

The Impact of Mercury on North American Songbirds

*Effects, Trends, and
Predictive Factors*

About this Publication

To inform policy efforts and advance public understanding, a group of 61 scientists collaborated on producing 15 papers that describe the impacts of mercury on songbirds across the United States and Canada. These papers are collected in the October 2020 special issue of *Ecotoxicology*. This publication, *The Impact of Mercury on North American Songbirds*, highlights the major findings of those studies and collaborative effort.

Journal Article Numbering System within this Publication



The studies in the special issue of *Ecotoxicology* are listed on page 21. Reference to each study is identified through this booklet with this icon.

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About Biodiversity Research Institute

Biodiversity Research Institute (BRI), headquartered in Portland, Maine, is a nonprofit ecological research group whose mission is to assess emerging threats to wildlife and ecosystems through collaborative research, and to use scientific findings to advance environmental awareness and inform decision makers.



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Introduction

In 2012, Biodiversity Research Institute (BRI) published groundbreaking research results in *Hidden Risk: Mercury in Terrestrial Ecosystems of the Northeast* (Evers et al. 2012). At the time, it had been well documented that aquatic environments contained mercury, which, when converted to its organic form methylmercury, entered food webs and adversely affected the health of wildlife that are part of that ecosystem. However, there was little known about mercury in the terrestrial environment.

Hidden Risk underscored the magnitude of the problems caused for wildlife by mercury in the environment, particularly for songbird species that included: Bicknell's Thrush (Rimmer et al. 2005); Rusty Blackbird (Edmunds et al. 2010); Saltmarsh Sparrow (Lane et al. 2011); and other songbird invertivores (species that eat insects and spiders; Evers et al. 2005).

Now, nearly a decade later, further research published in a special issue of the journal *Ecotoxicology* reveals the far-reaching impacts mercury has on wildlife and ecosystems, specifically for songbirds. BRI researchers have now sampled nearly half of the songbird species in the U.S. and Canada—studies show that 41 percent of these songbirds are experiencing adverse effects to their reproduction due to mercury exposure.

Methylmercury can biomagnify to levels of concern in terrestrial species such as insectivorous songbirds, particularly in wetlands (Jackson et al. 2015; Ackerman et al. 2016) where methylmercury concentration in avian invertivores can even exceed those of associated avian piscivores (fish-eaters; Evers et al. 2005). This is because the biomagnification process is related to trophic level amplification of methylmercury,

which can be elevated in terrestrial systems by predatory invertebrates such as spiders (Cristol et al. 2008). The availability of methylmercury can be enhanced in areas with ecosystem sensitivity, such as those habitats with low pH, elevated dissolved organic carbon, water level fluctuations, and vegetated habitats that experience wet-dry cycles during the year (Driscoll et al. 2007).

Wetland habitats represent areas where associated foraging songbirds may be at the greatest risk of mercury exposure. These habitats include bogs and beaver ponds (Edmunds et al. 2010), emergent wetlands (Evers et al. 2005), river floodplains (Jackson et al. 2011a), montane habitats (Rimmer et al. 2005), and estuaries (Lane et al. 2011, 2020).

Mercury in Songbirds

To inform policy efforts and advance public understanding, a group of 61 scientists collaborated on producing 15 papers that describe the impacts of mercury on songbirds across the United States and Canada (Cristol and Evers 2020). This publication, *The Impact of Mercury on North American Songbirds*, highlights the major findings of those studies and collaborative effort.

The 15 scientific papers representing laboratory and field studies are now published in a special issue of the journal *Ecotoxicology* (October 2020). The papers reflect five general categories of research on mercury in songbirds: (1) effects on health and physiology; (2) temporal trends; (3) landscape variations; (4) bioindicators; and (5) migration.

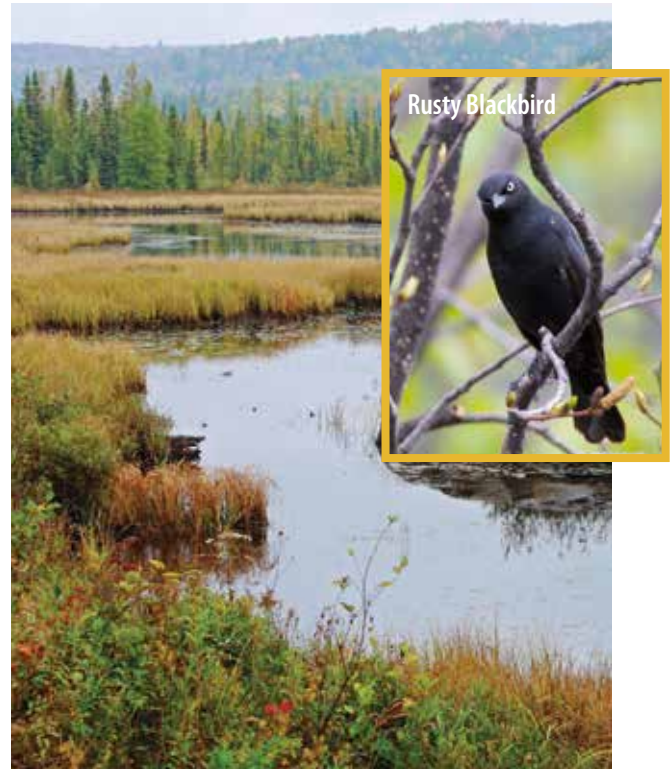


Saltmarsh Sparrow

Estuary ecosystems have a high capacity of methylating mercury that can contribute to elevated methylmercury levels to biota such as Saltmarsh Sparrows.

Major Findings—*Ecotoxicology* Special Issue

- Laboratory studies on Zebra Finch show methylmercury exposure can potentially impact chick development and eventually reproduction (Heddle et al. 2020), as well as brain development (Scoville et al. 2020) and sexually-selected traits such as bill color (Spickler et al. 2020).
- Temporal trends in mercury body burdens examined retrospectively in feathers showed large increases of mercury exposure over the past century in six of the seven species examined. Samples collected post-2000 ranged between 2 and 17 times greater than historic specimens (Perkins et al. 2020).
- Studies from Puerto Rico to Alaska found the methylation of mercury differed greatly between sites and that many factors create this broad spatial variation:
 - While wetlands are well-established as the habitat types of greatest risk, the choice of species, their foraging guild, and other factors remain critical for assessing risk (Brasso et al. 2020).
 - Riparian wetlands were found to be important habitats in Oregon for enhancing methylmercury concentrations in songbirds; point sources demonstrated an ability to stretch well downstream (Jackson et al. 2020).
 - Tropical freshwater wetlands in Puerto Rico did not have an expected ability to enhance methylmercury availability in songbirds, perhaps because of local abilities to demethylate mercury (Shanley et al. 2020).
 - Songbirds in tundra habitats were also found to have lower than established effect levels in far northern-nesting species such as the Arctic Warbler and Northern Wheatear (Stenhouse et al. 2020).
- Mercury has the potential to disrupt many physiological processes and interfere with navigation, flight endurance, oxidative balance, and stopover refueling that make long-distance migration possible (Seewagen 2020).
- Spring and fall migrants may have different responses to mercury exposure (Adams et al. 2020).
- Understanding the factors that contribute risk of mercury exposure in songbirds is vital to selecting the most appropriate songbird species as bioindicators of methylmercury availability. Selecting the right species, the right biological materials (e.g., blood or feathers), the right time of year, (e.g., breeding, migration, or winter), and the habitat to assess future changes in the threat to songbirds from mercury will require careful attention to recent research and standardization among researchers (Low et al. 2020; Knutsen and Varian-Ramos 2020; Winder et al. 2020).
- Saltmarsh Sparrows in eastern estuaries exhibit elevated levels across much of their breeding range (Lane et al. 2020).
- Mercury levels in Bicknell's and Swainson's Thrushes did not correlate with atmospheric mercury deposition (Rimmer et al. 2020).



Bogs are highly efficient in methylating mercury and can be a source of concern in remote areas to species such as the Rusty Blackbird and Palm Warbler.

BY THE NUMBERS

3 Billion

Number of birds that disappeared in North America since 1970.

40

Number of lab and field studies that now show adverse effects from mercury on immune, endocrine, neurological, and reproductive functions in songbirds.

286

Number of songbird species that breed in North America (restricted to U.S. and Canada).

141

Number of songbird species sampled by BRI in North America (restricted to U.S. and Canada)

58 (41%)

Number (and percent) of songbird species sampled showing demonstrated effect levels.

Effects of Mercury

Mercury in its organic form, methylmercury, is classified as a persistent bioaccumulative toxin. Once ingested, methylmercury can bioaccumulate over time, especially when intake exceeds the physiological abilities of animals to either demethylate (e.g., in the liver or kidney) or depurate (e.g., release through feathers).

Trophic Levels and Biomagnification

Methylmercury that bioaccumulates within individuals can pass from prey to predator, becoming more concentrated as it moves through trophic levels of the food web—a process called biomagnification. Due to biomagnification, even small quantities of methylmercury in water can result in concentrations that are up to 10 million times higher in upper trophic level species. Each trophic level or step generally results in an increase of methylmercury of an order of magnitude. In freshwater aquatic and marine ecosystems, organisms in higher trophic levels (i.e., predatory) are optimal bioindicators for mercury monitoring programs.

Thresholds for Mercury Effects

One of the most useful interpretive endpoints for ecological effects of mercury is reproductive success, as it is meaningful and scalable. For example, in the Carolina Wren, a 10 percent reduction in nesting success per territorial pair occurs with blood mercury concentrations at 0.7 parts per million (ppm), 20 percent reduction at 1.2 ppm, 30 percent reduction at 1.7 ppm, and a significant population level impact of 40 percent at 2.2 ppm (Table 1). The thresholds for avian invertivores are often lower for reproductive loss than avian piscivores (Heinz et al. 2009).

Table 1. Estimated effect mercury concentrations in avian invertivores using an endpoint of lowered reproductive success for four levels of impact (Evers 2018; Jackson et al. 2011b). Tissue type concentrations are shown for blood and eggs (wet weight) and feathers (fresh weight).

Avian Invertivores		
Tissue Type	Effect	Threshold (ppm) with % Impact
Adult blood	Lowered nesting success	0.70 µg/g (10%) 1.20 µg/g (20%) 1.70 µg/g (30%) 2.20 µg/g (40%)
Egg	Equivalent to lowered nesting success	0.11 µg/g (10%) 0.20 µg/g (20%) 0.29 µg/g (30%) 0.36 µg/g (40%)
Adult body feather	Equivalent to lowered nesting success	2.40 µg/g (10%) 3.40 µg/g (20%) 4.50 µg/g (30%) 5.30 µg/g (40%)
Adult tail feather	Equivalent to lowered nesting success	3.00 µg/g (10%) 4.70 µg/g (20%) 6.40 µg/g (30%)

Louisiana Waterthrush



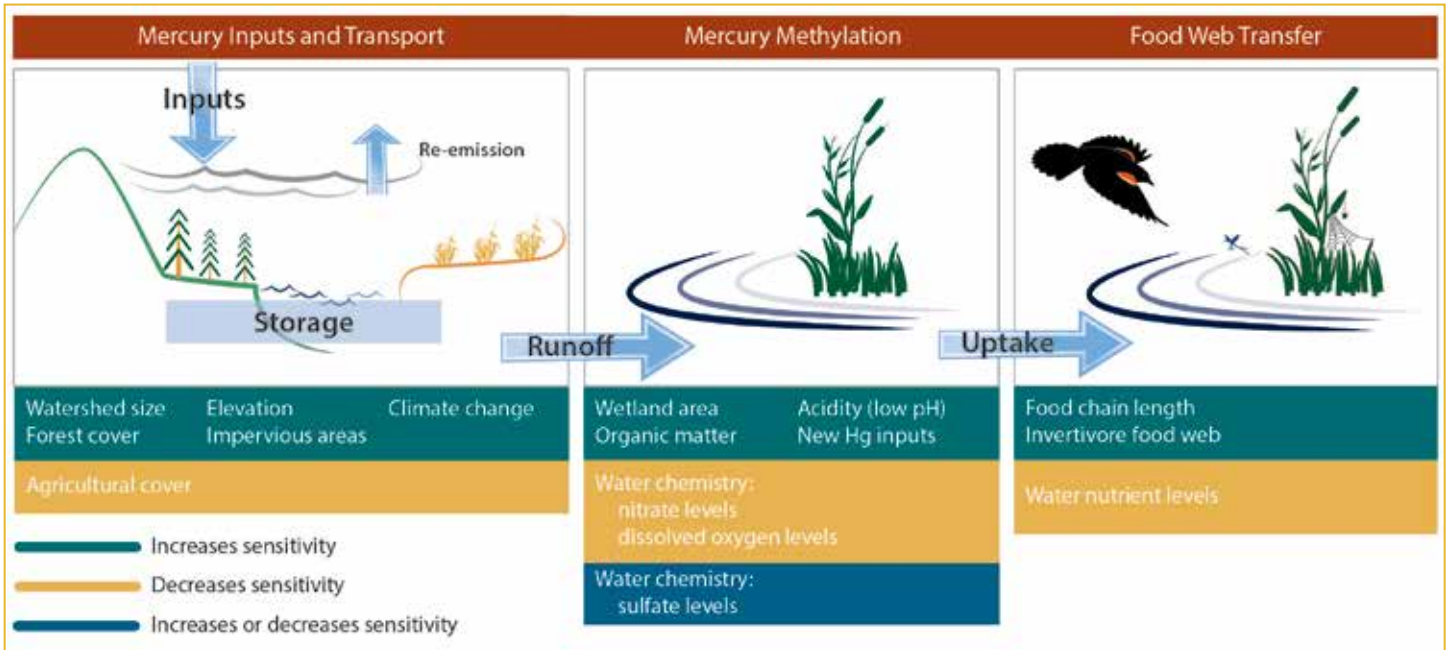


Figure 1. Watershed mercury sensitivity connects landscape features related to mercury input and transport, methylation potential, and food web transfer.

Mercury exposure in songbirds is based on methylation capabilities in various habitats that relate to: 1) mercury inputs and transport; 2) mercury methylation; and 3) food web transfers. Mercury profiles have been developed by BRI biologists over the past 20 years in nine countries for 281 species based on >20,000 samples (~13,000 blood and ~7,000 feather; Figure 1). Songbird species with the highest blood mercury concentrations measured to date in the U.S. are diverse and include flycatchers, gnatcatchers, sparrows, swallows, thrushes, vireos, warblers, and wrens (Figure 2).

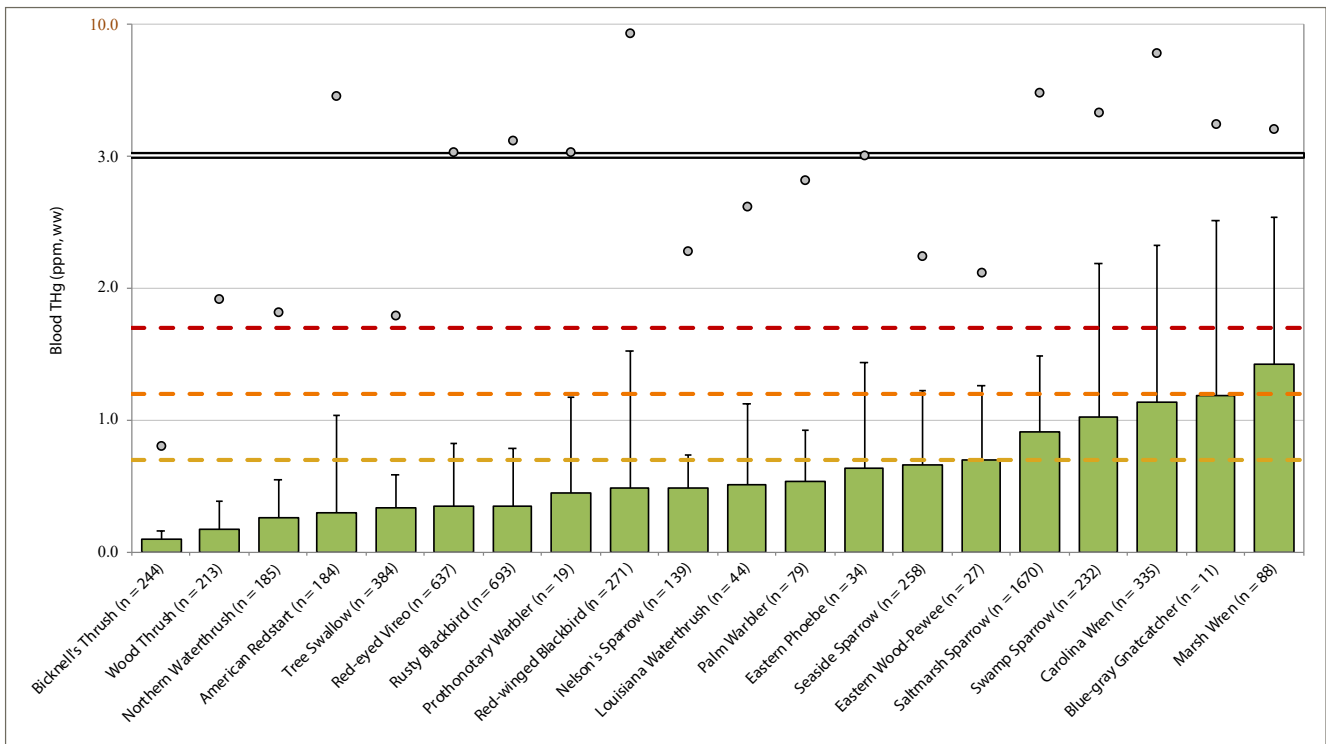


Figure 2: Blood mercury concentrations of 20 songbird species that place them at risk of reduced nesting success. Dashed lines show blood mercury concentrations: 10% (yellow – 0.7 ppm), 20% (orange – 1.2 ppm), and 30% (red – 1.7 ppm) associated with lowered nesting success. Data Sources: BRI Global Biotic Mercury Synthesis Database; Evers and Sunderland 2019

Songbird Study Sites



Rusty Blackbird

Historical patterns in mercury exposure for North American songbirds. Multiple sites

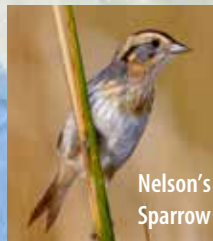
STUDY NO. 7



Arctic Warbler

A preliminary assessment of mercury in the feathers of migratory songbirds breeding in the North American subarctic. Denali National Park & Preserve, Alaska

STUDY NO. 14



Nelson's Sparrow

Wetland water management may influence mercury bioaccumulation in songbirds and ducks at a mercury hotspot. Kellys Slough National Wildlife Refuge Complex, North Dakota

STUDY NO. 15



Common Yellowthroat



Zebra Finch

Lab Research on Zebra Finches

- Continuous exposure to mercury during embryogenesis and chick development. British Columbia
- Mercury delays cerebellar development. Virginia
- Sexually-selected traits as bioindicators. Virginia

STUDY NO. 3

STUDY NO. 10

STUDY NO. 13



Varied Thrush

Spatial variation in aquatic invertebrate and riparian songbird mercury exposure across a river reservoir system with a legacy of mercury contamination. Willamette River system in western Oregon

STUDY NO. 4



Western Wood Pewee

Explaining variation in Colorado songbird blood mercury using migratory behavior, foraging guild, and diet. Fountain Creek watershed on the Front Range of Colorado

STUDY NO. 8



Eastern Bluebird

Do songbirds in wetlands show higher mercury bioaccumulation relative to conspecifics in nonwetland habitats? Southeast Missouri

STUDY NO. 2



Tree Swallow

Legend

- ★ Biodiversity Research Institute
- Field Study Sites
- Lab Study Sites
- Museum Study Sites
- ◆ Literature Review
- Lab and Museum Studies (multiple sites)





Bicknell's Thrush

Patterns of blood mercury variation in two long-distance migratory thrushes on Mount Mansfield, Vermont

STUDY NO. 9



Swainson's Thrush




Saltmarsh Sparrow

Long-term monitoring of mercury in breeding Saltmarsh Sparrows. Massachusetts, Maine, New York

STUDY NO. 5

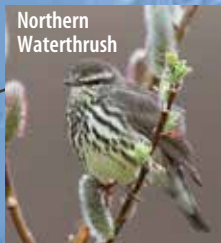
bri BRI Headquarters—Portland, Maine
 River Point Migratory Bird Banding Station—Falmouth, Maine




Blackpoll Warbler

The Threat of Global Mercury Pollution to Bird Migration: Potential Mechanisms and Current Evidence.

STUDY NO. 11



Northern Waterthrush

Mercury exposure in migrating songbirds. Key Biscayne, Florida

STUDY NO. 1



Red-legged Thrush

High mercury deposition, but low bio-accumulation. Northeastern Puerto Rico

STUDY NO. 12

bri BRI Biostation - Belize
 (in partnership with the Runaway Creek Nature Preserve/Foundation for Wildlife Conservation)




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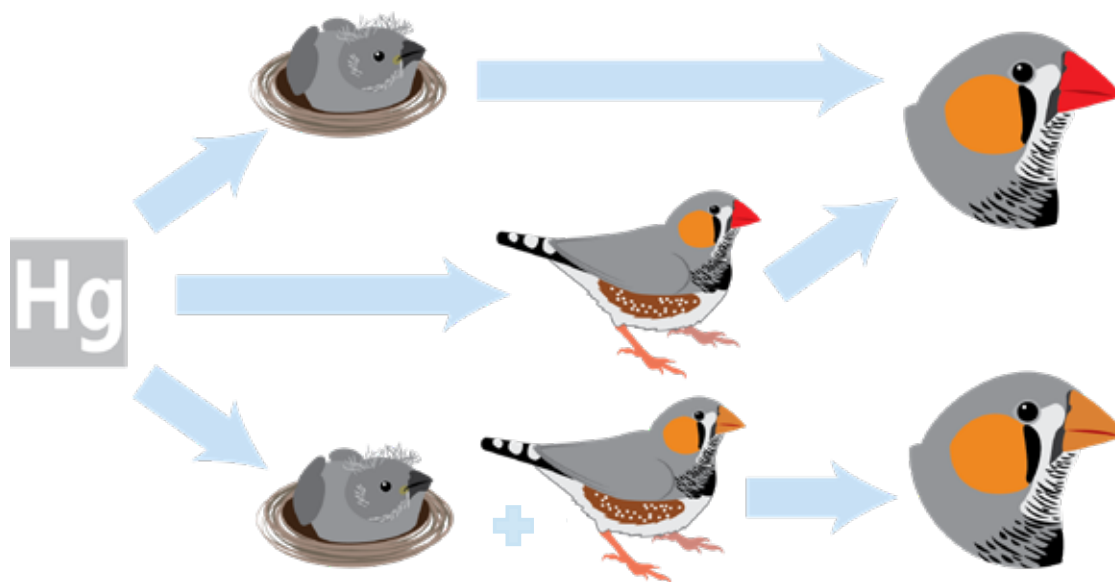
Effects on Health and Physiology

The effects of mercury exposure on avian health and physiology have been the subject of a few published studies: 1) Since 1988, only 20 laboratory studies (including those in this special issue) show adverse effects from mercury on immune, endocrine, neurological, and reproductive functions; and 2) 20 field studies show adverse effects from mercury to body condition and immune function. Further research is needed to gain a clearer understanding of how mercury exposure impacts physiology, and how those impacts may affect factors such as survival, behavior, overall health, longevity, and productivity.

The studies summarized here examine the results of mercury exposure during different stages of early development on specific aspects of neurological development, survival, and expression of sexually-selected physical traits in Zebra Finches.

Sexually-selected Traits as Bioindicators: Exposure to Mercury (Hg) Affects Carotenoid-based Male Bill Color in Zebra Finches

Jessica L. Spickler, John P. Swaddle, Rebecca L. Gilson, Claire W. Varian-Ramos, Daniel A. Cristol



Study Findings

Researchers examine whether sexually selected traits are sensitive bioindicators of environmental toxicants by assessing the effects of exposure to environmentally relevant dietary concentrations of MeHg on pigment coloration in domestic Zebra Finches:

- Bill coloration, which is a sexually selected trait, was less red in males with lifetime exposure to methylmercury, compared to controls.
- Neither adult, nor developmental exposure influenced bill color in adult males, with the possible exception of early exposure of nestlings. In females, where bill color is not under strong sexual selection, exposure to methylmercury did not affect bill color.
- This is a comprehensive experimental test of the proposal that sexually selected traits may be useful bioindicators of the stress imposed by environmental toxins such as methylmercury.

STUDY NO.
13

Continuous Exposure to Mercury During Embryogenesis and Chick Development Affects Later Survival and Reproduction of Zebra Finches

Cybele Heddle, John Elliott, Tanya Brown, Margaret Eng, Marie Perkins, Niladri Basu, Tony Williams

Authors examine the short and long-term effects of mercury exposure in a domesticated songbird, the Zebra Finch (*Taeniopygia guttata*). Exposure was either in ovo, as nestlings, or with a combined egg + nestling treatment through injections into eggs and oral dosing of nestlings.

Study Findings

- In ovo exposure to methylmercury reduced hatching success, but there was no effect on chick growth. In ovo or chick-only exposure did not have long-term effects.
- Found evidence for longer-term effects of combined “in ovo + chick” exposure on post-fledging survival and potentially sex-biased survival, which resulted in very few “in ovo + chick” exposed females surviving to breed.
- These females also had lower overall breeding productivity that was mainly due to lower hatching success of their eggs.
- Combined embryonic and nestling methylmercury exposure may have compounding latent effects on productivity.

STUDY NO.
3

LAB STUDIES: ZEBRA FINCH

EFFECT	CITATION
Neurological function	Scheuhammer 1988
Immune function	Lewis et al. 2013
Oxidative stress	Henry et al. 2014
Endocrine function	Moore et al. 2014
Reproduction	Varian-Ramos et al. 2014
Endocrine function	Maddux et al. 2014
No Immune effect	Caudill et al. 2015
Behavior (foraging)	Kobiela et al. 2015
Reproduction	Yu et al. 2016
Behavior (nesting)	Chin et al. 2017
Hearing	Wolf et al. 2017
Behavior, Cognition	Swaddle et al. 2017
Neurological function	Yu et al. 2017
No behavior effect	Greene et al. 2018
No immune effect	Smith et al. 2018
Reproduction	Paris et al. 2018
No behavior effect	Morran et al. 2018
Reproduction	Heddle et al. 2020
Neurodevelopment	Scoville et al. 2020
Coloration	Spickler et al. 2020

Studies summarized by Whitney and Cristol (2017) plus those in this special issue. See Table 1. for threshold effects.



Zebra Finches

The Zebra Finch, a domesticated variety of a wild species that breeds well in captivity, is a popular lab study subject.

Mercury Delays Cerebellar Development in a Model Songbird Species, the Zebra Finch

Sheila A. Scoville, Claire W. Varian-Ramos, G. Alden Adkins, John P. Swaddle, Margaret S. Saha, Daniel A. Cristol

Authors test whether mercury exposure can disrupt development of the cerebellum, part of the brain essential for coordination of movement including flight through a complex environment. This study describes normal development of the cerebellum in a model altricial songbird (needing parental care upon hatching), the Zebra Finch and determines the effect of exposure to mercury on cerebellar maturation.

Study Findings

- Researchers document, for the first time, the schedule of brain development in an altricial bird, and concludes that all treatments of methylmercury caused a delay in brain maturation as compared to a control group.
- Displaced Purkinje neurons, a pathology typical of methylmercury exposure in developing vertebrate brains, were more numerous in methylmercury-exposed birds, and persisted at least until the age of independence. Delays in maturation of the cerebellum could delay fledging in altricial bird species, with potential serious implications for the fitness of exposed individuals, as predation rates in the nest are often quite high.

STUDY NO.
10

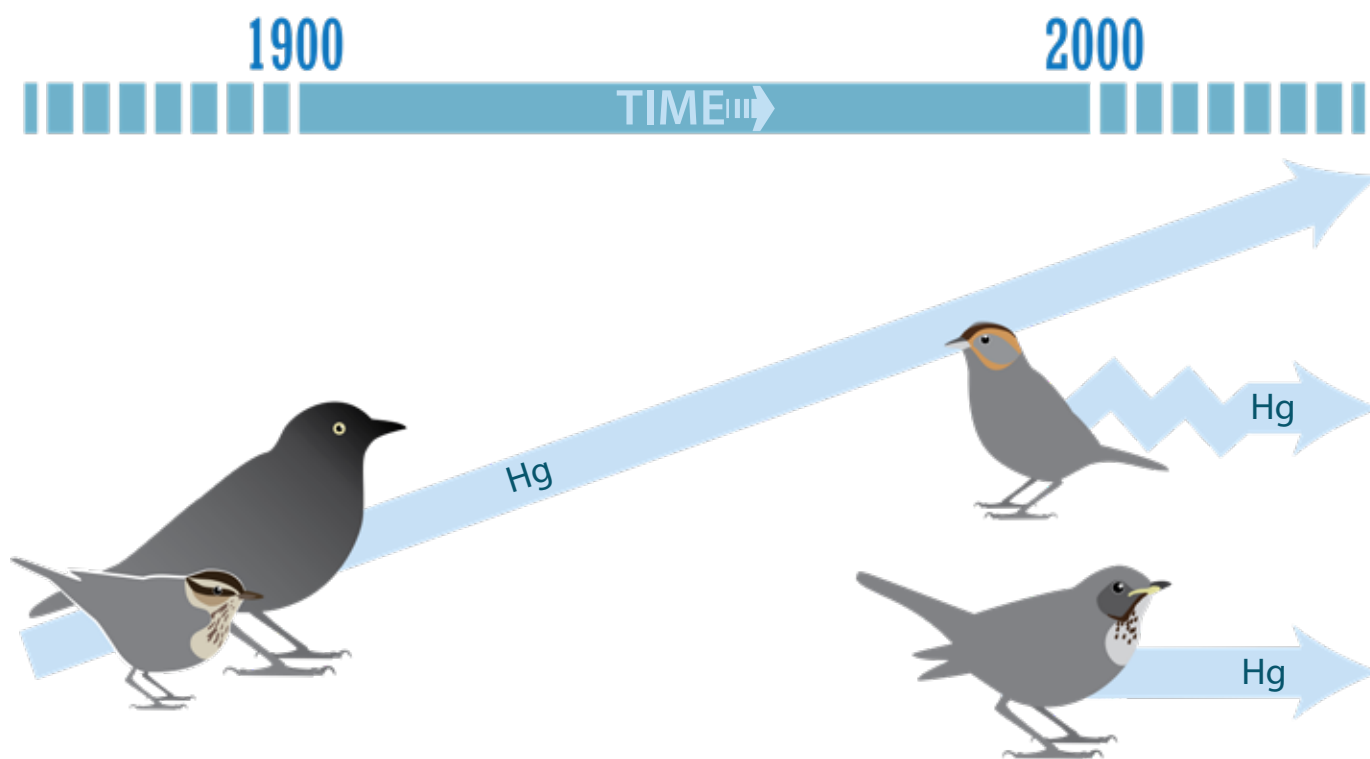
Temporal Trends in Mercury

The study of temporal trends reveals how a given parameter has changed over time. In the case of mercury exposure in birds, the studies featured here provide insight into historic trends over the past century, as well as detailed examinations of more recent trends (in the past two decades). Specifically, feather samples dating back to the late 1800s have been used to demonstrate general historic changes in mercury exposure over time, while more recent intensive long-term (2000-2017) studies have focused on further scrutinizing trends in specific species with particular habitat associations.

Overall, while examination of historic samples shows that mercury exposure in birds has generally increased in the past century (with some species showing more increase than others), the study of current trends and specific species (with specific associated habitat types) yields complicated results. Recent efforts indicate a field that is in need of further investigation.

Historical Patterns in Mercury (Hg) Exposure for North American Songbirds

Marie Perkins, Oksana P. Lane, David C. Evers, Amy Sauer, Evan M. Adams, Nelson J. O'Driscoll, Samuel T. Edmunds, Allyson K. Jackson, Julie C. Hagelin, Jeremiah Trimble, Elsie M. Sunderland



Study Findings

- Mercury concentrations in feathers collected post-2000 ranged between 1.9 and 17 times (mean 6.6) greater than historic specimens. The proportion of individual songbirds with feather concentrations that exceeded modeled toxicity benchmarks increased in samples collected after 1940.
- The greatest increase in feather mercury concentrations was observed for the Rusty Blackbird, a species that is declining and breeds in wet habitats.

STUDY NO.
7

Patterns of Blood Mercury Variation in Two Long-distance Migratory Thrushes on Mount Mansfield, Vermont

Christopher C. Rimmer, John D. Lloyd, Kent P. McFarland, David C. Evers, Oksana P. Lane

This study explored if mercury exposure is decreasing in long-distance migratory songbirds at a high-elevation forest site in Vermont, USA.

Study Findings

- Detected no temporal trend in either atmospheric deposition or blood mercury in Bicknell's Thrush (*Catharus bicknelli*) and Swainson's Thrush (*C. ustulatus*), long-distance migratory songbirds, from 2000–2017, at a montane forest site in north-central Vermont.
- Sampling date had the strongest effect on blood mercury concentration, which declined seasonally.
- Absence of a relationship between local atmospheric deposition and thrush blood mercury concentrations suggests that mercury cycling dynamics, mechanisms of transfer, and timing of uptake by montane forest biota are complex and poorly understood.

STUDY NO.
9



A neotropical migrant, the Bicknell's Thrush breeding range is restricted within montane areas of northeastern North America—areas where atmospheric mercury deposition is elevated.

Long-term Monitoring of Mercury in Adult Saltmarsh Sparrows Breeding in Maine, Massachusetts, and New York, USA 2000-2017

Oksana Lane, Evan Adams, Nancy Pau, Kathleen M. O'Brien, Kevin Regan, Michael Farina, Tara Schneider-Moran, John Zarudsky

This is one of the few long-term (2000-2017) studies of mercury exposure of a songbird species. Authors assess mercury in blood and feathers of the Saltmarsh Sparrow (*Ammodramus caudacutus*) breeding in salt marshes across three states.

Study Findings

- Mercury exposure differed by site and year but there was no consistent temporal trend across sites. Blood mercury concentrations declined only at one site - Rachel Carson National Wildlife Refuge in southeastern Maine, USA.
- Study observed a seasonal variation in blood mercury concentrations in sparrows, increasing during the breeding summer season, peaking in July.

STUDY NO.
5

CASE STUDY: RUSTY BLACKBIRD

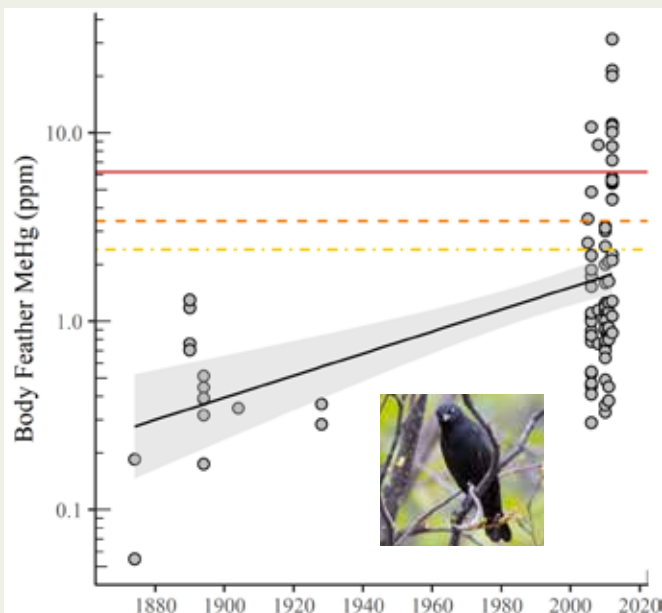


Figure 3: Methylmercury (MeHg) levels (ppm) in Rusty Blackbird body feathers derived from museum (<1930) and field sampling (>2000). The black line is a simple linear regression indicating a trend of increasing Hg concentrations through time ($n=95$, $p<0.001$, $R^2 = 0.22$) with the gray shaded area indicating 95% confidence intervals. Colored lines show blood mercury levels associated with 10% (2.4 ppm), 20% (3.4 ppm), and 50% (6.2 ppm) reduced nesting success (Evers 2018).

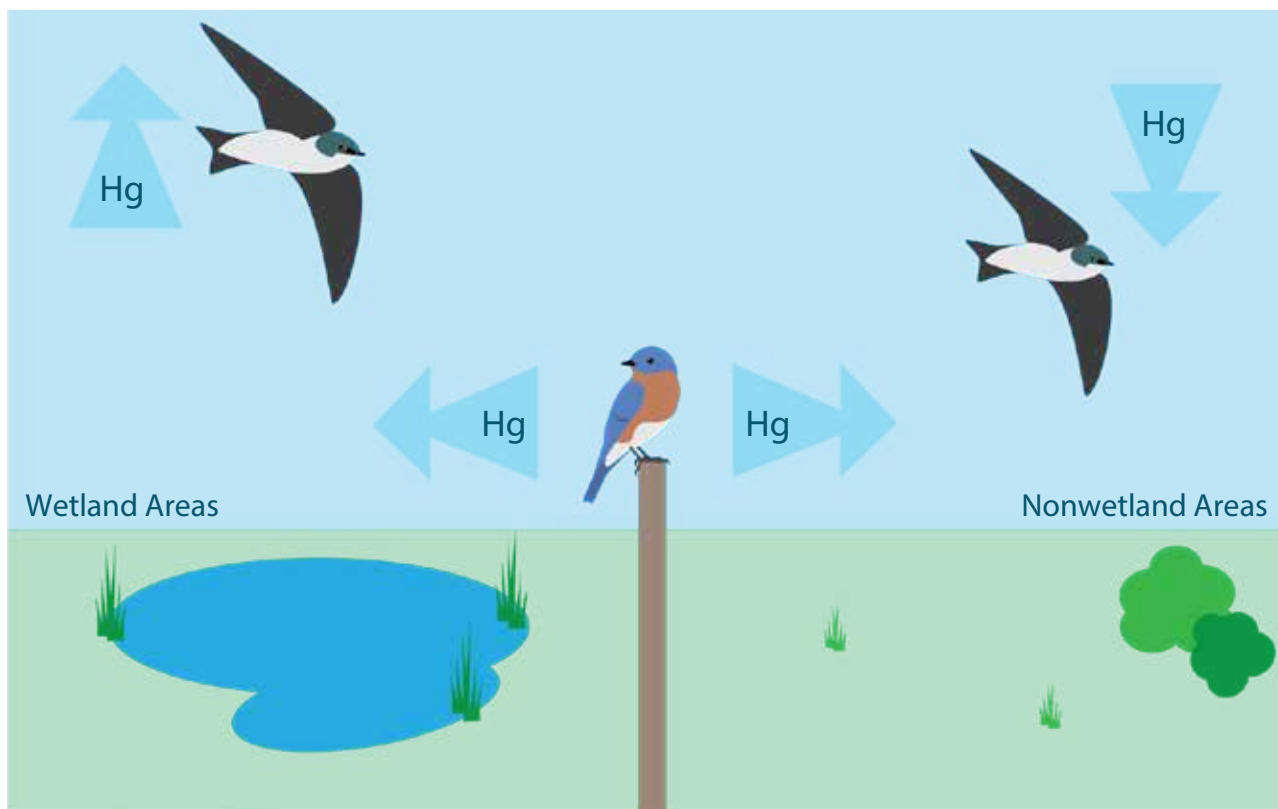
Landscape and Management Factors

The study of spatial variations helps to illustrate where on the landscape certain conditions occur. Such investigations may also help answer questions about why or how certain landscape attributes affect risk of mercury exposure.

The studies presented here examine mercury exposure in wildlife from a landscape perspective. Specifically, these studies explore topics from describing general mercury exposure in regions where little data exists, to investigating refined questions regarding specific locations, circumstances and habitats. Overall, these studies—while answering many questions—reveal complexities with respect to how landscape features and other factors affect mercury availability.

Do Songbirds in Wetlands Show Higher Mercury (Hg) Bioaccumulation Relative to Conspecifics in Nonwetland Habitats?

Rebecka Brasso, Katie Ann Rittenhouse, Virginia L. Winder



Study Findings

Authors question the dogma that Hg exposure is higher for songbirds living in wetlands than in nonwetland habitats, with a combined field study and review paper.

- Blood mercury concentrations in adult Tree Swallows breeding in wetlands were significantly higher than in nonwetland areas and significantly higher than in Eastern Bluebirds.
- Adult Eastern Bluebirds had similar blood mercury concentrations at wetland and nonwetland sites.
- The results of this and other studies suggest that no single factor can be used to predict risk of contaminant bioaccumulation.
- Use caution against assuming that songbirds occupying wetlands will have higher mercury bioaccumulation than conspecifics living in other habitats. Species selection in study design is important.

STUDY NO.
2

Spatial Variation in Aquatic Invertebrate and Riparian Songbird Mercury Exposure across a River-Reservoir System with a Legacy of Mercury Contamination

Allyson K. Jackson, Collin A. Eagles-Smith, Colleen Emery

Authors focus on mercury movement into riparian food webs and how this is modulated by habitat characteristics in a river system. Researchers characterize differences in mercury exposure in aquatic invertebrates and riparian songbirds across the Willamette River system in western Oregon, starting at a mercury-contaminated Superfund site in the headwaters and including a reservoir known to methylate mercury.

Study Findings

- Methylmercury concentrations in aquatic invertebrates varied spatially among habitat categories and invertebrate orders.
- Total mercury in songbird blood also varied among habitat categories and bird species. The highest mercury concentrations occurred near the mercury mine, but mercury did not decline linearly with distance from the source of contamination.
- Findings suggest that mercury risk to riparian songbirds can extend beyond point-source contaminated areas, highlighting the importance of assessing exposure in surrounding habitats, such as reservoirs and wetlands where methylmercury production may be elevated.

STUDY NO.
4



Arctic Warbler

The Arctic Warbler is a cryptic species recently split from two other Phylloscopus warblers. They are known to travel between southeast Asia and Alaska each year. Ecosystems in southeast Asia are prone to elevated levels of atmospheric deposition of mercury.

Resolving a Paradox—High Mercury Deposition, but Low Bioaccumulation in Northeastern Puerto Rico

James B. Shanley, Mark Marvin-DiPasquale, Oksana Lane, Wayne Arendt, Steven Hall, William H. McDowell

At a “clean air” trade winds site in Puerto Rico, researchers found an apparent paradox: atmospheric total mercury deposition was highest of any site in the U.S. Mercury Deposition Network, but assimilation into the local food web was quite low. Avian blood total mercury concentrations (n=31, from eight species in five foraging guilds) ranged widely from 0.2 to 32 ppm.

Study Findings

- Total mercury was significantly greater at a low-elevation site near a wetland compared to an upland montane site.
- Potential rates of demethylation were 3 to 9-fold greater than those for mercury-methylation, but rates of change of ambient methylmercury pools showed a slight net positive mercury-methylation.
- The resolution of the paradox is that methylmercury degradation approximately keeps pace with methylmercury production in surface soil and sediment. Further, any net production of methylmercury is subject to frequent flushing by high rainfall on chronically wet soils. The interplay of these microbial processes and hydrology appears to shield the local food web from adverse effects of high atmospheric mercury loading. This scenario may play out in other humid tropical ecosystems as well, but it is difficult to evaluate because coordinated studies of mercury deposition, methylation, and trophic uptake have not been conducted at other tropical sites.

STUDY NO.
12

A Preliminary Assessment of Mercury in the Feathers of Migratory Songbirds Breeding in the North American Subarctic

Iain Stenhouse, Evan Adams, Laura M. Phillips, Scott Weidensaul, Carol L. McIntyre

In this preliminary study, researchers quantify mercury exposure in feathers of 12 migratory songbird species breeding at subarctic latitudes, in Denali National Park and Preserve, interior Alaska, U.S.

Study Findings

- Overall, mercury exposure observed was low for songbirds breeding in the subarctic. Further examination would prove useful in clarifying mercury exposure and ecological relationships in this under-studied region.

STUDY NO.
14

Use of Songbirds as Bioindicators

Monitoring mercury in wildlife is an established pathway to understanding spatial variations, temporal trends, and magnitude of environmental concern at a scale of refinement that cannot be ascertained using air, water, or sediment sampling. Upper trophic-level (top of the food chain) species serve as the best indicators for environmental mercury due to the phenomenon of bioaccumulation, which magnifies mercury up the food chain.

Songbirds include groups of high-trophic-level consumers, as well as species with highly specific habitat and foraging preferences. This allows for the selection and study of specific species that are well suited to tease out information relevant to very specific landscapes, habitats, circumstances and conditions.

The studies presented here serve to: inform biologists which species to select as indicators of mercury pollution in future projects; investigate the usefulness of different tissue sample types for mercury monitoring using songbirds; and demonstrate how using birds as bioindicators for mercury can help inform management decisions.

Songbird Feathers as Indicators of Mercury Exposure: High Variability and Low Predictive Power Suggest Limitations

Katherine E. Low, Danielle K. Ramsden, Allyson K. Jackson, Colleen Emery, W. Douglas Robinson, Jim Randolph, Collin A. Eagles-Smith

This study examines feathers as a reliable tissue for mercury monitoring and the variation in mercury among tissues including feathers from six tracts (primary, crown, breast, belly, back, and flank), nails, liver, and muscle; in thrushes and sparrows. All birds used in this study were collected from lethal accidents such as car and window collisions.

Study Findings

- Despite their current use in the literature, feathers are not a suitable sampling matrix for mercury monitoring in some songbird species.
- Mercury concentrations in all feather tracts and nails were higher than in the liver and muscle, and mercury was higher in the thrushes than in the sparrows.
- Although bird nails better predicted internal tissue mercury concentrations in the thrushes and sparrows, they may not be an effective sampling option for all bird species because the collection of sizable nail mass could harm living birds, particularly small songbirds.

STUDY NO.
6

Explaining Variation in Colorado Songbird Blood Mercury Using Migratory Behavior, Foraging Guild, and Diet

Carley J. Knutsen and Claire W. Varian Ramos

Authors examine interspecific variation in blood mercury levels in songbirds of various foraging guilds in the Fountain Creek watershed on the Front Range of Colorado. This work can inform biologists which species to select as indicators of mercury pollution in future projects.

Study Findings

- Certain species had blood mercury concentrations over 75 times higher than other species.
- Carnivores had the highest blood mercury levels, but ground foraging and long distance migrants also had higher mercury concentrations.

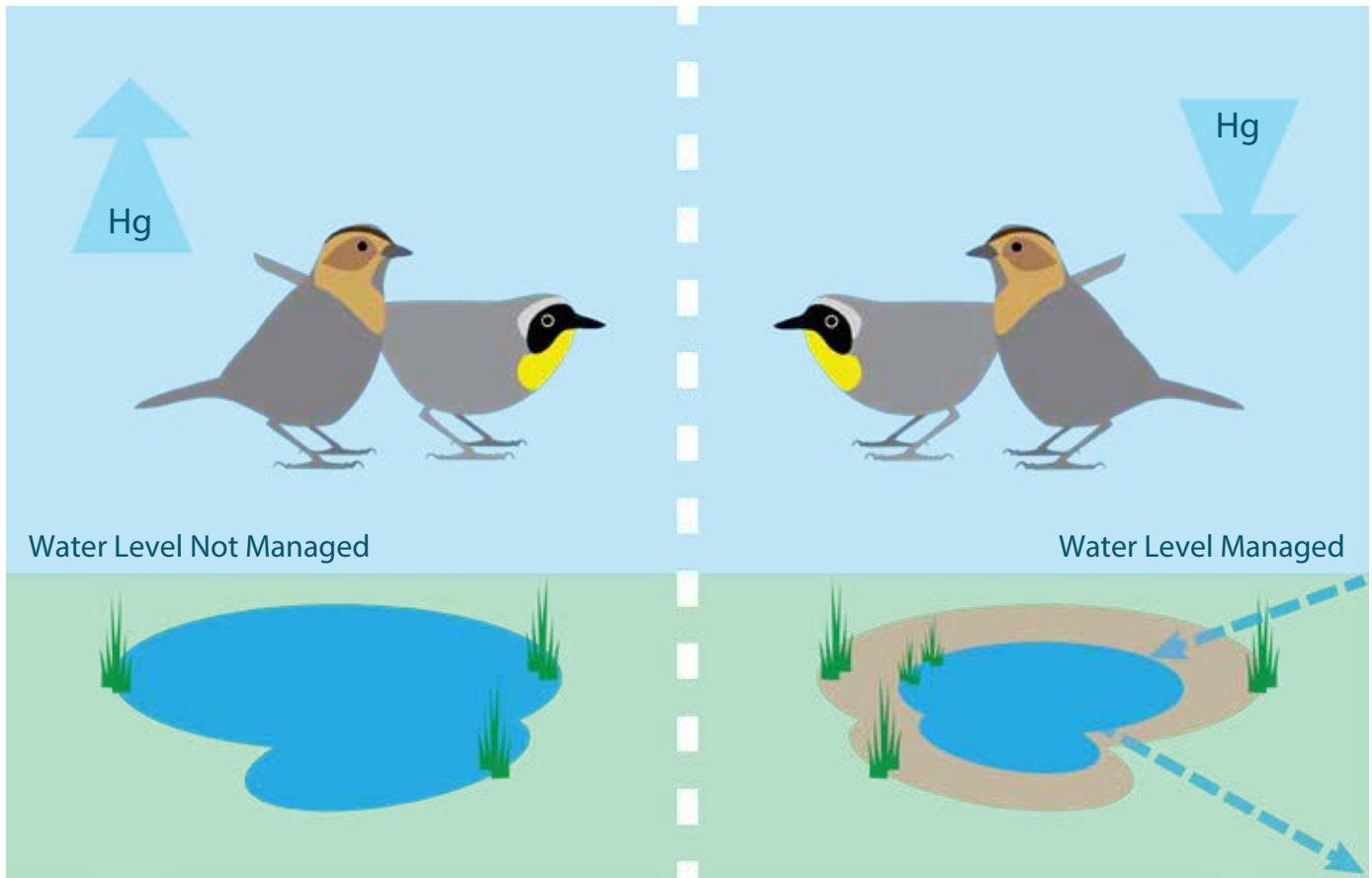
STUDY NO.
8



The Varied Thrush is used as a bioindicator of mercury in western forests where little is known about mercury input to sensitive ecosystems.

Wetland Water Management May Influence Mercury (Hg) Bioaccumulation in Songbirds and Ducks at a Mercury Hotspot

Virginia Winder, Michael J Anteau, Mark R Fisher, Mary Kate Wilcox, Lawrence D Igl, Joshua Ackerman



Study Findings

Authors examine the efficacy of management techniques in altering mercury bioavailability. Applied research like this study is surprisingly scarce and needed.

- Nelson's Sparrow blood mercury concentrations were elevated and similar to those reported six years previously. Mercury in songbird blood and duck eggs varied among wetland water-management classifications. Songbirds and ducks had 67% and 49% lower mercury concentrations, respectively, in wetlands that were drawn down with water flow compared to individuals occupying isolated-depressional wetlands with no outflow.
- Songbirds within impounded and partially drawn-down wetlands with water flow had mercury concentrations 26–28% lower, respectively, than individuals that occupy isolated, depressional wetlands with no outflow.
- Study confirms that mercury concentrations in songbirds at Kellys Slough National Wildlife Refuge in North Dakota, which is designated as an area of global importance, continue to be elevated and suggest that water management could be an important tool for wetland managers to reduce bioaccumulation of mercury in birds.

Mercury: A Migratory Threat

Migratory species can encounter mercury contamination on their breeding grounds, as well as along migratory routes and on wintering grounds. Moreover, migrating birds might be at greater risk to the toxic effects of mercury.

Mercury is stored in muscle; most birds will use their muscle reserves to help fuel their migratory flights especially during stressful times when fat reserves are expended. This muscle burn could potentially give birds a high dose of mercury during migration.

Migration accounts for nearly 75 percent of all annual mortality rates in some songbirds; the added burden of toxic mercury exposure may make the process even more challenging (Seewagen 2020). While mercury exposure during the breeding season is well documented, contamination during migration and over the winter is still relatively unknown. Migration and its linkages across hemispheres make understanding the risks of mercury exposure all the more difficult.

Conservation Complexities

Understanding migratory connectivity, the strength of connections between wintering and breeding areas, has become vital to the conservation of migratory birds. When a species has strong connectivity, traditional conservation measures may not be effective.

For example, if the New England breeding population of the Northern Waterthrush (*see Case Study*) was declining and landscape managers wanted to protect it throughout its annual life cycle, one strategy might be to purchase wintering ground habitat and manage it for waterthrushes.

If this population only wintered in the Caribbean, then it makes sense to conserve land in the Caribbean. Without this information well-intentioned efforts might protect land in Central America, but actually achieve very little in meaningful results for the breeding population.

Understanding the complexities of migration is crucial to making effective conservation decisions.

Mercury Exposure in Migrating Songbirds: Correlations with Physical Condition

Eván Adams, Kathryn A. Williams, Brian J. Olsen, David C. Evers

Mercury exposure can be remobilized from the muscle tissue during the stressful time of migration, and potentially alter migratory behavior and physiology of songbirds via neurological impairment.

Study Findings

- The relationship between body condition and mercury concentrations in bird tissues was different during spring versus fall migration, and the timing of high mercury exposure varied within season across species:
 - Northern Waterthrush individuals with higher mercury migrated earlier.
 - American Redstart showed the opposite pattern.
- There is evidence that mercury exposure and physical condition are correlated but that the effect was not very large.

STUDY NO.
1

The Threat of Global Mercury Pollution to Bird Migration: Potential Mechanisms and Current Evidence

Chad L. Seewagen

This paper examines the physiological and histological effects of mercury on nonmigrating birds and nonavian vertebrates to identify potential mechanisms by which mercury might hinder migration performance.

Study Findings

- Mercury has potential to disrupt many of the physiological processes and interfere with navigation, flight endurance, oxidative balance, and stopover refueling that make long-distance migration possible.
- Migration performance and possibly survival might be limited by the immunosuppressive effects of mercury on birds at a time when exposure to novel pathogens and parasites is great.
- Mercury pollution is likely to be further challenging what is already a difficult and perilous phase of a bird's annual cycle, potentially contributing to global declines in migratory bird populations.

STUDY NO.
11



CASE STUDY: NORTHERN WATERTHRUSH



Feather mercury body burdens found in the Northern Waterthrush during winter, over migration, and on breeding grounds are consistently elevated (Figures 4, 5). Mean mercury concentrations are generally near lowest effect levels, especially during fall migration where some individuals are well above the threshold mark of 30 percent lowered nesting success (6.4 ppm). This demonstrates that dietary uptake of methylmercury is a year-round concern, and species such as the Northern Waterthrush have a low ability for ridding their body of mercury burdens during times of low environmental mercury exposure. This chronic exposure to methylmercury toxicity may be of high conservation concern for neotropical migrants.

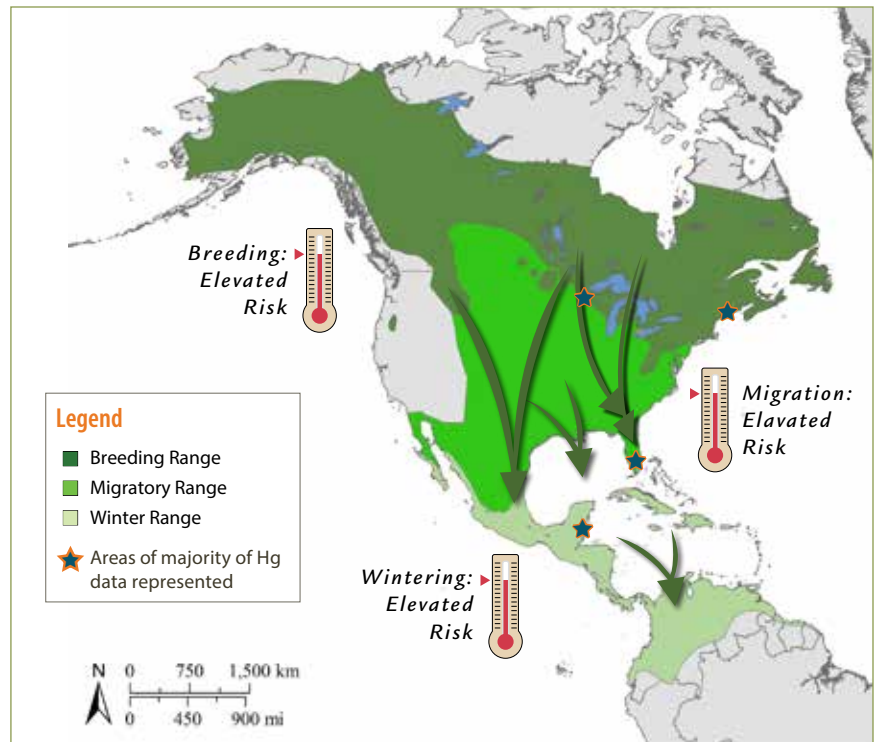


Figure 4: Northern Waterthrush's breeding range, wintering areas, and migratory routes. This species is one of the few neotropical migrants for which BRI has year-round information on mercury exposure, but many other declining neotropical migrants are potentially exposed similarly (see sidebar).

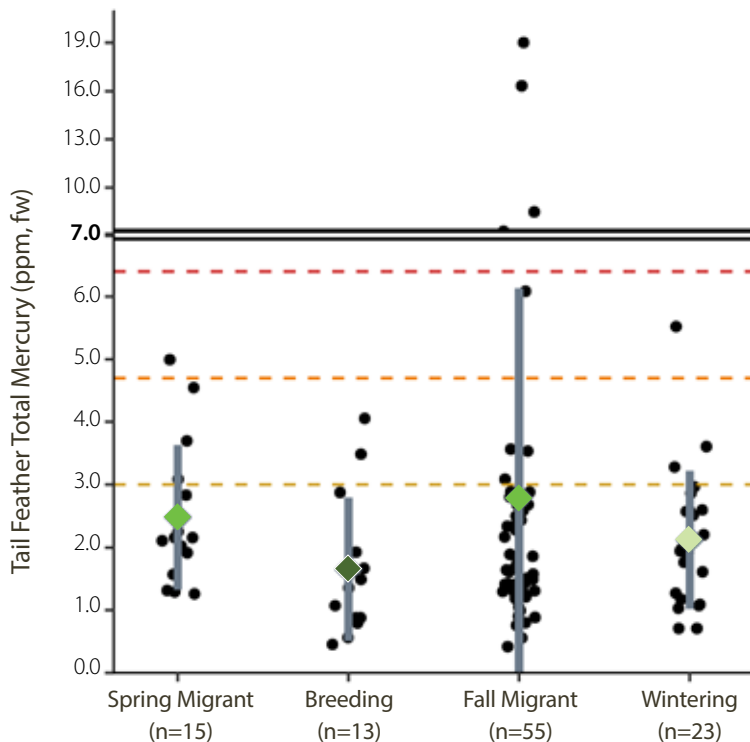


Figure 5. Feather mercury concentrations in Northern Waterthrush during the four seasons of their annual cycle (n=106). Diamonds ± error bars are mean ± standard deviation. Black points are individual values. Lines indicate blood mercury concentrations associated with a 10% (3.0 ppm), 20% (4.7 ppm), and 30% (6.4 ppm) lowered nesting success.

Neotropical Migrant Songbirds of Conservation Concern* from Environmental Mercury Loads



Olive-sided Flycatcher
44-year decline=78%



Wood Thrush
44-year decline=59%



Louisiana Waterthrush
44-year decline=42%



Prothonotary Warbler
44-year decline=34%

*Based on range-wide
North American Breeding Bird Survey data

Bioindicators by Habitat

High Elevation Forests

Primary Indicator: Bicknell's Thrush (East)

Secondary Indicators: Blackpoll Warbler, Swainson's Thrush, Yellow-bellied Flycatcher

Reduce acid deposition

Acid deposition created from the burning of fossil fuels can intensify the leaching of calcium from the soil. In areas that are also subject to a high amount of mercury deposition (enhanced by regularly occurring fog events), this can become a dangerous combination of threats. Besides the need for control of mercury emissions, forests can be managed for reducing soil acidification that will alleviate the effect of multiple environmental stressors.



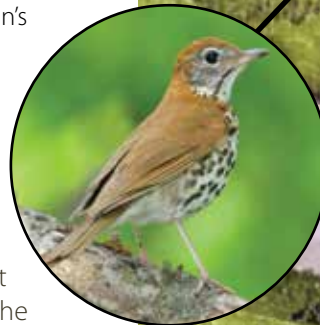
Upland Forests

Primary Indicators: Wood Thrush (East), Varied Thrush (West)

Secondary Indicators: Acadian Flycatcher, American Redstart, Cerulean Warbler, Eastern Wood Pewee, Kentucky Warbler, Red-eyed Vireo, Swainson's Warbler, Worm-eating Warbler

Improve fire management

Forest fires have the ability to mobilize mercury sequestered in the soils and vegetation of forests. This mercury is then free to enter the atmosphere or be remobilized into nearby habitats and then ingested by organisms. Fire is often necessary for the overall health of forests, but allowing for more frequent, less severe forest fires will reduce the risk of large scale mobilization of mercury into the ecosystem.



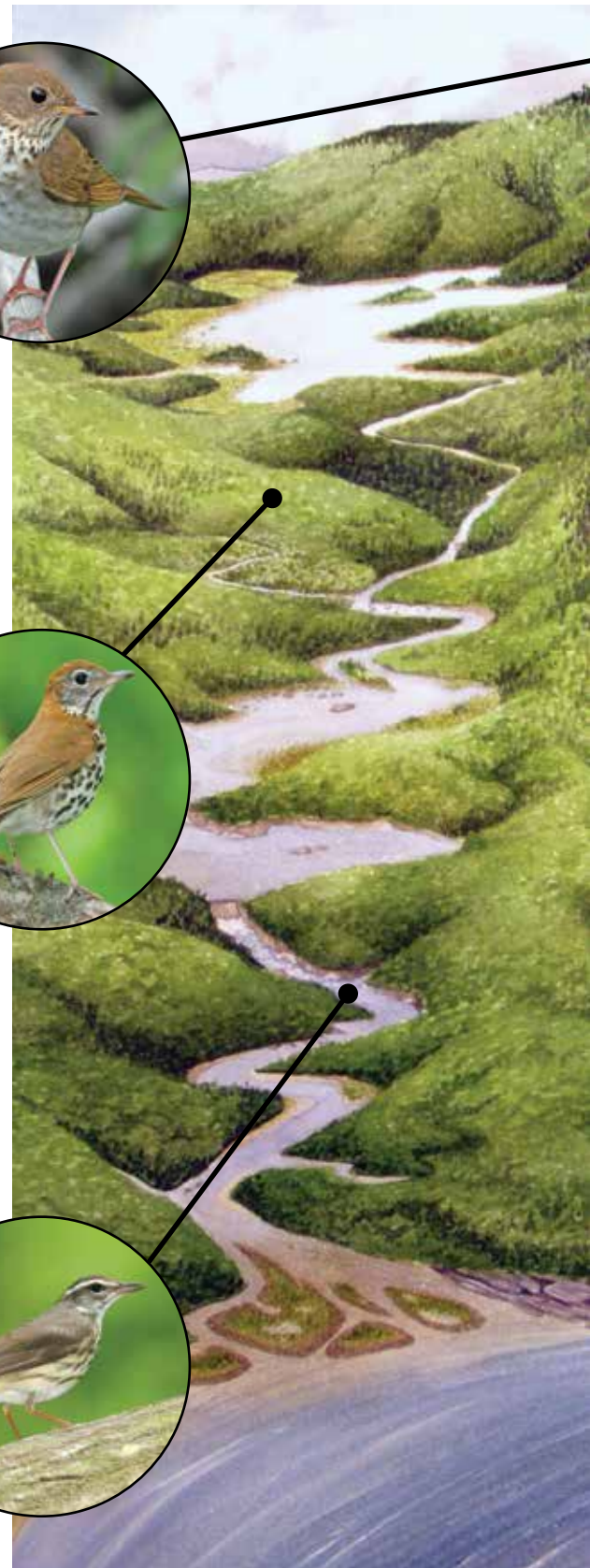
Forested Rivers and Creeks

Primary Indicators: Louisiana Waterthrush (East), American Dipper (West)

Secondary Indicators: Black Phoebe, Blue-gray Gnatcatcher, Carolina Wren, Eastern Phoebe, Hooded Warbler, Northern Waterthrush, Prothonotary Warbler, Yellow-throated Warbler,

Restrict logging near water bodies

Logging near forested rivers and creeks not only enhances erosion, it also remobilizes mercury previously sequestered in the soils. By restricting logging near water bodies, direct movement of mercury into the watershed can be minimized. The contamination of streams and rivers in one place may have significant ramifications more than 80 miles downstream.





Reservoirs and Beaver Ponds

Primary Indicators: Rusty Blackbird (East), Tree Swallow (East and West)

Secondary Indicators: Canada Warbler, Olive-sided Flycatcher, Tree Swallow, Violet-green Swallow

Control reservoir water level fluctuations

Large fluctuations in water levels within reservoirs can intensify the amount of mercury methylation in an ecosystem. The repeated wetting and drying of water body edges allows the bacteria that methylate mercury to thrive and increase the amount of biologically available mercury. The most reasonable way to control this methylation is to maintain more constant water levels in these reservoirs, particularly in late summer and early fall.

Emergent Wetlands and Bogs

Primary Indicators: Red-winged Blackbird (East), Yellow-headed Blackbird (West)

Secondary Indicators: Common Yellowthroat, Marsh Wren, Palm Warbler, Sedge Wren, Song Sparrow, Swamp Sparrow, Yellow Warbler

Reduce mercury emissions

Mercury emissions must be controlled at the source, and the U.S. EPA's Mercury and Air Toxics Standards (MATS) rule to regulate mercury emissions from power plants in the U.S. is possibly being repealed. Continued implementation of this rule is necessary for protection of ecosystem health, including emergent wetlands that are particularly sensitive and/or close to sources that are likely biological mercury hotspots.

Estuaries

Primary Indicator: Saltmarsh Sparrow (East), Song Sparrow (West)

Secondary Indicator: Nelson's Sparrow, Seaside Sparrow

Trace hidden or unknown point sources

Because of its prevalence in various industrial processes and wastewater treatment plants, mercury has historically been released in varying quantities into many different water bodies throughout the U.S. Estuaries are often the final destination for this source of mercury, and the high degree of methylation in coastal wetlands allows for much of it to become available to wildlife. Although many of these point sources have known inputs, there are many that are unknown and unexplored. In some cases, the solution can be as easy as discovering and cleaning up the legacy dump site. Without intensive biomonitoring in our nation's estuaries, we will not be able to determine where these "hotspots" of high mercury levels in wildlife occur.

A Case for Songbird Bioindicators

This collection of 15 studies demonstrates that appropriate songbird bioindicators can be identified for properly tracking mercury and assessing its impact in the environment. An ability to standardize the use of bioindicators is key for policymaking and landscape management needs. An important facet for the use of bioindicators is the knowledge of effect levels.

Based on published evidence to date, there are 20 laboratory studies that have identified adverse impacts from methylmercury, including immune and endocrine functions, neurological impacts, and reproduction. These laboratory studies have been important in relating findings to field conditions, where 20 studies have identified adverse impacts from methylmercury to body condition, immune function, and reproductive success (Whitney and Cristol 2017, Evers 2018; Cristol and Evers 2020).

The findings in this special issue combine with the existing literature to provide a basis for creating and defining a ranking matrix that could be used to identify risk to songbird species. Variables that have been identified as important for assessing the suitability of a bioindicator include:

- Habitats used during either the breeding or non-breeding seasons
- Foraging preferences during either the breeding or nonbreeding seasons
- Migration distance

The Influence of Habitat Type

The type of habitat use during the breeding season has an important influence on the methylation process and subsequent methylmercury availability in food webs. Moist habitats, such as wetlands, have a far greater propensity for mercury to methylate than dry habitats. Species that forage within wetland habitats tend to be exposed to methylmercury at the highest levels within a landscape (Evers et al. 2005; Jackson et al. 2015). Although, wetlands are variable in methylation abilities (Hall et al. 2020).

Forested habitats have a greater ability to scavenge air mercury and increase dry deposition versus nonforested habitats in both temperate (Driscoll et al. 2007; Jackson et al. 2015) and tropical systems (Gerson et al. In Review). So, forested landscape combined with wetlands that regularly include wet-dry cycles (intra- and inter-season) and are acidic with organic matter have greater methylmercury availability than alkaline and agricultural areas with little precipitation.

Mercury Exposure and Biomagnification

Methylmercury that bioaccumulates within individuals can pass from prey to predator, becoming more concentrated as it moves through trophic levels of the food web—a process called biomagnification.

The biomagnification of methylmercury is closely related to trophic level because methylmercury concentrations are highest in the upper trophic levels and in terrestrial ecosystems, and invertivorous songbirds often occupy some of the highest trophic levels (Evers et al. 2005; Abeysinghe et al. 2017). Songbirds that regularly forage on predatory invertebrates (e.g., spiders; Cristol et al. 2008) are at the highest trophic level and therefore maintain the greatest body burdens of methylmercury.

The Influence of Migration

High body burdens of mercury may be exacerbated by migration, and we predict that the greater the distance the more chance that mercury will interact negatively with the demands of migration (Adams et al. 2020; Seewagen 2020). While the initial mercury body burden of a neotropical or paleotropical migrant is important for a songbird's fitness level for completing its migration, the levels of methylmercury bioavailability at the destination habitat are also important within a bird's annual cycle.

While the exposure to methylmercury in temperate areas is increasingly understood as an important risk to certain breeding songbird populations and species, the exposure in their nonbreeding areas is not. And, for many long-distance migrants, winter habitats are increasingly becoming mercury hotspots because of emerging activities related to artisanal small-scale gold mining, such as in Peru for neotropical migrants (Markham and Sangermano 2018; Diringner et al. 2019), and legacy or ongoing contamination from industrial sources, such as in China for far-northern nesting migrants (Abeysinghe et al. 2017).

Factors in Choosing Songbird Bioindicators

Ultimately, the selection of songbird bioindicators for assessing and monitoring environmental mercury loads is dependent on a number of factors including:

- Objective (e.g., to identify spatiotemporal trends or assess conservation concern)
- Ecological attributes such as landscapes occupied (e.g., breeding, migration and nonbreeding) and geographical distribution across its annual life cycle
- Potential ability for bioaccumulation over the individual's lifetime.

The choice of indicator biota is actively being assessed now to fulfill the long-term obligations of a global multilateral treaty, the Minamata Convention on Mercury (Evers and Sunderland 2019), and to connect biotic dietary uptake of methylmercury with differing source types of mercury (using mercury isotopes; Tsui et al. 2018). The findings of this special issue significantly further that goal.

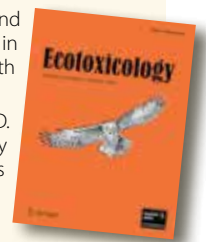
Mercury in Songbirds Special Issue in *Ecotoxicology* 2020

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