The Impact of Mercury Exposure on the Common Loon (*Gavia immer*) Population in the Adirondack Park, New York, USA

Author(s): Nina Schoch, Michale J. Glennon David C. Evers Melissa Duron Allyson K. Jackson, Charles T. Driscoll John W. Ozard and Amy K. Sauer

The Impact of Mercury Exposure on the Common Loon (*Gavia immer*) Population in the Adirondack Park, New York, USA

Nina Schoch[1,*], Michale J. Glennon[2], David C. Evers[1], Melissa Duron[1], Allyson K. Jackson[1,5], Charles T. Driscoll[3], John W. Ozard[4] and Amy K. Sauer[1]

[1]Biodiversity Research Institute, 19 Flaggy Meadow Road, Gorham, ME, 04038, USA

[2]Wildlife Conservation Society's Adirondack Program, 132 Bloomingdale Avenue, Suite 2, Saranac Lake, NY, 12983, USA

[3]Syracuse University, Department of Civil and Environmental Engineering, 151 Link Hall, Syracuse, NY, 13244, USA

[4]Wildlife Diversity Unit, New York State Department of Environmental Conservation, 625 Broadway, Albany, NY, 12233, USA

[5]Current address: Oregon State University Department of Fisheries and Wildlife, 104 Nash Hall, Corvallis, OR, 97331, USA

[*]Corresponding author; E-mail: nina.schoch@briloon.org

Abstract.—The Common Loon (*Gavia immer*), a top trophic-level piscivorous predator, was used as an indicator species to assess mercury exposure and risk in aquatic ecosystems in the Adirondack Park of New York State. Mercury levels in Common Loons were related to long-term reproductive success to evaluate the effects of mercury contamination on the breeding population in the Park and enable the development of a mercury hazard profile. Common Loons were sampled and monitored on selected study lakes from 1998-2007. Lake acidity correlated with Common Loon mercury levels, with more acidic lakes exhibiting higher mercury concentrations in Common Loons. Based on mercury body burden estimated by blood mercury exposure, 21% of males and 8% of females were at high risk for behavioral and reproductive impacts, while feather mercury exposure estimated that 37% of males and 7% of females were at high risk. Female and male Common Loons in the highest exposure category showed a 32% and 56% reduction, respectively, in the number of chicks fledged per year, compared to individuals in the lowest exposure category. Thirteen percent of the Adirondack Common Loon eggs sampled were at high risk for mercury exposure. Population model results indicated that the portion of the Adirondack Common Loon population with high mercury levels has a reduced growth rate ($\lambda = 1.0005$), compared to Common Loons with low body burdens of mercury ($\lambda = 1.026$). The results of this project will assist in the continued refinement of State and Federal policies and regulations that effectively address the ecological impacts mercury and other environmental contaminants pose to freshwater ecosystems. *Received 21 January 2013, accepted 26 May 2013.*

Key words.—acid deposition, Adirondack Park, Common Loon, *Gavia immer*, methylmercury, population model.

Environmental mercury (Hg) is a naturally occurring element in the landscape with high concentrations prevalent in aquatic biota. Analyses of lake sediment cores indicate that the current rate of mercury deposition in northeastern North America is two to five times greater than pre-1940s historical levels (Swain *et al.* 1992). Scientists have traced this mercury increase to dry and wet atmospheric particulate fallout that primarily originates from anthropogenic sources, such as coalburning power plants and incinerator emissions. Studies comparing fish mercury concentrations with atmospheric deposition have found that anthropogenic sources are a major contributor to the aquatic system load (Northeast States for Coordinated Air Use Management 1998).

The current availability of methylmercury (MeHg), the biologically toxic form of mercury that accumulates and magnifies within food webs, in aquatic ecosystems of northeastern North America poses risks to human and ecological health. This is reflected in the number of State-mandated fish consumption advisories for many water bodies in New York State, including a blanket advisory for the Adirondack Park for many species of fish (New York State Department of Health 2013). The concentration of mercury in aquatic ecosystems varies considerably in response to methylmercury availability and is affected by environmental variables such as lake hydrology, biogeochemistry, habitat type, topography, and proximity to airborne sources. Mercury is of particularly high concern in acidic environments, such as

in many northeastern lakes, where elemental mercury is converted at a higher rate to methylmercury, and thus made more bioavailable to wildlife inhabiting these acidic systems.

The Common Loon (*Gavia immer*), a Species of Special Concern in New York State, breeds on waterbodies throughout New York's 2.4-million-ha Adirondack Park. Common Loons (loons) are piscivorous predators at the top of the food chain and have the potential to be affected detrimentally by toxins, such as mercury, that bioaccumulate and biomagnify through the environment. Methylmercury, a neurotoxin, has been demonstrated to affect the reproduction, behavior, and survival of Common Loons and other aquatic and terrestrial wildlife (Thompson 1996; Meyer *et al.* 1998; Nocera and Taylor 1998; Evers *et al.* 2008). Recent studies have shown that blood mercury concentrations above 3.0 µg/g (wet weight, ww) in Common Loons cause detrimental impacts to reproduction, potentially leading to long-term population level declines (Burgess and Meyer 2008; Evers *et al.* 2008). Specifically, evidence has demonstrated that Common Loons with elevated mercury exposure experience numerous negative neurotoxic, physiologic, and reproductive impacts, including the production of smaller eggs (Evers *et al.* 2003), increased time spent in low-energy behaviors (Evers *et al.* 2004, 2008), reduced diving frequency (Olsen *et al.* 2000), decreased time spent incubating eggs (Evers *et al.* 2004, 2008), reduced chick feeding rates by adults (Counard 2001), and less backriding by chicks (Nocera and Taylor 1998). Scheuhammer *et al.* (2008) also correlated brain mercury concentrations with changes in neurotransmitter receptor concentration and other neurochemical effects. Evers *et al.* (2008) found that loons with elevated blood mercury levels spent less time engaged in high energy behavioral activities, such as foraging and incubating eggs, than birds with low mercury levels. These behavioral changes may contribute to overall decreased viability of eggs and survival of chicks, reinforcing findings related to decreased productivity in loons with high mercury body burdens (Evers *et al.* 2008).

This study is the first long-term research and monitoring project to evaluate how mercury impacts the Common Loon population in New York's Adirondack Park. Based on risk categories developed from the literature and *in situ* studies by Biodiversity Research Institute and their collaborators, preliminary results from 1998-2000 indicated that 17% of the loons sampled in the Adirondacks were estimated to be at risk for harmful effects from mercury contamination (Schoch and Evers 2002). The results from this work and regional collaborations provide a better assessment of the neurologic, behavioral, and physical impacts of mercury exposure on Common Loon populations.

The main objectives in this study were to: 1) develop a mercury hazard profile based on blood, feather and egg mercury values to determine what percentage of the Adirondack loon population is at risk of reduced productivity; 2) assess the effect of mercury and lake acidity on loon reproductive success; and 3) use the productivity dataset in a Common Loon population model to assess potential long-term effects of environmental mercury pollution on the Adirondack Common Loon population.

METHODS

Tissue Sample Collection

Common Loons were captured from 77 lakes in New York's Adirondack Park between 1998 and 2007 using night-lighting and playback techniques (Evers 2001). Loon tissue sample collection followed established protocols (Evers *et al.* 1998, 2003, 2005). Loon blood samples were collected non-lethally from the tibiotarsal vein to evaluate short-term mercury accumulation in the loons. Feather samples, including two central tail feathers and a secondary feather from each wing, were collected from adult and juvenile loons to provide an indication of long-term mercury accumulation. Morphometric measurements, such as bill length (mm), tarsus length (mm), and weight (g), were recorded. Adult and juvenile (if large enough to hold an adult band) loons were banded with a combination of U.S. Geological Survey aluminum and plastic colored bands, enabling identification of individual birds by field biologists during subsequent observations. Abandoned nonviable loon eggs were opportunistically collected to assess their mercury levels. Egg samples were processed for mercury analysis following standardized protocols (Evers *et al.* 2003).

A constraint of this study is that the ability to capture loons is primarily restricted to birds that produce chicks. Thus, long-term Common Loon mercury and productivity data may be limited for highly acidic lakes (pH < 5.0) and for those with elevated mercury exposure levels, as loons with highly elevated blood mercury concentrations may not successfully hatch chicks and so are not responsive to the night-lighting and playback capture technique.

Banded Loon Monitoring

To determine the annual return rate and reproductive success of color-banded Common Loons, trained field staff conducted weekly observations using 10 x 40 binoculars from a canoe or kayak on the territories where the birds were originally captured. Observations were conducted for an 11- to 15-week period between late May and early September during the summers of 1999-2007. To determine the reproductive success of the banded loons, the following parameters for each territory were recorded: presence of a territorial pair, presence of a nesting pair, nesting attempts, hatching success, and fledging success. Fledging success is defined as a chick that survived to 6 weeks of age or older, as a majority of chicks that survive past 6 weeks are likely to survive to the actual fledging age of 11 weeks (Evers *et al.* 2004).

The number of chicks fledged per territorial pair (CF/TP) was used as the reproductive endpoint of interest since a fledged chick carries the most biological significance with respect to long-term population trends (Evers *et al.* 2004, 2008). While studies on other species frequently use nesting attempts or hatching success as indicators of reproductive success, the number of chicks fledged was used as the most accurate assessment of overall reproductive success in Common Loons because nests can fail prior to detection and hatched chicks can die before being visually confirmed.

Laboratory Analysis

Laboratory protocols for analyzing total mercury in Common Loon tissues followed Evers *et al.* (2003) for eggs and Evers *et al.* (1998) for blood and feathers. Analyses for methylmercury in loon tissues were not conducted as more than 95% of blood mercury in birds is in the form of methylmercury (Wolfe *et al.* 2007). Analyses of loon blood and feathers were conducted by the Animal Health Diagnostics Laboratory, Pennsylvania State University, and analyses of blood and eggs were conducted at the Trace Element Research Laboratory, Texas A&M University. Loon feathers from 2003 to 2005 were analyzed by the Harvard School of Public Health and from 2006-2007 by the University of Connecticut's Center of Environmental Sciences and Engineering Metals Laboratory.

Statistical Analysis

Common Loon unit calculations. To best evaluate and use existing data from various biotic compartments, mercury concentrations require a single common unit. Since Common Loon mercury data are from multiple tissues, including adult male and female blood, juvenile blood, and loon eggs, comparisons between locations and years can be difficult to conduct or assess. To address this issue, a Common Loon dataset from New York (1998-2008, $n = 381$) was compiled. Subsets of the data, in which there were multiple mercury data points from a single territory and year, were used to develop relationships between mercury in different tissues. These models were then applied to the larger dataset to present data from all tissue types, territories and years in a common unit, designated as the female loon unit (FLU; Evers *et al.* 2011). Egg mercury levels are correlated with female mercury exposure, as female loons depurate mercury into their eggs (Evers *et al.* 2003). Juvenile loon mercury levels, likewise, could be assumed to be highly correlated with female mercury as they tend to eat prey of similar size. No clear link exists between egg mercury or juvenile blood mercury levels with adult male blood mercury levels. Therefore, all male blood mercury, juvenile blood mercury, and egg mercury were each separately regressed with female blood mercury to convert all tissues to FLUs. Female adult blood levels were also converted into male loon units (MLUs), as male loons on the breeding grounds tend to have higher mercury levels than females regardless of body weight, presumably due to the depuration of female body mercury into eggs. Thus, presentation of mercury data in FLUs presents a different picture than in MLUs. FLUs are a more universal unit since they include egg and juvenile data and they represent the expected or observed blood mercury of adult females. As male mercury exposure is generally higher than for females, even in the same locations and years, examination of the data in the form of MLUs is useful for predicting male exposure in the region.

Mercury hazard profile. Published estimates for risk associated with blood, feather, and egg mercury concentrations in Common Loons (Evers *et al.* 2008) were used to assess what proportion of the breeding Adirondack loon population is at risk of reproductive impairment from mercury contamination. Study birds were assigned to a mercury category based on their blood mercury levels. Male loon units were grouped into four categories: low (0-1 µg/g), low-moderate (1-2 µg/g), moderate-high (2-3 µg/g), and high-extra high (> 3 µg/g). Female loon units were grouped into three categories: low (0-1 µg/g), low-moderate (1-2 µg/g), and moderate-high (2-3 µg/g). Lake pH was grouped into two categories: high acidity (pH < 6.3) and low acidity (pH > 6.3) based on previous studies (Meyer *et al.* 1995; Alvo 1996) and were compared for loon blood mercury level and lake pH using a generalized linear model (GLM) and a non-parametric Kruskal-Wallis test.

Common Loon productivity. Data were collected from 1999-2007 on the reproductive success of banded Common Loons on 77 loon study lakes throughout the Adirondack Park to calculate the number of fledglings produced per territorial pair per year. The average number of fledglings produced per territorial pair per year is referred to as the overall productivity (CF/TP) of each territory. To evaluate the interactions among mer-

cury contamination, lake acidity, and loon productivity, only territories that were monitored every year for 3 or more years were included in the analysis.

Common Loon population model. Grear *et al.*'s (2009) density-independent stage-based matrix population model was used to determine a population growth rate (λ) estimate for the Adirondack loon population.

$$\lambda_{\text{Adks}} = \frac{\{P_j\, F_a\}}{\{G_j\, P_a\}}$$

where P_j is the probability of juvenile survival without transitioning to adulthood (estimated at 0.5702), G_j is the probability of a juvenile growing into the adult class (estimated at 0.1842), F_a is the number of female offspring produced per adult female per year (= $P_a^{(10/12)}$ $b*m*r$, where b = pairing propensity, m = number of chicks fledged per territorial pair (CF/TP), and r = the sex ratio of chicks, which was set at 50:50), and P_a is the annual adult survival (estimated at 0.9200; Mitro *et al.* 2008).

The overall Adirondack loon study population included all loons sampled for this study. The population growth rate was also evaluated separately for both the low-moderate and high-extra high mercury risk categories of loons.

Common Loon population model projections. Population growth rates were calculated to project the Adirondack loon population growth over a time span of 50 years across four different scenarios of mercury risk. Beginning with an estimated population of 1,000 adult birds (based on loon population surveys conducted in the Adirondacks in the mid-1980s by Parker *et al.* 1986), calculations were made to determine how many loons would fall into each risk category. These results were then used to model the population growth (based on calculations of λ) for each subset of the population. Overall population growth was determined by combining the projections for low-moderate and high-extra high groups, allowing for a direct comparison between different mercury risk scenarios. It is important to note that these

projections did not include effects of competition, such as density dependence, for limited breeding habitat, or other potential limits to loon populations, such as predation and impacts from human disturbance.

RESULTS

Between 1998 and 2007, we sampled one or more types of loon tissue (blood, feather, or egg) at each study lake. The mean adult blood mercury level was 1.97 µg/g (ww) (SE = ± 0.173) with a wide amount of variation across lakes (range 0.58-5.62 µg/g) (Table 1). Females averaged lower blood (1.716 µg/g (ww)) and feather (11.631 µg/g (fw)) mercury loads than males (2.164 µg/g (ww) and 19.792 µg/g (fw), respectively). Blood mercury levels in juvenile Common Loons were considerably lower than adults, averaging 0.239 µg/g (ww) (SE = ± 0.029) with a range from 0.01 µg/g to 0.76 µg/g. Adult male and female feathers showed a large amount of variation in mercury levels, ranging from 3.94 µg/g (fw) to 73.21 µg/g (fw). Eggs were collected at 29 study lakes and total mercury concentrations ranged from 0.35 µg/g (ww) to 2.15 µg/g (ww) with a mean value of 0.8 µg/g (SE = ± 0.085).

Mercury Hazard Profile

Established mercury risk categories for Common Loons based on mercury exposure

Table 1. Summary statistics for mercury levels in Adirondack Common Loons (*Gavia immer*), 1998-2007.

Parameter	Variable[a]	n	Mean	SE	Min	Max	1st Quartile	Median	3rd Quartile
Loon									
Blood[b]	Female Blood	36	1.72	0.17	0.43	5.87	1.08	1.46	2.27
	Male Blood	37	2.16	0.17	0.52	5.36	1.34	1.90	2.92
	All Adult Blood	42	1.97	0.15	0.58	5.62	1.24	1.85	2.53
	All Juvenile Blood	34	0.24	0.03	0.01	0.76	0.13	0.20	0.29
Loon Feather[c]	Female Feather	34	11.63	0.94	3.94	35.26	8.69	10.53	13.56
	Male Feather	36	19.79	2.13	5.19	73.21	13.57	15.55	21.14
	All Adult Feathers	40	16.39	1.35	4.57	48.21	12.17	13.74	19.19
Loon Egg[b]	Eggs	29	0.80	0.09	0.35	2.15	0.49	0.61	0.96
Loon Units[b]	Average Female Loon Unit	44	1.47	0.13	0.31	4.13	0.81	1.35	1.99
	Average Male Loon Unit	42	2.26	0.15	0.74	5.66	1.51	2.21	2.85

[a]All Hg values in parts per million (µg/g).
[b]Values reported at wet weight (ww).
[c]Feather Hg in fresh weight (fw).

levels and biological effects (Thompson 1996; Evers *et al.* 2003, 2008; Burgess and Meyer 2008) were used to assess the proportion of the Adirondack loon population at risk for impacts from environmental mercury pollution. We determined that 21% of the male Adirondack Common Loons and 8% of the female Common Loons examined in this study are at high risk to detrimental impacts, such as behavioral impairment or decreased reproductive success, based on their blood mercury levels (Fig. 1). Feather mercury loads reflect that 37% of male Common Loons are at risk of adverse effects while 7% of females are at a similar risk (Fig. 1). Approximately 13% of nonviable Adirondack Common Loon eggs evaluated in this study exceeded the guidelines associated with high mercury levels (Fig. 1).

Spatial Distribution of Mercury

To better understand if mercury contamination in loons was concentrated in one area of the Adirondack Park, female loon units for each lake were grouped into four risk categories (Evers *et al.* 2005). While the data did not indicate any strong trends of loon mercury levels in one part of the Park, they did appear to show that the southern end of the study area tended to have lakes with higher FLU values (Fig. 2). This pattern was stronger when MLU values were considered, as there were more male birds in the moderate-high and high-extra high risk categories (Fig. 3). Mercury concentrations for both female and male loon units were negatively correlated with lake pH (FLU: $r^2 = 0.1796$, $F = 9.20$, $P = 0.004$; MLU: $r^2 = 0.1219$, $F = 5.55$, $P = 0.024$; Figs. 4a and 4b).

Between 1999 and 2007, 564 re-observations were recorded of banded loons on 77 lakes for a total of 541 loon territory-years (defined as a pair of Common Loons observed on a territory for a breeding season) to assess the reproductive success of study birds. The annual productivity across all study lakes was 0.594 (SE = 0.046) CF/TP per year. Study birds were grouped by mercury exposure levels; the productivity of the low-moderate mercury loons was 0.673 CF/TP, which was greater than that of the

high/extra-high mercury loons, which averaged 0.483 CF/TP. The low-moderate mercury loons also hatched more chicks (1.16 chicks hatched per nesting pair (CH/NP)) than did the high/extra-high mercury birds (0.866 CH/NP; Table 2).

To examine the interactions of mercury and pH on reproductive success, only territories that were monitored annually for three or more years were assessed; this included 304 territory-years of loon productivity data from 53 territories. Because mercury and pH can be correlated, we ran a generalized linear model to better understand if Common Loon mercury and pH combined to affect annual productivity. We found a good fit for a GLM that included MLU, pH, and MLU*pH interaction ($\chi^2 = 8.156$, df = 3, $P = 0.043$). Within this model, however, the only significant beta estimate was the effect of MLU on productivity ($\beta = -0.1494$, $P = 0.0208$), while the effect of both pH ($\beta = 0.0731$, $P = 0.5045$) and pH*MLU ($\beta = -0.0848$, $P = 0.4098$) was not significant. We found no support for a GLM predicting productivity based on FLU, pH, and FLU*pH interactions ($\chi^2 = 5.506$, df = 3, $P = 0.138$).

Because the interaction between mercury and pH did not appear to be important within our dataset, for clarity we present data for the effect of mercury (based on MLU and FLU) on productivity alone. FLUs were used to compare annual productivity between three different mercury groups (Fig. 5): low risk (0-1 μg/g; Hg = 0.680 μg/g: avg CF/TP/year = 0.697, SE = 0.076, $n = 19$); low-moderate risk (1-2 μg/g; Hg = 1.351 μg/g: avg CF/TP/year = 0.563, SE = 0.064, $n = 24$); and moderate-high risk (> 2 μg/g; , Hg = 2.505 μg/g: avg CF/TP/year = 0.474, SE = 0.120, $n = 10$). Using a non-parametric Kruskal-Wallis test, a marginally significant difference was detected between all the mercury groups ($\chi^2 = 5.136$, df = 2, $P = 0.077$), and a significant difference when comparing low to moderate-high groups ($P = 0.036$; Fig. 5a). The trends indicate a 19% reduction in productivity between low and moderate groups and a 32% reduction in productivity between low and moderate-high groups (Fig. 5b).
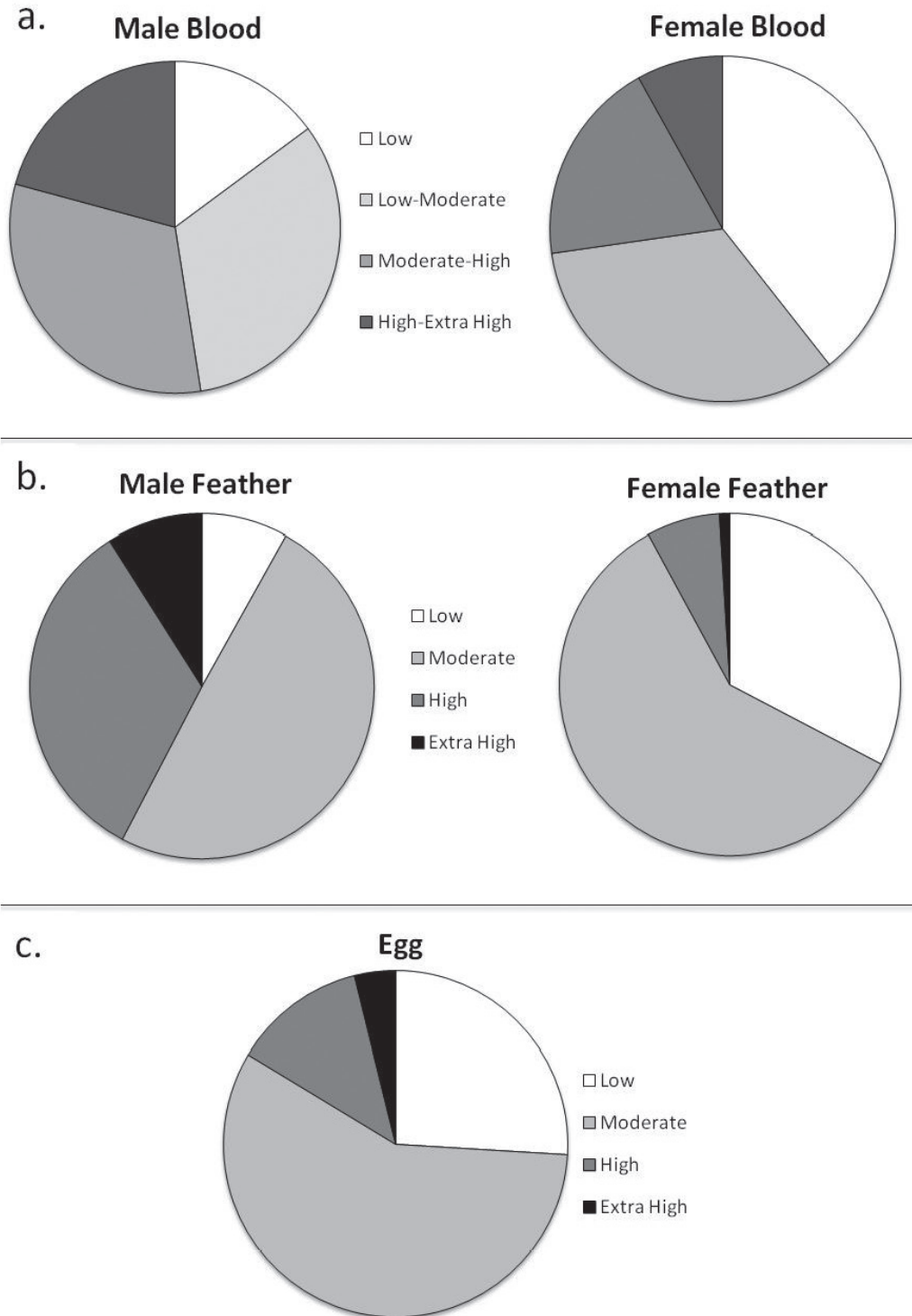
Figure 1. Risk ratios for Common Loon mercury exposure based on (a) adult blood mercury exposure groups: low (0-1 µg/g), low-moderate (1-2 µg/g), moderate-high (2-3 µg/g), high-extra high (> 3 µg/g); (b) adult feather mercury exposure groups: low (0-9 µg/g), moderate (9-20 µg/g), high (20-35 µg/g), and extra high (> 35 µg/g); and (c) egg mercury exposure groups: low (0-0.5 µg/g), moderate (0.5-1.3 µg/g), high (1.3-2.0 µg/g) and extra high (> 2.0 µg/g).
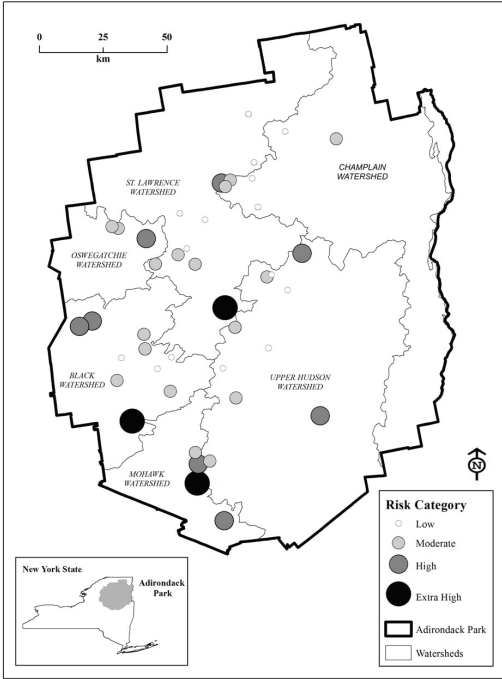
Figure 2. Spatial distribution of lakes with low, moderate, high and extra high Common Loon female loon units. Low (0-1 μg/g), low-moderate (1-2 μg/g), moderate-high (2-3 μg/g), and high-extra high (> 3 μg/g).
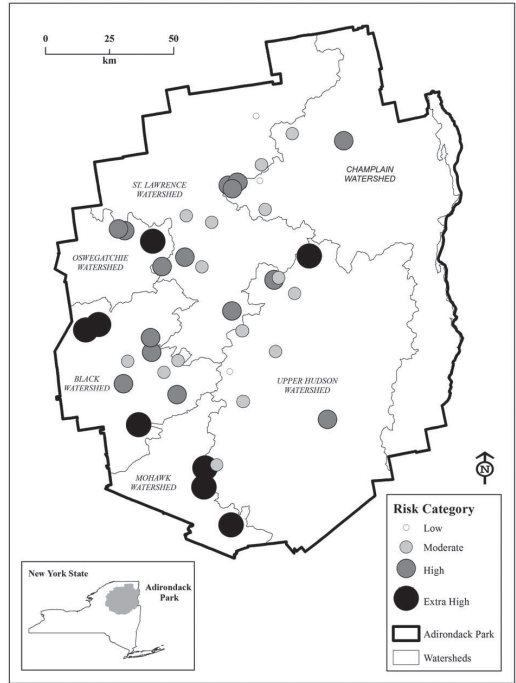
Figure 3. Spatial distribution of lakes with low, moderate, high and extra high Common Loon male loon units. Low (0-1 μg/g), low-moderate (1-2 μg/g), moderate-high (2-3 μg/g), and high-extra high (> 3 μg/g).

The productivity data for MLUs was divided into four groups (Fig. 6): low risk (0-1 μg/g, Hg = 0.771 μg/g: avg CF/TP/year = 0.467, SE = 0.167, n = 5); low-moderate risk (1-2 μg/g, Hg = 1.551 μg/g: avg CF/TP/year = 0.736, SE = 0.056, n = 22); moderate-high risk (2-3 μg/g, Hg = 2.493 μg/g: avg CF/TP/year = 0.572, SE = 0.091, n = 18); and high-very high risk (> 3 μg/g, Hg = 3.805 μg/g: avg CF/TP/year = 0.320, SE = 0.078, n = 7). A significant difference was detected between groups using a Kruskal-Wallis test (χ^2 = 10.897, df = 3, P = 0.0012), and a significant difference was found between low-moderate and very high mercury groups (P < 0.05; Fig. 6a). There was a 56% difference in annual productivity between these groups (Fig. 6b).

To examine the effect of pH on productivity in our system, study lakes were classified into two groups based on pH: high acidity (pH < 6.3; pH = 5.86: avg CF/TP/year = 0.570, SE = 0.07, n = 6) and low acidity (pH > 6.3; pH = 6.90: avg CF/TP/year = 0.660, SE = 0.07, n = 29). Although a significant difference in

productivity was not detected between the two groups (χ^2 = 0.734, df = 1, P = 0.392), there was an increasing trend in productivity from highly acidic lakes to those with low acidity (Fig. 7).

Model for Long-Term Effect of Mercury

To assess if mercury body burden affects the population growth of Adirondack Common Loons, three categories of productivity (average chicks fledged per territorial pair) were assigned to the study birds for incorporation into Grear *et al.*'s (2009) loon population model. A value of > 1 generally predicts that current vital rates (i.e., birth and survival rates) are sufficient to support a stable or growing population, but it is important to note the inherent error associated with models of this type. These projections are meant as estimates of overall population growth across many years; high variability within the population could cause yearly population growth to range below one.

For the Adirondack Common Loon study population, the overall productivity (CF/
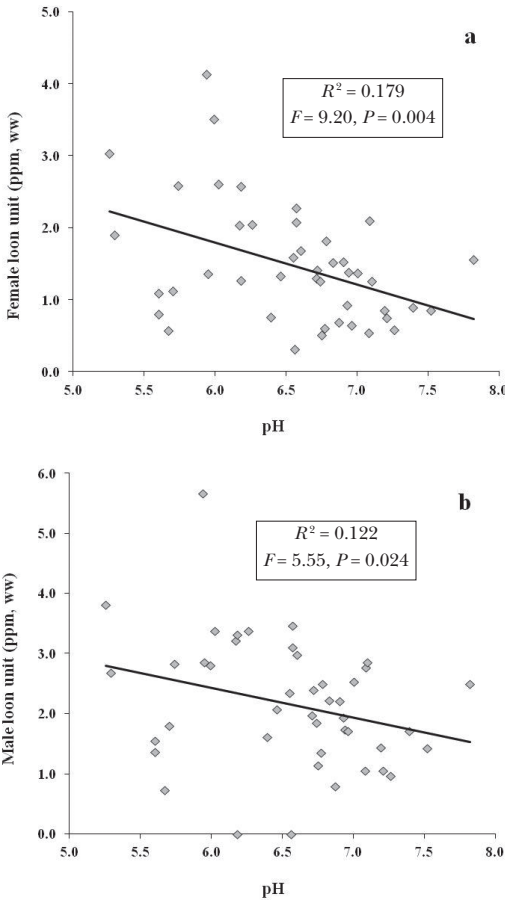
Figure 4. Correlation between lake pH and mercury for (a) female loon units and (b) male loon units.

TP) of this group was 0.594 ($n = 360$ TP with 332 nest attempts; $n = 558$ productivity years), resulting in $\lambda_{Adk-overall} = 1.0157$. Study birds with low-moderate mercury body burdens had a CF/TP value of 0.673 ($n = 211$ TP with 192 nest attempts; $n = 338$ productivity years), resulting in $\lambda_{Adk-Low-ModHg} = 1.0260$. Adirondack loons exhibiting a high or extra-high mercury body burden had a CF/TP value of 0.483 ($n = 149$ TP with 140 nest attempts; $n = 220$ productivity years), resulting in $\lambda_{Adk-High/X-HighHg} = 1.0005$ (Fig. 8).

Population Model Projections

To assess how the resulting population growth rates would affect a hypothetical Adirondack loon population over time, a projection of the adult loon population growth

Table 2. Loon productivity parameters by mercury exposure for all territorial Common Loon pairs observed from 1999-2007.

| Productivity by Mercury Exposure	#Territorial Pairs (TP)	#Nesting Pairs (NP)	NP/TP	#Chicks Hatched (CH)	#Chicks Fledged (CF)	CH/NP	CF/NP	Chick Survival (CF/CH)	CH/TP	Overall Productivity (CF/TP)
Low-Moderate[a] Hg Loons	211	168	0.80	195	142	1.161	0.845	0.728	0.924	0.673
All Loons Combined	360	287	0.80	298	214	1.038	0.746	0.718	0.828	0.594
High/Extra High[b] Hg Loons	149	119	0.80	103	72	0.866	0.605	0.699	0.691	0.483

[a] < 3.0 µg/g
[b] > 3.0 µg/g
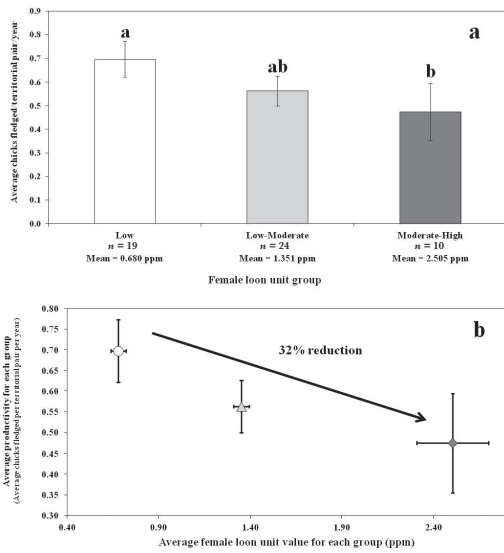
Figure 5. Comparison of annual productivity of Common Loon by female loon unit groups for (a) three mercury risk groups and (b) average mercury value within each group. Risk group categories: Low (0-1 μg/g), low-moderate (1-2 μg/g), moderate-high (2-3 μg/g). Numbers within bars indicate number of territories where productivity and female loon unit were both measured, letters indicate marginally significant differences between groups (Kruskal-Wallis χ² = 5.136, df = 2, P = 0.077) and error bars indicate standard error.
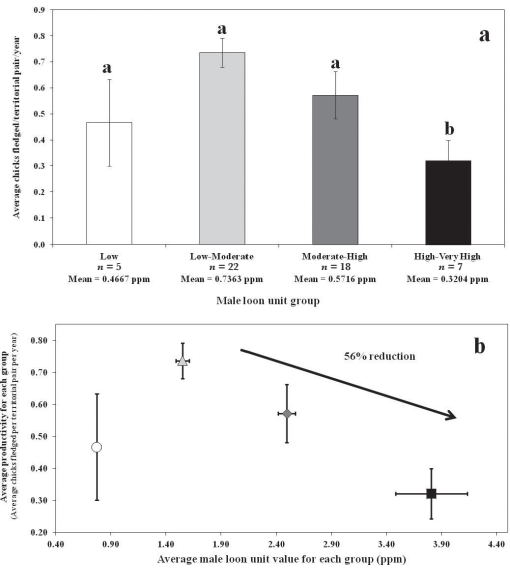
Figure 6. Comparison of annual productivity of Common Loon by male loon unit groups for (a) four mercury risk groups and (b) average mercury value within each group. Risk group categories: Low (0-1 μg/g), low-moderate (1-2 μg/g), moderate-high (2-3 μg/g), and high-extra high (> 3 μg/g). Numbers within bars indicate number of territories where productivity and male loon unit were measured, letters indicate significant differences between groups (Kruskal-Wallis χ² = 10.897, df = 3, P = 0.0012) and error bars indicate standard error.

over 50 years was conducted, beginning with a hypothetical population of 1,000 adult loons (estimated from the Adirondack Common Loon population survey conducted in the 1980s by Parker *et al.* 1986). The mercury risk models in this study indicated that not all loons in the Adirondack Park were exposed to mercury levels high enough to cause reproductive impairment. Mercury risk ratios were based on the comparison of loon blood, feather and egg samples to current accepted risk categories, and it was determined that between 8% (based on female blood) and 37% (based on adult feathers) of the population is likely to fall within the high or extra-high risk categories. This range of estimates for the overall impact of mercury within the loon population necessitated that different scenarios for population growth be explored based on varying proportions of the population being under risk (Fig. 9).

The first scenario in which all loons were in the low and moderate groups (i.e., S.1 Hy-

pothetical No Hg Risk) projected the population growth for a hypothetical population with no mercury risk, and found a population of 3,600 adult loons after 50 years. The second scenario (i.e., S.2 Current Low Hg Risk) used the mercury risk ratios developed for female loon blood in the Adirondack Park, which shows that approximately 8% of the population is within the high and extra high risk groups and predicted a population of 3,386 adult loons after 50 years. The third scenario (i.e., S.3 Current High Hg Risk) used the mercury risk ratios developed for adult male loon feather concentrations, which shows that approximately 37% of the population is at high or extra high risk, and resulted in a population of 2,642 adult birds after 50 years. The fourth scenario (i.e., S.4 Hypothetical Complete Hg Risk) estimated population growth under a worst-case-scenario, where all the loons are in the high and extra high risk groups, and resulted in a predicted population of 1,028 adult loons after 50 years (Fig. 9).
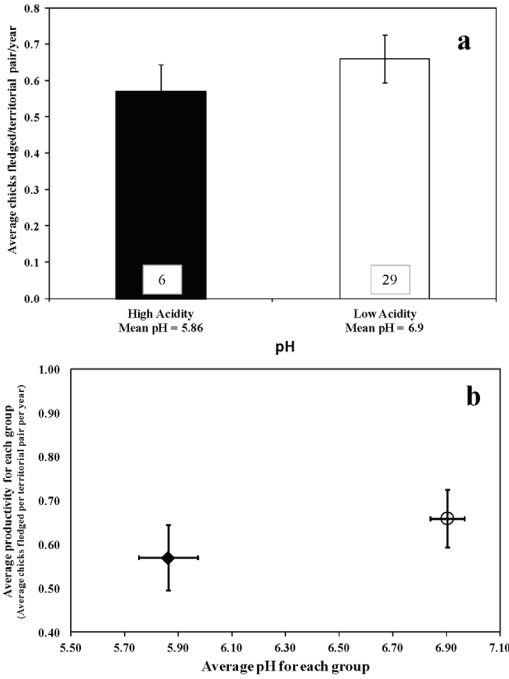
Figure 7. Comparison of annual productivity of Common Loon by pH groups for A) two lake acidity risk groups and B) based on average pH within each group. Numbers within bars indicate number of territories where pH and productivity data were collected, there was no significant difference between groups ($\chi^2 = 0.734$, $P = 0.392$), and error bars indicate standard error.

DISCUSSION

In this project, we employed the Common Loon as an indicator species to assess the mercury exposure and risk in aquatic ecosystems in New York's Adirondack Park. We found varying results based on the three
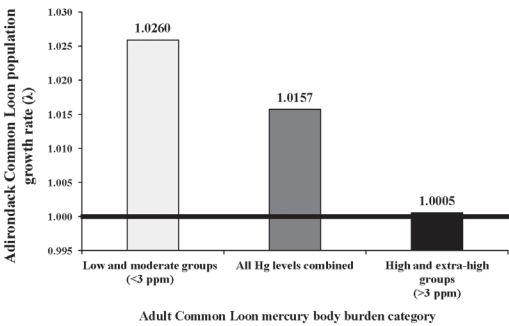
Figure 8. Adirondack adult Common Loon population growth rate by mercury body burden category, based on Grear et al. (2009) loon population model. Black line shows = 1.0, or no change in population size.

different tissue types used to determine risk of detrimental impacts of mercury concentration; minimal risk was assessed through female feather concentrations, which indicated that 7% of the population was at high risk, while maximal risk was assessed through male feather concentrations, which indicated that 37% of the population was at risk. We documented a 32% and 56% reduction in chick production between low and moderate-high mercury risk groups for females and males, respectively, with possible consequences for population growth rate in the park.

As in other studies, male loon blood and feather mercury levels in the Adirondacks were greater than female blood and feather levels, possibly due to the larger males consuming larger, and likely older, higher mercury prey items, and the ability of females to sequester mercury in the eggs they lay (Evers et al. 2004). Adult blood mercury levels were significantly higher than chick blood mercury levels, reflecting an increase in mercury body burden over the lifetime of an individual, combined with increased exposure of adults resulting from the consumption of larger, higher trophic level prey items. Feather mercury provides insight into the lifetime mercury body burden of an individual loon, as muscle protein reservoirs are remobilized during feather molt. Evers et al. (2008) found that loon feather mercury increased by an average of 8.4% per year.

Adult loons with blood mercury concentrations of more than 3.0 µg Hg/g or feather mercury > 20 µg Hg/g, or loon eggs with mercury > 2.0 ug Hg/g, are at high risk for significant adverse physiological, behavioral and reproductive effects (Evers et al. 2008). The results from this study indicated that 21% of adult male and 8% of adult female Adirondack loons were at high risk of behavioral and reproductive impacts based on body burden estimated by blood mercury exposure, and 37% of male and 7% of female study birds were at high risk based on feather mercury exposure. Considering the high proportion of the Adirondack breeding population that is above the lowest observed adverse effect level, mercury exposure is likely contributing to population-level impacts (Evers et al. 2011). Female blood
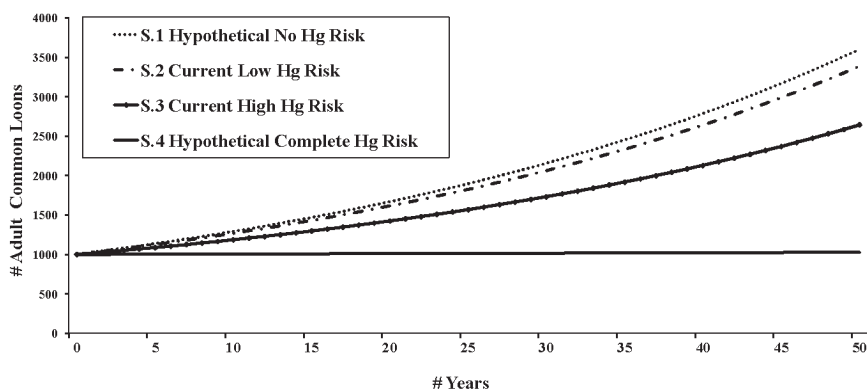
Figure 9. Comparison of overall population growth for Adirondack Common Loons in four different scenarios based on varying proportions of the population being at risk. S.1 Hypothetical No Hg Risk: 100% population = low-moderate Hg group; S.2 Current Low Hg Risk: 92% population = low-moderate Hg group + 8% population = high to extra-high Hg group; S.3 Current High Hg Risk: 63% population = low-moderate Hg group + 37% population = high to extra-high Hg group; and S.4 Hypothetical Complete Hg Risk: 100% population = high to extra-high Hg group.

mercury levels are highly correlated with egg mercury levels (Evers *et al.* 2003, 2004, 2008; Burgess and Meyer 2008), thus eggs are also relevant tissues for predicting mercury risk within a breeding territory. Thirteen percent of the Adirondack loon eggs sampled were at high risk for mercury exposure, indicating that if the chicks hatched, their behaviors would be abnormal and they would have a reduced likelihood of surviving to fledging. Additionally, several controlled studies have found that mercury exposure impairs egg development and hatchability at levels (i.e., 0.5-4.4 μg/g) that were found in this study (Borg *et al.* 1969; Fimreite *et al.* 1971; Spann *et al.* 1972; Gilbertson 1974; Heinz 1979).

The southwestern region of the Adirondack Park was documented to have lakes with higher loon blood mercury levels, corresponding with increased acid deposition in that region (Evers *et al.* 2011). In an associated study assessing mercury exposure levels within various food web compartments in Adirondack lakes, acidic lakes in the southwestern part of the Park also correlated with higher mercury levels found in fish and zooplankton than those sampled in non-acidic lakes (Yu *et al.* 2011). The highest loon blood mercury lake (FLU = 4.135) had five-fold greater mercury levels than the lowest lake (FLU = 0.685) and was also considerably more acidic (pH = 5.94 vs. pH = 6.87). Loon mercury levels negatively correlated with lake pH, reinforcing that

mercury uptake in loons was driven by an increased bioavailability of mercury due to increased methylation rates within acidic lakes. Therefore, loons that breed in documented mercury hotspots, such as the southwestern region of the Adirondack Park (Driscoll *et al.* 2007; Evers *et al.* 2007), are likely to increase their mercury body burden annually due to the inability to depurate and demethylate sufficiently an elevated dietary uptake of mercury. Ultimately, mercury hotspots have the potential to cause age-related increases in mercury exposure leading to a reduction in an individual's lifetime reproductive success, and eventually skewing the age-structure of the population toward younger individuals (Evers *et al.* 2008).

In this study, Adirondack loon productivity decreased significantly with increasing mercury body burdens. High risk territorial pairs (> 3.0 μg/g) fledged approximately 20% fewer chicks per pair than loons with lower mercury levels (< 3 μg/g). Like the work by Burgess and Meyer (2008), this study also found that some loons with low mercury exposure also had low productivity, indicating intrinsic (e.g., species longevity, intraspecific interactions due to density), extrinsic (e.g., predation, weather), or anthropogenic (e.g., human disturbance, other contaminants) stressors other than mercury are impacting their reproductive success. However, similar to results documented in Wisconsin, New Brunswick, and Nova Scotia (Burgess

and Meyer 2008), our results indicated that loon productivity in the Adirondack region was never high when mercury exposure levels were high. These findings add to the literature from the Great Lakes and Northeast (Evers *et al.* 2004; Burgess and Meyer 2008), indicating that mercury appears to be a primary anthropogenic stressor for Common Loon populations across North America.

The relationships among lake acidity, loon productivity, and mercury exposure were examined to assess potential impacts of acid deposition to aquatic ecosystems. Alvo (2009) attributed the low fledging success of loons breeding on acidic lakes in Ontario, Canada, to the decreased availability of food resources in those lakes. Parker *et al.* (1986) and Parker (1988) concluded that the presence of loons and breeding, hatching, and fledging success were not affected by the acidity of a lake. Alvo (2009) and Parker (1988) did not, however, examine the potentially confounding factor of increased mercury exposure affecting loon productivity on acidic breeding lakes. The results of our study support the conclusion that the increased mercury exposure of loons breeding on acidic lakes detrimentally affects their productivity, as indicated by a negative trend between loon reproductive success and decreasing lake pH and increasing blood mercury levels. In Wisconsin, loons occupying low pH (< 6.3) lakes had significantly higher blood mercury levels in comparison to loons nesting on neutral pH lakes (Meyer *et al.* 1995). Burgess and Meyer (2008) concluded that the increased mercury exposure of loons living on acidic lakes is more likely to be the cause of reduced fledging success.

Using the Grear *et al.* (2009) population growth model, the estimated population growth rates (λ) for the three estimates of mercury body burden in Adirondack loons were all above 1.0, indicating that the current birth and survival rates of the Adirondack loon population are likely able to support a stable or growing population. The overall population growth rate is estimated at 1.6%, a much lower rate than the 7% annual growth rate calculated by Parker *et al.* (1986) in the 1980s. It is notable that the high/extra-high mercury group had a considerably lower population growth

rate (0.05%, just high enough for maintenance of a population) when compared to the low mercury group (2.6%), suggesting that environmental mercury contamination has indeed affected the growth of a portion of the Adirondack loon population. Grear *et al.*'s (2009) population matrix model indicates that loon populations producing fewer than 0.48 chicks fledged per territorial pair are population sinks (Evers *et al.* 2008). The Adirondack high/extra-high mercury Common Loons are producing 0.483 CF/TP and, thus, are probably acting as a population sink. The remaining Adirondack Common Loon population is likely acting as a buffer population by filling unoccupied territories and producing enough chicks to maintain, and possibly even expand, the population as a whole.

The projected population simulations over 50 years for the different mercury body burden scenarios provide a graphic extrapolation of how the Adirondack loon population could grow based on the effect of mercury contamination. Nevertheless, because of natural environmental variability and other population stressors, it is unknown if these numbers are indeed sufficient to ensure long-term population growth. It is important to consider that these scenarios are representing a hypothetical situation in which mercury is the only factor affecting population growth, and that, in reality, numerous other intrinsic (e.g., intraspecific competition), extrinsic (e.g., predation, carrying capacity of the habitat/availability of high-quality territories) and anthropogenic (e.g., recreational disturbance, lakeshore development) stressors affect the Adirondack loon population, and could potentially negatively impact the population growth rate. The productivity (CF/TP) patterns correlated with patterns of the mercury body burden in the loons, but determining the causative relationship can be difficult as such factors as lake acidification and size could affect food availability and may also be contributing factors influencing loon population growth.

For example, some of our models predict a loon population of over 3,000 birds after 50 years, but it is unlikely that enough habitat exists in the Adirondack Park to support a population of this size. We did not set out

to measure the carrying capacity of the area, however, so we decided to include these density-independent projections as representations of what differences in λ could mean for the population. A population can experience yearly disruptions as well as catastrophic events that limit population growth independent of mercury contamination, and these projections give us an estimate of how well the population would be able to recover from these setbacks. Similarly, we can use these projections to estimate how mercury exposure is likely to limit the growth of loon populations if other limitations or stressors (e.g., disease, human disturbance, and predation) could be removed through restoration or conservation.

In summary, the results of our study indicate that: 1) mercury appears to be a primary anthropogenic stressor for the Adirondack Common Loon population, resulting in decreased productivity; 2) increased mercury exposure of loons breeding on acidic lakes detrimentally affects their productivity; and 3) the Adirondack loon population appears to be increasing, although at a much lower rate than the 7% annual growth rate previously calculated by Parker *et al.* (1986) in the 1980s.

The results from this study provide valuable new information that documents the extent of mercury contamination and its impacts on the Common Loon population in New York's Adirondack Park and establishes baseline information critical for detecting future changes in biotic impacts resulting from atmospheric mercury deposition. Ultimately, this study provides science-based justification and support for the critical need to regulate mercury and acidic emissions stringently on local, regional, and national scales to protect biota living in aquatic ecosystems from the impacts of environmental mercury contamination.

Literature Cited

Alvo, R. 1996. Sudbury Loon Study, 1996 Final Report. Unpublished report to the Canadian Wildlife Service, Ottawa, Ontario.

Alvo, R. 2009. Common Loon, *Gavia immer*, breeding success in relation to lake pH and lake size over 25 years. Canadian Field Naturalist 123: 146-156.

Borg, K., H. Wanntorp, K. Erne and E. Hanko. 1969. Alkyl mercury poisoning in Swedish wildlife. Viltrevy 6: 301-379.

Burgess, N. M. and M. W. Meyer. 2008. Methylmercury exposure associated with reduced productivity in Common Loons. Ecotoxicology 17: 83-91.

Counard, C. J. 2001. Mercury exposure and effects on Common Loon (*Gavia immer*) behavior in the upper Midwestern United States. M.S. Thesis, University of Minnesota, St. Paul.

Driscoll C. T., Y. J. Han, C. Y. Chen, D. C. Evers, K. F. Lambert, T. M. Holsen, N. C. Kamman and R. K. Munson. 2007. Mercury contamination in forest and freshwater ecosystems in the Northeastern United States. BioScience 57: 17-28.

Evers, D. C. 2001. Common Loon population studies: continental mercury patterns and breeding territory philopatry. Ph.D. Dissertation, University of Minnesota, St. Paul.

Evers D. C., O. P. Lane, L. Savoy and W. Goodale. 2004. Assessing the impacts of methylmercury on piscivorous

wildlife using a wildlife criterion value based on the Common Loon, 1998-2003. BRI 2004-05 submitted to Maine Department of Environmental Protection, Biodiversity Research Institute, Gorham, Maine.

Evers, D. C., K. M. Taylor, A. Major, R. J. Taylor, R. H. Poppenga and A. M. Scheuhammer. 2003. Common Loon eggs as indicators of methylmercury availability in North America. Ecotoxicology 12: 69-81.

Evers, D. C., J. D. Kaplan, M. W. Meyer, P. S. Reaman, W. E. Braselton, A. Major, N. Burgess and A. M. Scheuhammer. 1998. Geographic trend in mercury measured in Common Loon feathers and blood. Environmental Toxicology and Chemistry 17: 173-183.

Evers, D. C., N. M. Burgess, L. Champoux, B. Hoskins, A. Major, W. M. Goodale, R. J. Taylor, R. Poppenga and T. Daigle. 2005. Patterns and interpretation of mercury exposure in freshwater avian communities in northeastern North America. Ecotoxicology 14: 193-221.

Evers, D. C., K. A. Williams, M. W. Meyer, A. M. Scheuhammer, N. Schoch, A. Gilbert, L. Siegel, R. J. Taylor, R. Poppenga and C. R. Perkins. 2011. Spatial gradients of methylmercury in an avian piscivore in the Great Lakes basin. Ecotoxicology 20: 1609-1625.

Evers, D. C., Y. J. Han, C. T. Driscoll, N. C. Kamman, M. W. Gooodale, K. F. Lambert, T. M. Holsen, C. Y. Chen, T. A. Clair and T. Butler. 2007. Biological mercury hotspots in the Northeastern United States and Southeastern Canada. BioScience 57: 29-43.

Evers, D. C., L. Savoy, C. R. DeSorbo, D. E. Yates, W. Hanson, K. M. Taylor, L. S. Siegel, J. H. Cooley, Jr., M. S. Bank, A. Major, K. Munney, B. F. Mower, H. S. Vogel, N. Schoch, M. Pokras, W. Goodale and J. Fair. 2008. Adverse effects from environmental mercury loads on breeding Common Loons. Ecotoxicology 17: 69-81.

Fimreite, N., W. N. Holsworth, J. A. Keith, P. A. Pearce and I. M. Gruchy. 1971. Mercury in fish and fish-eating birds near sites of industrial contamination in Canada. Canadian Field Naturalist 85: 211-220.

Gilbertson, M. 1974. Pollutants in breeding herring gulls in the lower great lakes. Canadian Field Naturalist 88: 273-280.

Grear, J. S., M. W. Meyer, J. H. Cooley, Jr., A. Kuhn, W. H. Piper, M. G. Mitro, H. S. Vogel, K. M. Taylor, K. P. Kenow, S. M. Craig and D. E. Nacci. 2009. Population growth and demography of Common Loons in the northern United States. Journal of Wildlife Management 73: 1108-1115.

Heinz, G. H. 1979. Methylmercury: reproductive and behavioral effects on three generations of Mallard ducks. Journal of Wildlife Management 43: 394-401.

Meyer, M. W., D. C. Evers, T. Daulton and W. E. Braselton. 1995. Common Loons (Gavia immer) nesting on low pH lakes in northern Wisconsin have elevated blood mercury content. Water, Air, and Soil Pollution 80: 871-880.

Meyer, M. W., D. C. Evers, J. J. Hartigan and P. S. Rasmussen. 1998. Patterns of Common Loon (Gavia immer) mercury exposure, reproduction, and survival in Wisconsin, USA. Environmental Toxicology and Chemistry 17: 184-190.

Mitro, M. G., D. C. Evers, M. W. Meyer and W. H. Piper. 2008. Common Loon survival rates and mercury in New England and Wisconsin. Journal of Wildlife Management 72: 665-673.

New York State Department of Health. 2013. Health advice on eating sportfish and game. Unpublished report, New York State Department of Health, Albany, New York.

Northeast States for Coordinated Air Use Management. 1998. Northeast States and eastern Canadian Provinces mercury study: a framework for action. Unpublished report, Northeast States for Coordinated Air Use Management, Boston, Massachusetts.

Nocera, J. and P. Taylor. 1998. In situ behavioral response of Common Loons associated with elevated mercury exposure. Conservation Ecology 2: 10.

Olsen B., D. C. Evers and C. DeSorbo. 2000. Effect of methylated mercury on the diving frequency of the Common Loon. Journal of Ecological Research 2: 67-72.

Parker, K. E. 1988. Common Loon reproduction and chick feeding on acidified lakes in the Adirondack Park, New York. Canadian Journal of Zoology 66: 804-810.

Parker, K. E., R. L. Miller and S. Isil. 1986. Status of the Common Loon in New York State. Unpublished report, New York State Department of Environmental Conservation, Delmar, New York.

Scheuhammer, A. M., A. M. Basu, N. Burgess, N. M. Elliot, J. E. Campbell, G. D. Wayland, M. Chapoux and J. Rodgrigue. 2008. Relationships among mercury, selenium, and neurochemical parameters in common loons (Gavia immer) and bald eagles (Haliaeetus leucocephalus). Ecotoxicology 17: 93-101.

Schoch, N. and D. C. Evers. 2002. Monitoring mercury in Common Loons: New York field report, 1998-2000. Report BRI 2001-01 submitted to U.S. Fish and Wildlife Service and New York State Department of Environmental Conservation. Biodiversity Research Institute, Falmouth, Maine.

Spann, J., R. G. Heath, J. F. Kreitzer and L. N. Locke. 1972. Ethyl mercury p-toluene sulfonanilide: lethal and reproductive effects on pheasants. Science 175: 328-331.

Swain, E. B., D. R. Engstrom, M. E. Brigham, T. A. Henning and P. L. Brezonk. 1992. Increasing rates of atmospheric mercury deposition in midcontinental North America. Science 257: 784-787.

Thompson, D. R. 1996. Mercury in birds and terrestrial animals. Pages 341-355 in Environmental Contaminants in Wildlife: Interpreting Tissue Concentrations (W. N. Beyer, G. H. Heinz and A. W. Redmon-Norwood, Eds.). Lewis Publishing, Clemson, South Carolina.

Wolfe, M. F., T. Atkeson, W. Bowerman, K. Burger, D. C. Evers, M. W. Murray and E. Zillioux. 2007. Wildlife indicators. Pages 123-189 in Ecosystem Response to Mercury Contamination: Indicators of Change (Harris R, D. P. Krabbenhoft, R. Mason, M. W. Murray, R. Reash and T. Saltman, Eds.). CRC Press, Boca Raton, Florida.

Yu, X., C. T. Driscoll, D. C. Evers, M. Duron, N. Schoch and N. Kamman. 2011. Spatial patterns of mercury in Adirondack lakes. Ecotoxicology 20: 1543-1554.