GEOGRAPHIC TREND IN MERCURY MEASURED IN COMMON LOON FEATHERS AND BLOOD

DAVID C. EVERS,††† JOSEPH D. KAPLAN,‡ MICHAEL W. MEYER,§ PETER S. REAMAN,‡
W. EMMETT BRASELTON,‖ ANDREW MAJOR,§ NEIL BURGESS,†† and ANTON M. SCHEUHAMMER‖‖
†Department of Fisheries and Wildlife, University of Minnesota, 200 Hodson Hall, St. Paul, Minnesota 55108, USA
‡BioDiversity, Inc., 195 Main Street, Freeport, Maine 04032, USA
§Bureau of Research, Wisconsin Department of Natural Resources, 1350 Femrite Drive, Monona, Wisconsin 53716, USA
‖Department of Veterinary Pathobiology, The Ohio State University, Columbus, Ohio 43210, USA
‖‖National Wildlife Research Centre, Canadian Wildlife Service, 100 Gamelin Boulevard, Hull, Quebec K1A 0H3, Canada

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Abstract—The common loon (Gavia immer) is a high-trophic-level, obligate piscivore at risk from elevated levels of Hg through biomagnification and bioaccumulation. From 1991 to 1996 feather (n = 455) and blood (n = 381) samples from adult loons were collected between June and September in five regions of North America: Alaska, northwestern United States, Upper Great Lakes, New England, and the Canadian Maritimes. Concentrations of Hg in adults ranged from 2.8 to 36.7 μg/g (fresh weight) in feathers and from 0.12 to 7.80 μg/g (wet weight) in whole blood. Blood Hg concentrations in 3 to 6-week-old juveniles ranged from 0.03 to 0.78 μg/g (wet weight) (n = 183). To better interpret exposure data, relationships between blood and feather Hg concentrations were examined among age and sex classes. Blood and feather Hg concentrations from the same individuals were significantly correlated and varied geographically (r squared ranged from 0.03 to 0.48). Blood and feather Hg correlated strongest in areas with the highest blood Hg levels, indicating a possible carryover of breeding season Hg that is depurated during winter remigial molt. Mean blood and feather Hg concentrations in males were significantly higher than concentrations in females for each region. The mean blood Hg concentration in adults was 10 times higher than that in juveniles, and feather Hg concentrations significantly increased over 1 to 4-year periods in recaptured individuals. Geographic stratification indicates a significant increasing regional trend in adult and juvenile blood Hg concentrations from west to east. This gradient resembles U.S. Environmental Protection Agency-modeled predictions of total anthropogenic Hg deposition across the United States. This gradient is clearest across regions. Within-region blood Hg concentrations in adults and juveniles across nine sites of one region, the Upper Great Lakes, were less influenced by variations in geographic Hg deposition than by hydrology and lake chemistry. Loons breeding on low-pH lakes in the Upper Great Lakes and in all lake types of northeastern North America are most at risk from Hg.

Keywords—Loon Mercury Avian exposure Bioaccumulation Biomagnification

INTRODUCTION

Mercury is a natural element in aquatic ecosystems. However, analysis of sediment cores indicates the current rate of Hg loading in lakes in midcontinental North America is three to four times greater than preindustrial levels [1], and virtually all of it is atmospherically deposited [1–3]. Increases in Hg are of concern because of the potentially small margin of safety between background levels of exposure and concentrations that can cause harm in humans and other organisms [4]. Additionally, most anthropogenic Hg deposited in watersheds is retained in the soil and biota for more than a decade [5]. Although global inputs and natural removal mechanisms are not fully understood, annual increases of global atmospheric Hg concentrations may be 1% [6].

Numerous studies have investigated negative effects of environmental Hg to waterbird health and reproductive performance in laboratory dose–response studies [7–12] and in situ studies [13,14]. Few studies, however, have systematically measured Hg exposure in a high-trophic-level wildlife species.

We identified the common loon (Gavia immer) as a good species for investigating environmental Hg exposure for wildlife because (1) it can be reliably captured and recaptured, (2) is easily monitored and observed throughout the breeding season, (3) exhibits high territorial fidelity, (4) can acclimate to moderate levels of direct human disturbance, and (5) is piscivorous and bioaccumulates methylmercury (MeHg). Loons are a useful species for assessing the potential negative effects of Hg deposition because (1) their preferred habitat is lakes, where exposure to mercury would be expected to be highest; (2) they occupy a top trophic level; (3) they have elaborate social, reproductive, and behavioral demands that may be altered by neurological imbalances induced by contaminant interference; (4) they have a long life span of possibly more than 30 years, thereby providing ample time for bioaccumulation; and (5) they have had measured reproductive impairments associated with elevated Hg levels in fish [13].

Several studies have analyzed Hg concentrations in loon tissues [14–22]; however, this is the first systematic analysis of loon tissues from individuals breeding across a broad area of North America.

STUDY AREA AND METHODS

Geographic sampling strategy

From 1991 to 1996 we collected blood and feather samples from adult and juvenile loons across selected areas of North
Fig. 1. Distribution of North American study sites sampled for common loon blood and feather Hg concentrations, 1992–1996.

America. Five study regions were selected as long-term monitoring sites for Hg exposure in common loons (Fig. 1). Two regions, Alaska and the northwestern United States (Northwest), serve as potential reference sites for background Hg exposure, and the Upper Great Lakes (UGL), New England, and Canadian Maritimes regions likely receive elevated inputs of wet and dry anthropogenic Hg [23].

Following are sampling areas, by region and then specifically by study site: (1) Alaska—Kenai National Wildlife Refuge (NWR), Matanuska–Susitna River Valley, and Anchorage; (2) Pacific Northwest—western Cascade Mountains, northeastern corner of Washington, and Montana’s Clearwater–Swan River Valley; (3) Upper Great Lakes (Fig. 2)—Minnesota’s Voyageurs National Park (NP) and southeastern Itasca County, Wisconsin’s Turtle–Flambeau Flowage and a three-county area in the north-central region, and Michigan’s Ottawa National Forest (NF), Isle Royale NP, eastern Upper Peninsula (UP) (Seney NWR is separately treated from other lakes in the eastern UP), and central Ontario; (4) New England—Maine’s Rangeley Lakes region and Lake Umbagog NWR in New Hampshire and Maine; and (5) Canadian Maritimes—Kejimkujik NP, Nova Scotia and Lepreau area, New Brunswick. References in the text to the western UGL exclude the central Ontario site.

Sampling efforts varied over time, and sites were not selected according to biogeochemical parameters. We sampled the UGL from 1991 to 1996, and more than half of the samples originated from a three-county area of north-central Wisconsin. Samples from the Alaska, Northwest, and Canadian Maritimes study regions were gathered in 1995–1996, from New England in 1994–1996, and from Ontario in 1992. Mercury concentration data for feathers gathered in Wisconsin in 1991 were previously reported in the literature [21].

Loon capture and tissue collection

From June through August, 1991 to 1996, one to three teams captured adult and juvenile loons on their breeding lakes with a replicable, night-lighting technique [24]. Spotlights (400,000 to 1.5 million cp) were used to search lakes, and tape-recorded and mimicked calls attracted loons to the boat. Loons were netted with large landing nets, restrained, and transported to shore.
Second secondary feathers were removed by cutting the calamus (i.e., below the base of the vane). Blood samples were taken by venipuncture from either the cutaneous ulnar vein or the medial metatarsal vein. We used 20- to 25-gauge straight needles with 1- to 12-cc syringes, 21- to 25-gauge needles and 7-inch tubing with a multiple-sample Luer adapter into 5- to 10-cc Vacutainers®, or combinations of the above. All loons were marked with U.S. Fish and Wildlife Service aluminum or stainless-steel bands and plastic, colored leg bands glued with an acetone-based adhesive.

The secondary feathers were placed in polyethylene bags, labeled, and refrigerated within 12 h of collection. The initial selection of remigials was based on sufficient mass for contaminants analysis and a removal that would have no impact on loon behavior. Although species and age classes with sequential molting schemes have varying Hg concentrations in their flight feathers [25,26], adult and juvenile loons exhibit a simultaneous remigial molt, and selection should not bias analysis. Blood was collected in 5- to 10-cc green-top Vacutainers (with powdered sodium heparin) for subsequent Hg analysis. Ten percent buffered formalin was added to preserve the blood following U.S. Fish and Wildlife Service protocol (1:20 formalin: blood ratio) [27,28].

**Tissue sample analyses**

Feather and blood samples were analyzed within 2 to 8 months of collection at the Animal Health Diagnostic Laboratory (AHDL) at Michigan State University, East Lansing, Michigan, USA, except for 117 blood samples collected at the north-central Wisconsin study site. These samples were analyzed at Hazelton Environmental Services (HES), Madison, Wisconsin, USA, and 57 blood and 37 feather samples from Ontario analyzed at the National Wildlife Research Centre (NWRC), Hull, Quebec, Canada. All laboratories used a similar, standardized sample preparation and analysis protocol. Mercury concentrations in split samples of blood and feathers were not significantly different between AHDL and HES ($p > 0.01$) or between AHDL and NWRC ($p > 0.01$). The detection limit at each laboratory was 0.025 μg/g for blood and feathers.

Whole blood was homogenized in the original Vacutainer with an electronic homogenizer and sonic dismembrator. Aliquots of 100 mg of whole blood were then placed in 15-ml Teflon® containers, mixed with 2-ml concentration of HNO₃, sealed, and digested overnight at 90°C. Samples were quantitatively transferred to 25-ml (chicks) or 100-ml (adults) vol-
Accuracy was monitored by concurrent analysis of procedural blanks (in triplicate), oyster tissue SRM 1566a with Hg certified at 0.0642 ± 0.0067 μg/g (National Institute of Standards and Technology, Gaithersburg, MD, USA) and tort 2 lobster hepatopancreas with Hg certified at 0.27 ± 0.06 μg/g (National Research Council of Canada, Ottawa, ON, Canada).

**WATER CHEMISTRY PROCEDURES**

Water samples were collected from mid-June to mid-August, 1996, in I-Chem jars (except for sites in Wisconsin and Ontario). Water grab samples were collected at 1 m from the surface near the middle of small lakes or at least 50 m from the shore of larger lakes or those with convoluted shorelines. A portable pH meter (model Orion SA 250 with Orion Sure Flow electrode) was used for on-site analysis. In northern Wisconsin samples were collected at a depth of 1 m using clean polyethylene sample bottles with air-displacement caps in the summer of 1992–1993. Samples were refrigerated until analysis 2 to 4 d after collection. Lake pH was then measured at the Wisconsin Department of Natural Resources Research Laboratory (Monona, WI, USA) or the Wisconsin State Laboratory of Hygiene (Madison, WI, USA). In Ontario, water samples were collected during the summer of 1993 at 1 m depth and immediately placed on ice, refrigerated within 48 h, and analyzed at the Ministry of Natural Resources Laboratory (Sault Ste. Marie, ON, Canada).

**STATISTICAL PROCEDURES**

Data were statistically analyzed using SYSTAT 5.0 and Microsoft Excel Analysis ToolPak 5.0. A computerized one-way analysis of variance (ANOVA) was used for testing sex and study region and site effects. Tukey’s honestly significant difference test was used to compare multiple parameters if ANOVA showed significant differences. Normal probability plots of residuals indicated normality in blood and feathers for all regions and sites. Homoscedasticity was checked with Bartlett’s test, which is sensitive to the normality assumption. SYSTAT corrected for the inequity of unbalanced data sets. Blood and feather data were log_{10}-transformed to normalize their variance. In all cases, means are given with one SD unless noted otherwise.

**RESULTS**

Geographic trends in Hg concentrations are presented for adults and juveniles across North America. Sampling emphasis in the UGL was greater than other regions and therefore was selected for closer examination of hydrological and geochemical influences and two confounding variables, sex and age.

### Geographic trends in Hg concentrations in adult loons

Mean adult whole-blood Hg concentrations was $1.72 ± 1.17$ μg/g across North America (Table 1). For the five study areas, the lowest mean blood Hg concentration was $0.66 ± 0.13$ μg/g at 1 m depth and immediately placed on ice, refrigerated within 48 h, and analyzed at the Ministry of Natural Resources Laboratory (Sault Ste. Marie, ON, Canada).
0.30 μg/g in Alaska. Compared to levels in Alaska, mean blood Hg concentrations were 1.7 times higher in the Pacific Northwest (1.10 ± 0.49 μg/g), 2.4 times greater in the UGL (1.58 ± 0.92 μg/g), 3.5 times greater in New England (2.30 ± 0.99 μg/g), and 5.3 times greater in the Canadian Maritimes (3.53 ± 1.86 μg/g) (Fig. 3). Mean blood Hg concentration was significantly different among regions (F = 31.1, p < 0.001).

Mean adult feather Hg concentrations was 11.1 ± 4.7 μg/g across North America (Table 2). The difference in feather Hg concentrations between regions was significant (F = 21.5, p < 0.001). The lowest mean feather Hg concentration was 5.4 ± 2.8 μg/g in Alaska, and the highest was 13.1 ± 5.3 μg/g in New England (Fig. 3).

Regional differences in blood and feather Hg concentrations were not significant for three regions (Fig. 3). The overall west–east trend exhibited in the blood differed from feathers. Although summer blood Hg concentrations were highest in the Canadian Maritimes, the highest-risk region indicated by feather Hg loads was New England. Adult whole blood and feather Hg concentrations across North America showed a highly significant positive relationship (F = 55.4, p < 0.001); however, the correlation coefficient was weak (r² = 0.20) (Fig. 4). The blood–feather relationship increased from west to east. Data from Alaska showed no correlation between blood and feather concentrations (r² = 0.03), whereas the Canadian Maritimes site exhibited the highest correlation (r² = 0.48).

**Mercury concentrations in the UGL Region for adult loons**

Adult whole-blood Hg concentrations were significantly different between the nine sites in the UGL (F = 6.94, p < 0.001). Lowest mean concentrations (0.97–1.14 μg/g) were recorded in four study sites with generally well-buffered surface waters (except for two lakes with a pH of 5.1; lake pH ranged from 6.8 to 8.8). Higher but not significantly different Hg levels (1.41–1.44 μg/g) were recorded for loons from reservoirs in Minnesota’s Voyageurs NP and Wisconsin’s Turtle–Flambeau Flowage, and from a cluster of lakes with varying pH (5.1–7.9) in the Ottawa NF, Michigan. The highest mean blood Hg concentrations were found in north-central Wisconsin and central Ontario (1.92–2.06 μg/g), and they were significantly higher than those at the other seven study sites. A west–east trend was not evident in this region. Among the nine UGL sites, between-site variation was significant only for adult feather Hg concentrations from Ontario (F = 2.35, p = 0.02). The adult blood–feather relationship was weak in the UGL (r² = 0.11) but had a significant positive slope (F = 18.9, p < 0.001).

**Sex and age as confounding variables**

We found highly significant sex differences for Hg concentrations measured in adult blood among regions (F = 26.9, p < 0.001) and in the UGL (F = 24.3, p < 0.001) and in adult feathers among regions (F = 88.8, p < 0.001) and in the UGL (F = 63.9, p < 0.001). For the nine UGL sites, the mean blood Hg concentration was 1.78 ± 0.89 μg/g in males and 1.41 ± 0.99 μg/g in females, ranging 12 to 45% higher in males (mean = 19%) (Tables 1 and 2). Mean feather Hg concentrations in the UGL were 13.0 ± 4.8 μg/g in males and
9.6 ± 3.4 μg/g in females. Means between the nine study sites ranged from 9 to 44% higher in males than females (mean = 25%).

The relationship between male feather and blood Hg concentrations was more strongly correlated than that of their mates for each region. Male and female blood Hg concentrations were significantly different ($F = 6.41, p < 0.05$) in paired loons but showed a relatively strong correlation ($r^2 = 0.64$).

Adult blood and feather Hg concentrations were significantly higher than juvenile concentrations among regions and within the UGL ($p < 0.001$). Adult loons recaptured 1 to 4 years after their original sampling exhibited significant positive accumulation rates in their feathers ($p < 0.01$) but not in their blood ($p > 0.05$). More than 70% of the feather remeasures exhibited an increase ($n = 86$).

**Juvenile Hg exposure as measured in blood and feathers**

Mercury concentrations measured in the whole blood of 3- to 6-week-old juveniles ranged from 0.03 to 0.78 μg/g (Table 3). Similar to adult blood and feather concentrations, juvenile Hg concentrations increased significantly from west to east ($F = 10.99, p < 0.001$). The geographic order of Hg concentrations in North American juvenile loons had the same trend as the adults (Fig. 3). Adult blood concentrations significantly correlated with offspring blood concentrations ($p < 0.001$); females had a stronger relationship ($r^2 = 0.56$) than males ($r^2 = 0.48$) (Fig. 5). Juvenile blood Hg concentrations were approximately five times higher in northeastern North America versus Alaska.

In the UGL mean blood Hg concentrations showed differences between study sites, and their rankings generally matched those found in adult whole blood. Secondary feather Hg concentrations ranged from 0.61 to 13.6 for 7- to 11-week-old juveniles (Table 3) and increased with age. Blood Hg concentrations showed a significant and positive linear relationship with feathers ($r^2 = 0.66, F = 49.81, p < 0.001$).

**DISCUSSION**

**Blood as an indicator of Hg exposure during the breeding season**

Blood provides an indication of recent dietary Hg uptake. Nearly all Hg in the blood is MeHg bound to red blood cells. Because the half-life of MeHg in avian tissues is 2 to 3 months [33], loon blood samples represent Hg uptake from April to August, when loons are feeding on their breeding lakes. Adult and offspring blood Hg concentrations are correlated; therefore, blood Hg of either age group indicates Hg exposure on the nesting lake. The strength of this relationship is confounded by adult age and by adults foraging on neighboring lakes [34].

Mercury exposure in adults and juveniles significantly increased from western to eastern North America. The geographic order and significant differences of the five study regions were identical for both age classes. This pattern generally agrees with the U.S. Environmental Protection Agency (EPA) [23] model of atmospheric wet and dry Hg deposition and their predicted high impact areas, including low-pH lakes in the UGL and the northeastern United States. Results of the International Toxics Monitoring Program agree with the EPA model’s prediction for high levels of Hg deposition in northeastern North America through sampling of sphagnum moss and snow (T.A. Haines, personal communication).

Industrial centers of the lower Great Lakes and mid-Atlantic regions are major sources of Hg emissions [23] and likely influence the geographic exposure of local-scale and long-range deposition of the different forms of Hg. Hydrological and geochemical situations also play a critical role in Hg bioavailability. For example, Hg concentrations are higher than expected background levels in fish from reservoirs, particularly newly created ones [35,36], and in lakes with low buffering capacity [37–42]. Sampling efforts in the western UGL show higher adult and juvenile blood Hg concentrations in these lake situations, and Meyer et al. [21] found a highly significant linear relationship between adult loon red blood cell Hg content and lake pH in Wisconsin. Unlike the generally homogenous Hg deposition modeled for the western Great Lakes...
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Fig. 4. Relationship between adult blood and feather Hg concentrations in common loons at selected sites in North America, 1992–1996.

Table 3. Total Hg concentrations in juvenile common loon blood and feathers at selected sites in North America, 1992–1996

<table>
<thead>
<tr>
<th>Location</th>
<th>Blood Hg concn. (μg/g)</th>
<th>Feather Hg concn. (μg/g fresh weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Northwest (WA, MT)</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>Great Lakes</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>Isle Royale NP, MI</td>
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<td>0.01</td>
</tr>
<tr>
<td>Seney NWR, MI</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>Turtle–Flambeau Flowage, WI</td>
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<td>0.03</td>
</tr>
<tr>
<td>Voyageurs NP, MN</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>Eastern UP, MI</td>
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<td>0.10</td>
</tr>
<tr>
<td>Ontario, Canada</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Ottawa NF, MI</td>
<td>0.19</td>
<td>0.09</td>
</tr>
<tr>
<td>North-central Wisconsin</td>
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<td>0.13</td>
</tr>
<tr>
<td>New England (NH, ME)</td>
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<td>0.19</td>
</tr>
<tr>
<td>Canadian Maritimes (NS, NB)</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>All sites</td>
<td>0.16</td>
<td>0.13</td>
</tr>
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</table>

* NF = National Forest; NP = National Park; NWR = National Wildlife Refuge; UP = Upper Peninsula.

As measured in a composite of 2 second secondary feathers from each individual.

(e.g., northern Minnesota, Michigan, and Wisconsin), models predict higher deposition in the eastern Great Lakes [23]. The adult and juvenile blood Hg concentrations from central Ontario [22] appeared to reflect this geographic increase.

Generally, loon blood Hg concentrations are higher than those of some other obligate and facultative piscivores and seem a suitable bioindicator of lake MeHg bioavailability. Derr [43] found adult loon blood Hg concentrations to be significantly higher than those of common mergansers (Mergus merganser), hooded mergansers (Lophodytes cucullatus), red-necked grebes (Podiceps grisegena), and common goldeneyes (Bucephala islandica) in reservoirs of northern Minnesota. Mean blood Hg concentrations of juvenile loons were similar to those of juvenile bald eagles (Haliaeetus leucocephalus) sampled in Maine’s interior lakes [44].

Feathers as indicators of Hg exposure

Feathers are widely recognized as major excretory pathways for Hg, allowing adult birds to sequester 70 to 93% of their Hg body burden [45–48]. The mean feather Hg concen-
Fig. 5. Relationship between total blood Hg concentrations in adult common loons and their offspring at selected sites in North America, 1992–1996.

The chronic accumulation of MeHg in temperate aquatic environs now places the common loon as a species at high risk. Burger [48] summarized studies that measured feather Hg, highlighting two at-risk groups that exhibit feather Hg concentrations up to 3 times higher than those of common loons, seabirds, particularly long-lived species, and large raptors. However, seabirds may have physiological mechanisms to cope with naturally high environmental Hg levels, and studies of large raptors in Scandinavia were conducted during the peak of regional anthropogenic Hg releases in the 1960s. Most loon individuals are “seabirds” for 5 to 6 months of the year and therefore have evolved depuration avenues that include the demethylation and storage of nontoxic Hg in their liver and kidney [55].

Eisler [56] suggested a feather Hg concentration of 5.0 μg/g (fresh weight) as a minimal generic criterion for avian protection, and few species, other than some seabirds and raptors, typically surpass 15 μg/g [48]. Scheuhammer and Bond [29] concluded that individuals with feather Hg concentrations >20 μg/g should be considered at risk from toxic effects. In our study, 94% of feather Hg concentrations exceeded 5 μg/g, 18% exceeded 15 μg/g, and 5% exceeded 20 μg/g. More than 27%
of the male feather Hg concentrations exceeded 15 μg/g (3 times that of females), and 9% exceeded 20 μg/g.

Sex influences on Hg concentrations

Unlike other avian studies [8,48,54,57], we found highly significant sex differences for Hg concentrations measured in feathers and blood (p < 0.001). These differences were consistent across each of the five study regions and UGL study sites (Tables 1 and 2). Sex differences of blood Hg concentrations were not due to differences in packed cell volume (PCV: % of red blood cells in whole blood). We found a mean PCV for adult loons of 48 ± 3% (n = 38 males and 40 females) with no significant sex differences (p > 0.05). Reasons for sex differences in Hg concentrations may be partly derived from maternal transfer to eggs, differential diets, and dimorphism.

Sexual dimorphism contributes to differing prey preferences, and fish Hg content increases with fish age and size [58] and species [59–61]. The weights of male loons average 21% greater than those of females (n = 448) and may be explained by forage niche partitioning [62,63]. A geographic cline for loon size and the extent of sexual dimorphism was observed. The smallest loons and least pair dimorphism is in Minnesota (male mean, 4,300 ± 240 g; female mean, 3,500 ± 200 g; paired differences, 850 ± 280 g). Adult size increases north, west, and east of Minnesota. For example, adults average 26 to 30% heavier in New England than in Minnesota (male mean, 6,100 ± 330 g; female mean, 4,700 ± 300 g; paired differences, 1,450 g). Therefore, two factors that may contribute to our finding of higher levels of Hg exposure in New England and the Canadian Maritimes are that (1) larger loons tend to eat larger fish that have higher Hg loads and (2) larger loons exhibit greater sexual dimorphism with their mates (i.e., New England pairs have an average weight difference of 59% more than Great Lakes pairs).

Age influences on Hg concentrations

We found that Hg concentrations tend to increase with age because (1) adults had significantly higher levels than their offspring and (2) adult male feather Hg concentrations were increased in recaptured individuals.

Mean adult blood (1.72 μg/g) and feather (11.1 μg/g) Hg concentrations at all sites were significantly greater than juvenile Hg concentrations (mean blood, 0.16 μg/g; mean feather, 3.8 μg/g) (P < 0.001), more than 10 times greater in blood. In 20 of 21 studies summarized by Burger [48], feather Hg concentrations were 2 to 13 times higher in adults than juveniles of the same species (mean, 3.4 ± 2.7 times). Our adult/juvenile feather Hg concentration ratios are similar to the mean found by Burger [48] and by Burger et al. [20] in a study of dead or moribund loons (adult concentrations were 2 times greater than juvenile concentrations).

Other studies have not identified age-dependent Hg concentrations in adults [54,64]. Yet in our study, more than 70% of recaptured individuals showed a significant increase in feather Hg concentrations (p < 0.05). Summer blood Hg concentrations did not increase when remeasured in the same individuals over a 1- to 4-year period (p > 0.05). Therefore, it is possible that adult common loons, particularly older individuals and those that are exposed to elevated Hg levels, may be unable to demethylate or rid their entire body burden during their molt periods. This MeHg is stored in muscle tissue [55] and apparently is remobilized during their remigial molt sequence. Feather Hg usually does not solely reflect winter dietary Hg uptake. Furness et al. [26] support this finding and identified Hg body burdens to be the main sources of feather Hg content.

Geochemical and lake morphology patterns associated with high-risk levels of Hg exposure

Water bodies most at risk of Hg bioaccumulation in fish are those with low acid-neutralizing capacity and low pH [37,41,61], high dissolved organic carbon [65], high water temperatures [66], large watersheds [67], and high shoreline wetland lake and high exposed shoreline lake ratios. Newly created reservoirs and bog lakes commonly fit these criteria. However, our studies have also found elevated adult and juvenile blood Hg concentrations in lakes with substrates of naturally high Hg deposits and older reservoirs with increased Hg bioavailability because of multiple ecological factors. Lakes that pose a high risk to loons can be somewhat predicted through fish Hg concentrations. Scheuhammer et al. [22] found strong correlations between breeding adult blood and forage fish Hg concentrations.

Fish Hg concentrations that Barr [13] associated with impaired loon reproduction (0.3 μg/g fresh weight) are widespread in temperate North American waters. Loon forage fish with more than 0.3 μg/g have been found in (1) northern Wisconsin [37,38,59], (2) Michigan’s UP [68], (3) Minnesota [69], and (4) Maine [60]. Scheuhammer and Blancher [70] found that up to 30% of Ontario lakes have small (<250 g) fish with greater than 0.03 μg/g Hg in the axial muscle, depending on the species of fish analyzed. A similar proportion of comparably contaminated lakes were detected by Meyer et al. [21] in northern Wisconsin. Whether Hg toxicity affects loon survival, health, or reproduction is being investigated by the coauthors; however, widespread exposure at potentially toxic levels has been demonstrated for the UGL and northeastern North America (particularly for males). Because our sampling strategy is biased toward reproductively healthy individuals, population-wide exposure may be even higher than currently measured.

Assessing Hg exposure in common loons requires stratification of data by sex, age, tissue type, and geographic distribution. An understanding of intra- and interseasonal movements, trophic structure, prey composition and availability, selenium availability and chemical form, water chemistry, hydrology, physiological demethylation capabilities, and habitat features, both local and at a landscape level, will further aid interpretation. This knowledge base could eventually be used to develop risk assessment models for estimating the impact of Hg exposure on the common loon.

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REFERENCES


