al. 2019). We found evidence that wetland habitat, climate, and food webs combined to influence MeHg bioavailability in New York songbirds. The amount of nearby wetland habitat and the average maximum summer temperatures explained significant spatial variation in songbird blood Hg across New York. Summer precipitation had a marginally significant effect across all sites, while summer maximum temperature was highly variable in importance and effects across regions.

Variation in Hg bioaccumulation across songbirds

Species with elevated blood Hg concentrations are often useful for detecting spatiotemporal patterns in Hg distributions, as they show consistent accumulation of MeHg at sites and are efficient monitors of changes in MeHg availability (Furness 1993). Some of these species are distributed widely across regions; Swamp Sparrows, for example, were associated with freshwater wetland habitats with elevated Hg methylation rates and were found in multiple regions (e.g., New York City, Northern New York, Western New York, Tug Hill, and the Adirondack Mountains). Other species have narrow habitat requirements; Saltmarsh Sparrows and Seaside Sparrows are tidal marsh obligates (Correll et al. 2017) and while they were only found in two regions (New York City and Long Island) they had some of the highest average blood Hg concentrations found in this study.

Regional differences in Hg exposure results from a combination of many factors. Changes in atmospheric deposition of Hg over New York State (Mao et al. 2017a) and habitat- and soil-specific methylation rates (Ullrich et al. 2001; Podar et al. 2015; Rodenhouse et al. 2019) likely explain much of the observed variation. However, aside from species-level diet composition, we do not explore species-level traits as explanations for interspecies differences in Hg exposure. Annual schedules of nesting, migration, and molt can influence breeding ground blood Hg concentrations (Rimmer et al. 2005, Jackson et al. 2015, Seewagen 2018), and these trends are not accounted for in this study. Female birds eliminate Hg body burden during egg production (Heinz and Hoffman 2009), but we see no evidence of lower female body burden across all species in this study. This could be due to a non-random sampling of females overall (they were only 29% of the total sample), untested species-level variation, or sampling across multiple breeding stages.

Many of the species identified in this study are used as indicators in previous songbird Hg monitoring efforts. Previous studies in the northeastern United States suggest that Saltmarsh Sparrow, Common Yellowthroat, Swamp Sparrow, and Red-eyed Vireo have elevated tissue Hg concentrations (Jackson et al. 2015, Sauer et al. this issue), and several species have been used to assess environmental Hg bioavailability in other studies, including Tree Swallows (Longcore et al. 2007), *Catharus* thrushes (Townsend et al. 2014) and Northern Waterthrush (Adams et al. 2019). Some of these species, particularly tidal marsh endemics, are experiencing population declines and the role of MeHg in such trends is unclear (Lane et al. 2011, Correll et al. 2017). Monitoring efforts that include means to assess long-term effects of MeHg exposure are needed for species of conservation concern.

The effects of habitat and climate on MeHg exposure

Past research has suggested mechanisms for both habitat and climate to influence Hg deposition and methylation rates. Dry Hg deposition is elevated in forested landscapes while wet Hg deposition is dependent on rainfall (Mao et al. 2017a, 2017b; Risch and Kenski 2018; Ye et al. 2019). Rates of Hg methylation are highest in wetland soils and are increased by higher temperatures and flooding frequencies

(Ramlal et al. 1993; St. Louis et al. 2004; Windham-Myers et al. 2014). Causal connections between climate, habitat and songbird MeHg bioaccumulation have yet to be made, though the observations in this study emphasize the value of future work in this area. The role of wetland habitat area in Hg methylation rates seems clear (more wetlands increase MeHg production) but maximum summer temperatures could be associated with both Hg deposition or methylation rates (Meehl et al. 2007; Schindler 2001) and the mechanism of effect is unknown.

Regional variation in the relationship among wetland area, maximum summer temperatures, and songbird blood Hg suggest complex interactions dependent on habitat subtypes and spatial variation in Hg deposition. The regional effect of wetland area ranged from neutral to positive on songbird blood Hg and the mechanism of this effect is unknown. While data on this issue are limited, this result does not appear to be related to wetland subtype. Wetland area is most important to predicting songbird blood Hg concentrations in New York City (where the wetlands are almost entirely tidal marsh) and the Catskills (freshwater wetlands, lakes, and streams) but not extremely important in other similar regions. Given this observation, variation in biomagnification factor or species trophic niches across regions could be a major cause of this pattern. As this study observes the relative effect of habitat after accounting for species-level variation, this result could be dependent upon inconsistency in diet or habitat use within species. The effect of maximum summer temperatures on songbird blood Hg showed the most variation across regions. Northern New York shows a negative correlation between temperature and blood Hg, unlike the other regions where neutral to positive relationships were observed. These patterns are difficult to interpret due to the uncertainty of mechanism between temperature and terrestrial songbird Hg bioaccumulation. Spatial changes in this relationship could be due to variance in atmospheric Hg emissions or prevalence of appropriate Hg methylation conditions (Ullrich et al. 2001; Risch and Kenski 2018). A notable confounding variable could be elevation, which is correlated with both temperature and Hg deposition and would only influence regions with topographic variation (Yu et al. 2013).

Forecasted changes to wetland habitats and climate in North America in the coming decades have the potential to influence songbird MeHg bioavailability. Wetland habitat has declined globally (Zedler and Kercher 2005; Kirwan and Megonigal 2013) but appears stable in the northeastern United States partly due to human-created wetlands (Dahl 2011). Climate change is expected to increase both temperature and precipitation in the northeastern United States (Hayhoe et al. 2007, 2008). Moreover, changes to climate in New York also influences the amount of statewide wetland habitat, in both estuarine (Warren and Niering 1993) and palustrine systems (Hayhoe et al. 2007; Brooks 2009). The present study is based on continental-scale land cover data and 50-year climate averages; future work should focus on understanding the response of MeHg bioavailability to fine-scale changes in climate that will help build model-based forecasts of MeHg bioavailability.

The role of individual foraging niche on MeHg exposure

Individual trophic level is related to tissue Hg concentrations in biota across many ecosystems (Kidd et al. 1995; Cizdziel et al. 2002; Becker et al. 2002; Rodenhouse et al. 2019). While species-level traits can be useful for understanding variation in tissue Hg concentrations (Jackson et al. 2015), they do not explain much of the data observed in this study after species is accounted for. Moreover, regional variation in the relationship between $\delta^{15}N$ and blood Hg concentrations—a useful estimate of regional biomagnification factor—is significant in this study. Regional variation in food chain length is a potential explanation for this relationship (Cabana et al. 1994) and would further explain why species-level trophic level estimates are not predictive of the patterns seen in this study.

Given the lack of overall importance of $\delta^{13}C$ and significant regional differences in the relationship between $\delta^{13}C$ and songbird blood Hg concentrations, we find these data were not useful for explaining statewide patterns of MeHg bioavailability. While $\delta^{13}C$ is associated with mesic habitats with Hg methylation potential in past studies (Marra et al. 1998), it could also be associated with marine to freshwater transitions and other changes in C_3 and C_4 plant abundance (Kelly 2000). This lack of specificity limits the usefulness of these data to the present study, particularly due to the diversity of habitats sampled. Mercury isotopes are useful for identifying local sources of Hg in songbirds (Tsui et al. 2017), and these techniques show promise for understanding individual-level variation in songbird Hg exposure risk. Further work is needed to identify additional tools that accurately describe risk of increased Hg bioavailability across a range of habitats.

Conclusions

Using community sampling techniques, this study was able to estimate blood Hg concentrations across a large number of songbird species and determine how habitat and climate combine to influence relative changes in species Hg exposure across New York State. Wetland habitat and summer maximum temperatures influenced patterns in songbird blood Hg variably across regions. Blood Hg concentrations were also correlated with relative trophic position of individuals. The importance of habitat, climate, and trophic position varied by sampling region, which suggests that unmeasured differences in ecosystems are interacting with these variables to create multiple responses. While single-species study designs could lead to clear results when habitat is similar across study sites (e.g., Evers et al. 2007), this study showed that inference could be made across diverse species and habitats when sample size was sufficiently large and information was shared across species and regions. More research into the impact of sampling scheme on MeHg bioavailability is needed to assess current methods and develop new ones. A clear next step would be to add stable nitrogen sampling to all birds, as well as soils and invertebrates to better describe trophic relationships across regions.

While we have achieved an improved understanding of the scope and origin of songbird MeHg exposure in New York, there are many questions that remain. With some wetland habitats table in the northeast (Dahl 2011) and temperatures increasing (Hayhoe et al. 2007, 2008), future increases in terrestrial MeHg bioavailability appear likely. However, habitat and climate changes can create no-analog communities (Williams and Jackson 2007) that will make forecasting changes to MeHg bioavailability challenging. Recent industrial regulations in the United States appeared to reduce Hg emissions and depositions in the northeast (Driscoll et al. 2015) and reduction in emissions can lead to reductions in bioavailable MeHg (Lee et al. 2016), but these rules are currently in legal flux and their future is unclear. Thus, subsequent monitoring efforts must have the capacity to address multiple objectives: status and trends assessments will need to paired with connections to management actions and meaningful conservation decisions to maximize the knowledge that we gain and the impact of our science (Lyons et al. 2008). In this case, we must design projects that accurately estimate site- and species-level Hg exposure and trends while expanding our knowledge of the effect of habitat and climate and Hg bioaccumulation in terrestrial food webs. Studies that experimentally test mechanisms for climate and habitat interactions on MeHg bioavailability, while gathering detailed and site-specific data on habitat and climate in a variety of terrestrial ecosystems, will be critical to identifying species at risk to future adverse effects of Hg.

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Compliance with ethical standards

Conflict of interest This study was funded by the New York State Energy Research and Development Authority (NYSERDA, Award # 34358). All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Appendix. Estimates of methylmercury exposure across all species and all regions

Eighty-three species were sampled across all regions, including 214 unique species/region combinations. Here we include a figure that summarizes the average blood Hg concentrations (ppm ww) of all species/region combinations as estimated in the analysis. These averages (and 95% confidence intervals) are based on the generalized linear mixed modeling approach described in the text to identify species with elevated blood Hg concentrations in each region. Here we document the results for all species (Table 2).

Table 2 Model-estimated mean blood Hg concentrations for all species in each region using a general linear mixed modeling framework

Region	Species	Mean blood Hg estimate (ppm ww)	Lower 95% CI	Upper 95% CI	N
Adirondacks	Yellow Palm Warbler (*Setophaga palmarum*)	0.31	0.26	0.39	25
	Swamp Sparrow (*Melospiza georgia)*	0.3	0.23	0.42	6
	Blue-headed Vireo (*Vireo solitarius*)	0.29	0.23	0.36	11
	Yellow-rumped Warbler (*Setophaga coronata*)	0.25	0.21	0.29	32
	Savannah Sparrow (*Passerculus sandwichensis*)	0.24	0.17	0.34	4
	Common Yellowthroat (*Geothlypis trichas*)	0.22	0.19	0.28	21
	Lincoln's Sparrow (*Melospiza lincolnii*)	0.21	0.18	0.26	39
	Red-eyed Vireo (*Vireo olivaceus*)	0.2	0.18	0.23	71
	Red-breasted Nuthatch (*Sitta canadensis*)	0.17	0.13	0.24	6
	Canada Warbler (*Cardelli canadensis*)	0.15	0.11	0.19	9
	Song Sparrow (*Melospiza melodia*)	0.14	0.09	0.25	1
	White-breasted Nuthatch (*Sitta carolinensis*)	0.13	0.08	0.22	1
	Brown Creeper (*Certhia america)*	0.13	0.09	0.21	4
	American Redstart (*Setophaga ruticilla*)	0.13	0.11	0.15	22
	Blackburnian Warbler (*Setophaga fusca*)	0.12	0.1	0.14	24
	Black-and-white Warbler (*Mniotilta varia*)	0.12	0.09	0.17	6
	Magnolia Warbler (*Setophaga magnolia*)	0.12	0.09	0.17	6
	Black-throated Green Warbler (*Setophaga virens*)	0.11	0.09	0.14	20
	Hermit Thrush (*Catharus guttatus*)	0.11	0.1	0.13	37
	Swainson's Thrush (*Catharus ustulatus*)	0.11	0.1	0.13	43
	Nashville Warbler (*Leiothlypis ruficapilla*)	0.11	0.09	0.14	16
	Northern Parula (*Setophaga america*)	0.11	0.07	0.16	5
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.1	0.06	0.15	2
	Black-throated Blue Warbler (*Setophaga caerulescens)*	0.09	0.07	0.1	37
	Black-capped Chickadee (*Poecile atricapillus*)	0.09	0.07	0.12	10
	White-throated Sparrow (*Zonotrichia albicollis*)	0.08	0.07	0.1	19
	Field Sparrow (*Spizella pusilla*)	0.08	0.04	0.14	1
	Ovenbird (*Seiurus aurocapilla*)	0.07	0.06	0.08	47
	Dark-eyed Junco (*Junco hyemalis*)	0.05	0.04	0.07	10
	Downy Woodpecker (*Picoides pubescens*)	0.05	0.02	0.08	1
	Yellow-bellied Sapsucker (*Sphyrapicus varius*)	0.04	0.02	0.06	2
Capital region	Common Yellowthroat (*Geothlypis trichas*)	0.18	0.12	0.27	6
	Common Grackle (*Quiscalus quiscula*)	0.18	0.12	0.27	3
	Brown Thrasher (*Toxostoma rufum*)	0.16	0.09	0.28	4
	Eastern Bluebird (*Sialia sialis*)	0.15	0.09	0.25	5
	Orchard Oriole (*Icterus spurius*)	0.15	0.08	0.26	1
	Chipping Sparrow (*Spizella passeri)*	0.14	0.09	0.24	2
	Ovenbird (*Seiurus aurocapilla*)	0.14	0.09	0.25	1
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.14	0.08	0.24	1
	Prairie Warbler (*Setophaga discolor*)	0.13	0.08	0.21	1
	Red-winged Blackbird (*Agelaius phoeniceus*)	0.13	0.09	0.18	7
	Baltimore Oriole (*Icterus galbula*)	0.13	0.07	0.21	8
	Song Sparrow (*Melospiza melodia*)	0.13	0.08	0.21	4
	Gray Catbird (*Dumetella carolinensis*)	0.11	0.08	0.16	6
	Brown-headed Cowbird (*Molothrus ater*)	0.09	0.06	0.16	3

Table 2 (continued)

Region	Species	Mean blood Hg estimate (ppm ww)	Lower 95% CI	Upper 95% CI	N
	American Robin (*Turdus migratorius*)	0.09	0.05	0.15	1
	Cedar Waxwing (*Bombycilla cedrorum*)	0.05	0.03	0.1	3
	Purple Finch (*Haemorhous purpureus*)	0.04	0.02	0.07	3
Catskills	Red-winged Blackbird (*Agelaius phoeniceus*)	0.27	0.18	0.4	3
	Swamp Sparrow (*Melospiza georgia*)	0.25	0.2	0.31	20
	Eastern Towhee (*Pipilo erythrophthalmus*)	0.24	0.19	0.31	12
	Song Sparrow (*Melospiza melodia*)	0.24	0.2	0.28	34
	Eastern Phoebe (*Sayornis phoebe*)	0.23	0.14	0.37	2
	Eastern Wood-Pewee (*Contopus virens*)	0.22	0.16	0.34	4
	Eastern Kingbird (*Tyrannus tyrannus*)	0.21	0.12	0.35	1
	Alder Flycatcher (*Empidonax alnorum*)	0.21	0.12	0.39	1
	Great Crested Flycatcher (*Myiarchus crinitus*)	0.19	0.13	0.29	3
	Louisiana Waterthrush (*Parkesia motacilla*)	0.19	0.15	0.24	11
	Gray Catbird (*Dumetella carolinensis*)	0.18	0.16	0.22	48
	Carolina Wren (*Thryothorus ludovicianus*)	0.17	0.11	0.28	2
	American Redstart (*Setophaga ruticilla*)	0.17	0.14	0.21	27
	American Robin (*Turdus migratorius*)	0.17	0.11	0.24	3
	Wood Thrush (*Hylocichla musteli)*	0.16	0.12	0.22	7
	Yellow-rumped Warbler (*Setophaga coronata*)	0.16	0.12	0.23	7
	Common Yellowthroat (*Geothlypis trichas*)	0.16	0.13	0.17	64
	Red-eyed Vireo (*Vireo olivaceus*)	0.15	0.13	0.17	48
	Magnolia Warbler (*Setophaga magnolia*)	0.14	0.09	0.24	1
	Pine Warbler (*Setophaga pinus*)	0.14	0.09	0.24	2
	Black-throated Green Warbler (*Setophaga virens*)	0.14	0.08	0.21	1
	Acadian Flycatcher (*Empidonax virescens*)	0.14	0.08	0.23	1
	Tufted Titmouse (*Baeolophus bicolor*)	0.14	0.09	0.2	3
	Black-and-white Warbler (*Mniotilta varia*)	0.13	0.09	0.16	12
	Blackburnian Warbler (*Setophaga fusca*)	0.12	0.07	0.2	1
	Veery (*Catharus fuscescens*)	0.12	0.1	0.13	51
	Yellow Warbler (*Setophaga petechia*)	0.11	0.09	0.14	18
	Prairie Warbler (*Setophaga discolor*)	0.1	0.08	0.15	6
	White-breasted Nuthatch (*Sitta carolinensis*)	0.09	0.05	0.14	2
	Black-capped Chickadee (*Poecile atricapillus*)	0.09	0.06	0.11	9
	Field Sparrow (*Spizella pusilla*)	0.08	0.05	0.14	2
	Rose-breasted Grosbeak (*Pheucticus ludovicianus*)	0.08	0.05	0.14	1
	Ovenbird (*Seiurus aurocapilla*)	0.08	0.07	0.1	35
	Downy Woodpecker (*Picoides pubescens*)	0.08	0.05	0.12	4
	Worm-eating Warbler (*Helmitheros vermivorum*)	0.07	0.05	0.12	2
	Dark-eyed Junco (*Junco hyemalis*)	0.07	0.04	0.11	1
	Yellow-bellied Sapsucker (*Sphyrapicus varius*)	0.07	0.04	0.11	1
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.07	0.06	0.09	18
	Blue-winged Warbler (*Vermivora cyanoptera*)	0.06	0.04	0.09	5
	American Goldfinch (*Spinus tristis*)	0.06	0.04	0.1	2
	Northern Cardinal (*Cardinalis cardinalis*)	0.06	0.04	0.09	6
	Indigo Bunting (*Passeri cyanea*)	0.06	0.04	0.08	11
	Black-throated Blue Warbler (*Setophaga caerulescens)*	0.05	0.03	0.08	3

Table 2 (continued)

Region	Species	Mean blood Hg estimate (ppm ww)	Lower 95% CI	Upper 95% CI	N
Finger Lakes	Swamp Sparrow (*Melospiza georgia)*	0.24	0.18	0.3	17
	Gray Catbird (*Dumetella carolinensis*)	0.21	0.13	0.32	2
	Tree Swallow (*Tachycineta bicolor*)	0.2	0.13	0.31	2
	Eastern Phoebe (*Sayornis phoebe*)	0.18	0.11	0.29	2
	Wood Thrush (*Hylocichla musteli)*	0.18	0.12	0.26	4
	Marsh Wren (*Cistothorus palustris*)	0.16	0.09	0.28	1
	Eastern Wood-Pewee (*Contopus virens*)	0.15	0.08	0.26	1
	Common Yellowthroat (*Geothlypis trichas*)	0.15	0.12	0.19	17
	Song Sparrow (*Melospiza melodia*)	0.14	0.11	0.17	19
	Common Grackle (*Quiscalus quiscula*)	0.14	0.09	0.24	1
	Tufted Titmouse (*Baeolophus bicolor*)	0.13	0.08	0.23	1
	Willow Flycatcher (*Empidonax traillii*)	0.12	0.07	0.22	1
	Red-winged Blackbird (*Agelaius phoeniceus*)	0.12	0.08	0.17	4
	White-breasted Nuthatch (*Sitta carolinensis*)	0.12	0.07	0.2	1
	Warbling Vireo (*Vireo gilvus*)	0.11	0.08	0.15	9
	American Robin (*Turdus migratorius*)	0.09	0.06	0.16	3
	Downy Woodpecker (*Picoides pubescens*)	0.09	0.06	0.16	1
	Yellow Warbler (*Setophaga petechia*)	0.09	0.05	0.15	1
	Black-capped Chickadee (*Poecile atricapillus*)	0.08	0.06	0.11	7
	Hairy Woodpecker (*Picoides villosus*)	0.06	0.03	0.09	1
Long Island	Saltmarsh Sparrow (*Ammodramus caudacutus*)	0.62	0.54	0.7	237
	Seaside Sparrow (*Ammodramus maritimus*)	0.57	0.47	0.68	65
	Carolina Wren (*Thryothorus ludovicianus*)	0.26	0.18	0.38	5
	Eastern Phoebe (*Sayornis phoebe*)	0.26	0.18	0.39	5
	Marsh Wren (*Cistothorus palustris*)	0.21	0.15	0.29	9
	Wood Thrush (*Hylocichla musteli)*	0.2	0.13	0.31	3
	Great Crested Flycatcher (*Myiarchus crinitus*)	0.18	0.14	0.23	13
	House Wren (*Troglodytes aedon*)	0.17	0.13	0.22	14
	Common Yellowthroat (*Geothlypis trichas*)	0.17	0.12	0.23	8
	Veery (*Catharus fuscescens*)	0.17	0.09	0.29	1
	Red-eyed Vireo (*Vireo olivaceus*)	0.15	0.13	0.18	32
	American Redstart (*Setophaga ruticilla*)	0.14	0.1	0.18	15
	Red-winged Blackbird (*Agelaius phoeniceus*)	0.14	0.1	0.18	8
	Yellow-throated Vireo (*Vireo flavifrons*)	0.14	0.08	0.24	1
	Eastern Towhee (*Pipilo erythrophthalmus*)	0.14	0.09	0.24	2
	Common Grackle (*Quiscalus quiscula*)	0.12	0.09	0.17	8
	White-breasted Nuthatch (*Sitta carolinensis*)	0.12	0.09	0.17	7
	Prairie Warbler (*Setophaga discolor*)	0.11	0.07	0.18	3
	Song Sparrow (*Melospiza melodia*)	0.11	0.09	0.14	13
	Scarlet Tanager (*Piranga olivacea*)	0.11	0.07	0.17	2
	Tufted Titmouse (*Baeolophus bicolor*)	0.09	0.08	0.12	15
	Chipping Sparrow (*Spizella passeri)*	0.09	0.06	0.15	1
	Gray Catbird (*Dumetella carolinensis*)	0.09	0.08	0.11	81
	Hairy Woodpecker (*Picoides villosus*)	0.09	0.06	0.15	2
	Warbling Vireo (*Vireo gilvus*)	0.09	0.06	0.13	6
	Blue Jay (*Cyanocitta cristata*)	0.08	0.05	0.14	1

Table 2 (continued)

Region	Species	Mean blood Hg estimate (ppm ww)	Lower 95% CI	Upper 95% CI	N
	American Robin (*Turdus migratorius*)	0.08	0.06	0.1	14
	Yellow Warbler (*Setophaga petechia*)	0.07	0.06	0.1	10
	Downy Woodpecker (*Picoides pubescens*)	0.07	0.04	0.1	3
	Northern Cardinal (*Cardinalis cardinalis*)	0.06	0.05	0.08	12
	Black-capped Chickadee (*Poecile atricapillus*)	0.05	0.04	0.07	14
	House Finch (*Haemorhous mexicanus*)	0.03	0.02	0.06	1
Northern New York	Northern Waterthrush (*Parkesia noveboracensis*)	0.31	0.19	0.52	2
	Red-eyed Vireo (*Vireo olivaceus*)	0.29	0.2	0.45	5
	Swamp Sparrow (*Melospiza georgia*)	0.23	0.18	0.32	8
	Yellow-bellied Flycatcher (*Empidonax flaviventris*)	0.18	0.11	0.31	1
	Common Yellowthroat (*Geothlypis trichas*)	0.17	0.13	0.22	10
	Hermit Thrush (*Catharus guttatus*)	0.17	0.11	0.28	1
	White-throated Sparrow (*Zonotrichia albicollis*)	0.16	0.09	0.3	1
	Magnolia Warbler (*Setophaga magnolia*)	0.16	0.11	0.23	3
	Canada Warbler (*Cardelli canadensis*)	0.15	0.09	0.26	1
	Warbling Vireo (*Vireo gilvus*)	0.14	0.09	0.23	2
	Eastern Towhee (*Pipilo erythrophthalmus*)	0.13	0.09	0.19	3
	Yellow Warbler (*Setophaga petechia*)	0.13	0.08	0.2	3
	Golden-winged Warbler (*Vermivora chrysoptera*)	0.13	0.08	0.22	1
	Swainson's Thrush (*Catharus ustulatus*)	0.13	0.08	0.19	2
	Black-capped Chickadee (*Poecile atricapillus*)	0.12	0.07	0.18	1
	Song Sparrow (*Melospiza melodia*)	0.12	0.09	0.15	9
	Field Sparrow (*Spizella pusilla*)	0.11	0.06	0.2	1
	Gray Catbird (*Dumetella carolinensis*)	0.1	0.06	0.17	2
	Nashville Warbler (*Leiothlypis ruficapilla*)	0.1	0.06	0.17	1
	Black-billed Cuckoo (*Coccyzus erythropthalmus*)	0.09	0.06	0.17	1
	American Robin (*Turdus migratorius*)	0.08	0.05	0.15	1
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.08	0.05	0.14	1
	Cedar Waxwing (*Bombycilla cedrorum*)	0.08	0.05	0.13	1
	American Goldfinch (*Spinus tristis*)	0.05	0.03	0.08	1
	Purple Finch (*Haemorhous purpureus*)	0.03	0.02	0.05	1
NYC	Saltmarsh Sparrow (*Ammodramus caudacutus*)	0.24	0.2	0.27	152
	Seaside Sparrow (*Ammodramus maritimus*)	0.22	0.2	0.26	134
	Marsh Wren (*Cistothorus palustris*)	0.13	0.1	0.16	8
	Swamp Sparrow (*Melospiza georgia*)	0.12	0.09	0.15	3
Tug Hill	Swamp Sparrow (*Melospiza georgia*)	0.27	0.18	0.39	4
	Eastern Wood-Pewee (*Contopus virens*)	0.19	0.11	0.33	1
	Black-and-white Warbler (*Mniotilta varia*)	0.18	0.1	0.29	1
	Magnolia Warbler (*Setophaga magnolia*)	0.16	0.09	0.24	1
	Yellow-rumped Warbler (*Setophaga coronata*)	0.15	0.1	0.23	3
	American Redstart (*Setophaga ruticilla*)	0.15	0.09	0.24	3
	Wood Thrush (*Hylocichla musteli*)	0.14	0.1	0.24	4
	Red-eyed Vireo (*Vireo olivaceus*)	0.14	0.11	0.17	13
	Song Sparrow (*Melospiza melodia*)	0.13	0.09	0.18	7
	Black-throated Green Warbler (*Setophaga virens*)	0.12	0.07	0.19	2
	Common Yellowthroat (*Geothlypis trichas*)	0.12	0.08	0.16	7

Table 2 (continued)

Region	Species	Mean blood Hg estimate (ppm ww)	Lower 95% CI	Upper 95% CI	N
	Blackburnian Warbler (*Setophaga fusca*)	0.12	0.06	0.2	1
	Hermit Thrush (*Catharus guttatus*)	0.1	0.07	0.14	4
	Veery (*Catharus fuscescens*)	0.1	0.06	0.17	1
	Black-capped Chickadee (*Poecile atricapillus*)	0.09	0.06	0.15	2
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.08	0.05	0.14	2
	Ovenbird (*Seiurus aurocapilla*)	0.08	0.07	0.11	13
	Gray Catbird (*Dumetella carolinensis*)	0.07	0.04	0.13	2
Western NY	Blue-gray Gnatcatcher (*Polioptila caerulea*)	0.21	0.13	0.39	2
	Red-winged Blackbird (*Agelaius phoeniceus*)	0.2	0.13	0.27	4
	Red-eyed Vireo (*Vireo olivaceus*)	0.19	0.15	0.26	10
	American Redstart (*Setophaga ruticilla*)	0.19	0.12	0.27	4
	Swamp Sparrow (*Melospiza georgia*)	0.19	0.15	0.25	17
	White-breasted Nuthatch (*Sitta carolinensis*)	0.18	0.11	0.3	2
	Pine Warbler (*Setophaga pinus*)	0.17	0.1	0.29	1
	Willow Flycatcher (*Empidonax traillii*)	0.17	0.11	0.26	3
	Northern Waterthrush (*Parkesia noveboracensis*)	0.17	0.1	0.31	1
	Alder Flycatcher (*Empidonax alnorum*)	0.16	0.1	0.28	1
	Ovenbird (*Seiurus aurocapilla*)	0.13	0.08	0.21	1
	Eastern Phoebe (*Sayornis phoebe*)	0.13	0.08	0.22	1
	Common Yellowthroat (*Geothlypis trichas*)	0.12	0.09	0.15	19
	Gray Catbird (*Dumetella carolinensis*)	0.12	0.08	0.17	6
	Great Crested Flycatcher (*Myiarchus crinitus*)	0.12	0.06	0.2	1
	Chestnut-sided Warbler (*Setophaga pensylvanica*)	0.11	0.07	0.19	1
	Black-capped Chickadee (*Poecile atricapillus*)	0.11	0.08	0.15	8
	Song Sparrow (*Melospiza melodia*)	0.11	0.09	0.13	33
	Wood Thrush (*Hylocichla musteli)*	0.1	0.06	0.17	2
	Warbling Vireo (*Vireo gilvus*)	0.08	0.05	0.13	2
	Tufted Titmouse (*Baeolophus bicolor*)	0.08	0.05	0.13	3
	Yellow Warbler (*Setophaga petechia*)	0.06	0.05	0.09	17
	Yellow-bellied Sapsucker (*Sphyrapicus varius*)	0.06	0.04	0.09	2
	Downy Woodpecker (*Picoides pubescens*)	0.05	0.03	0.08	2

Modeled values are for males of each species, as they were the most common (though N is for all captures of the species included in the model). Species are ranked from highest to lowest average Hg values for each region they were found. Upper and lower 95% confidence intervals are shown for the model-estimated mean

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