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A Comparison of Mercury Levels in Feathers and Eggs of Osprey (*Pandion haliaetus*) in the North American Great Lakes

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Abstract. Osprey (*Pandion haliaetus*) eggs and chick feathers were collected for mercury analysis from nests at four Great Lakes study areas in Ontario (three "naturally formed" lakes in southern Ontario and one reservoir in northern Ontario) and two New Jersey study areas in 1991–1994. Adult osprey feathers were sampled from three Great Lakes study areas in 1991. Feathers sampled from chicks (approximately 28–35 days old) appear to be better indicators of local contaminant conditions since spatial patterns of mercury in known prey, yellow perch (*Perca flavescens*), also collected in these areas, were more similar to chick feathers than to eggs. Mercury levels were less variable in chick feathers than in eggs. Estimates of biomagnification factors using prey of known size at these areas were also less variable in feathers than in eggs. At naturally formed lakes, no significant correlation in mercury levels between eggs and chick feathers from the same nest was apparent, suggesting that the source of mercury contamination was not the same in these two tissues: mercury levels in eggs reflect mercury acquired on the breeding grounds, wintering grounds, and migratory route; mercury levels in chick feathers reflect local dietary conditions on the breeding grounds. Mercury levels in both osprey eggs and chick feathers were higher at the Ogoki Reservoir than at naturally formed lakes. Adult osprey feathers had higher mercury concentrations than chick feathers. Mercury levels in osprey eggs, chick feathers, and adult feathers did not approach levels associated with toxic reproductive effects.

Mercury arising from industrial sources (such as chlor-alkali plants and pulp mills), as well as natural sources, has been found to bioaccumulate in wildlife in aquatic ecosystems (Bryan 1984). Birds, in particular, have been adversely affected by mercury loading to the environment (Scheuhammer 1987). Mercury can accumulate in high concentrations in a wide variety of tissues such as the brain, kidney, liver, muscle, bone, eggs, and feathers (Burger 1993). Reproductive effects associated with exposure to mercury include reduced numbers of eggs laid (Heinz 1979; Barr 1986), decreased egg hatchability (Borg *et al.* 1969; Fimreite 1971), increased hatchling mortality in ducks (Finley and Stendell 1978), and altered reproductive behavior in loons (Barr 1986). Mercury poisoning as a result of exposure to higher levels of mercury has been shown to lead to neurological damage such as difficulties in walking and flying and an inability to coordinate muscle movement (Fimreite and Karstad 1971).

Birds are able to eliminate a substantial portion of their mercury body burden via their plumage (Honda *et al.* 1986a,b; Braune and Gaskin 1987; Lewis and Furness 1991) and, in the case of females, via the production and laying of eggs (Fimreite *et al.* 1974). During the molting period, mercury circulating through the blood is bound in high concentrations to keratin during feather formation (Crewther *et al.* 1965). Levels of mercury stored in internal tissues drop as mercury is sequestered into newly grown feathers (Furness *et al.* 1986; Honda *et al.* 1986b; Braune and Gaskin 1987). Continued deposition of mercury from the body is prevented when the feathers, at full growth, become physiologically separated from the rest of the bird (Voitkevich 1966). This process may impact the health of the bird as the entire plumage may contain as much as 85% of the total mercury body burden in chicks (DesGranges *et al.* 1994) and as much as 93% of the total mercury body burden in adults (Braune and Gaskin 1987). During the intermolt period levels continue to rise in internal tissues until the next molt, when the process is repeated (Braune and Gaskin 1987).

The production and laying of eggs is another process by which females can eliminate some of their mercury burden (Fimreite *et al.* 1974; Becker and Sperveslage 1989; Lewis *et al.* 1993). There is conflicting evidence about the importance of egg production and laying among bird species in reducing the total body burden of mercury. For some species, the amount of mercury transferred to eggs is a small proportion of the female bird's total burden and thus egg laying has been thought to be an insignificant pathway of mercury removal (Helander *et al.* 1982). Lewis (1991), on the other hand, reports that as much as 40% of the total mercury body burden may be removed. Deposition of mercury in the uropygial gland and salt gland (Burger and Gochfeld 1985) and excretion (Tejning 1967; Lewis and Furness 1991) are other pathways by which mercury is removed from the body.

Ospreys (*Pandion haliaetus*) are large raptors that eat only fish, and thus they are particularly vulnerable to the effects of

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mercury as a result of its biomagnification through the aquatic food chain (Johnels and Westermark 1969). Mercury found in fish is 50–100% methyl mercury (Cappon and Smith 1981), which is considered to be one of the most toxic forms of mercury (Bryan 1984). Osprey population declines and reproductive failures were of major concern in the northeastern United States from the 1950s to the early 1970s, when the detrimental effects associated with the widespread use of organochlorine pesticides, especially DDT, and other toxic contaminants were not yet understood (Schmid 1966; Henny 1977). As a result of their high trophic position, as well as their overall sensitivity and ability to accumulate high levels of contaminants, these birds of prey have been used as bioindicators of environmental contamination (Häkkinen and Häsänen 1980; Henny 1986; Furness 1993).

In the Great Lakes, mercury was routinely discharged in untreated effluents by the chlor-alkali industry, the petrochemical industry, and the pulp and paper industry until 1970 when control measures for mercury were implemented (NRCC 1979). Atmospheric transport of mercury may have also contributed to high levels of mercury detected in surficial sediment compared to background concentrations of mercury detected in sediment from the depositional basins of lakes Ontario, Erie, Huron, and Superior (Nriagu 1980; Mudroch *et al.* 1988). Regardless of these control measures, mercury continues to be available to biota. High mercury concentrations have been reported in fishes of the Great Lakes and fish consumption advisories are issued accordingly (IJC 1985). Other sources of mercury include resuspension of mercury-bound sediment and mercury emissions associated with municipal wastewater treatment facilities (NRCC 1979; Pelletier *et al.* 1989; Glass *et al.* 1990).

This study reports mercury levels in osprey eggs and feathers (from chicks and adults) at areas in Ontario, Canada, and New Jersey, USA, during an intensive ecotoxicological study in 1991 and 1992. This is the first detailed study of mercury contamination in ospreys on the North American Great Lakes; mercury has been reported previously in osprey eggs collected from other parts of North America (Grier *et al.* 1977; Wiemeyer *et al.* 1988; Noble and Elliott 1990; Steidl *et al.* 1991a). DesGranges *et al.* (1994) have also published an extensive report on mercury levels in tissues of osprey collected from Québec. In this paper, four hypotheses were tested: (1) Mercury in chick feathers is similar to that found in prey in the local environment and, thus, reflects the concentration of mercury in food eaten during the period of feather formation. (2) Mercury in eggs is similar to that found in prey in the local environment and, thus, reflects the concentration of mercury in food eaten during the period of egg formation. (3) Mercury levels in eggs and in chick feathers from the same nest and year are positively correlated indicating that the source of mercury contamination is the same. (4) Mercury levels are significantly higher at reservoirs than at naturally formed lakes.

Materials and Methods

Study Areas

In 1991, osprey nests were sampled for eggs as well as chick and adult feathers from nests at three main freshwater study areas that included the St. Marys River (SMR), Georgian Bay (GB), and the Kawartha Lakes (KL) (Figure 1). Study areas covered a discrete area of the Great Lakes and were selected based on the accessibility and abundance of osprey nests (at least 20 occupied osprey nests) in the area. The St. Marys River study area is located between Sault Ste. Marie (46°30'N, 84°20'W) and the archipelago between St. Joseph and Drummond Islands (46°05'N, 83°50'W) and contained osprey nests and foraging areas covering approximately 2600 km^2 in both Michigan and Ontario. The Georgian Bay study area is located along the outer shorelines of eastern Georgian Bay (Lake Huron), between Dillon (45°25'N, 80°20'W) to the head of Severn Sound (44°45'N, 79°40'W). The total area (including water) covers approximately 800 km^2. Both the St. Marys River and Georgian Bay study areas are within predominantly mesotrophic to oligotrophic waters. All osprey nest sites were within 5 km of the Great Lakes shoreline. The Kawartha Lakes study area consists of a series of interconnected shallow eutrophic lakes found inland in southern Ontario (from Buckhorn at 44°36'N, 78°20'W running west along the Trent Canal Waterway to Canal Lake at 44°36'N, 79°05'W). While this study area covers approximately 6600 km^2, large areas of this land are under agricultural use and are unsuitable for breeding or foraging osprey. Specifically, collections were made from osprey nests found on the following Kawartha Lakes and connecting creeks: Canal Lake, Mitchell Lake, Pigeon Lake, Scugog River, Lovesick Lake, Sturgeon Lake, Buckhorn Lake, McLaren Creek, and Emily Creek. In total, 43 different nests were studied in 1991 and 1992 for these three study areas combined.

In 1992, our range of collection areas was widened, and eggs and chick feathers were collected from nests at each of the three areas from 1991 as well as three additional areas: the Ogoki Reservoir (OR) in northern Ontario, Delaware Bay (DB) in New Jersey, and along the Atlantic Coast (AC) in New Jersey (Figure 1). The Ogoki Reservoir (50°53'N, 88°45'W), 48 km long and covering 160 km^2, comprises a flooded stretch of the Ogoki River valley and the inundated shores of Mojikit Lake and is located approximately 250 km north of Thunder Bay and approximately 56 km north of Lake Nipigon. The Ogoki River Diversion Project became operational in 1943 and was built to divert the northward flowing water of the Ogoki River, a tributary of the Albany River, southward into Mojikit Lake, Lake Nipigon, and the Great Lakes system providing additional power production at hydroelectric generating stations on the Nipigon, Niagara, and St. Lawrence rivers. The Delaware Bay study area (39°35'N, 75°28'W) represents a low-salinity estuarine environment and consists of an area approximately 70 km^2 in size located in southwestern Salem County, New Jersey. All nests were within 6 km of Delaware Bay. The Atlantic Coast study area (39°06'N, 74°43'W), along the northeast portion of New Jersey's Cape May peninsula, is located 80 km from the Delaware Bay study area and consists of three estuaries within 4 km of the Atlantic Ocean (total area approximately 130 km^2). In total, ten, six, and four different nests were sampled in 1992 from the OR, DB, and AC areas, respectively. Chick feathers were also sampled from DB and AC in 1993 and 1994.

Sampling Methods

Freshly laid eggs (subsequently called "random") were collected (where available) from completed clutches in late April and early May in 1991 and 1992 from the SMR, GB, and KL study areas. Freshly laid eggs were collected from nests at OR in early June. Each egg in the clutch was weighed and measured, and the smallest egg was taken for analysis. Previous studies of osprey have shown consistently that the smallest egg in the clutch is usually the third and last egg laid in the clutch (Poole 1982, 1989). Chicks that hatch from the smallest egg are generally the smallest and have a lower chance of survival relative to the other chicks (Poole 1989; P.J.E. personal observation). Eggs that failed to hatch (subsequently called "addled") were also collected in June or July at all six study areas when the expected hatch date had past by at least 10 days. Included in this grouping for analysis were eggs that

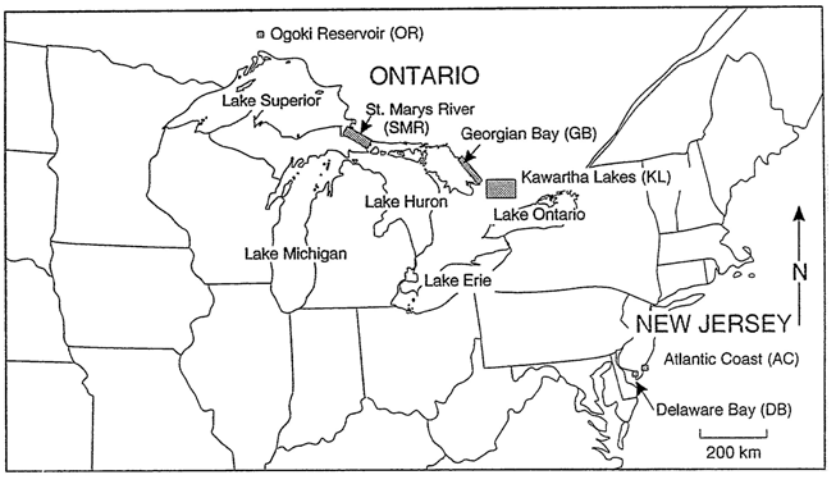

Fig. 1. Location of six study areas on the Great Lakes and in New Jersey, 1991–1994

were ejected from the nest or found damaged in or beneath the nest (e.g., a hole in the shell or broken egg with some yolk still present). Addled eggs (but no random eggs) were collected from SMR in 1991 and DB in 1992. All intact and partially broken eggs were stored in egg cartons at 4°C, within 3 days of collection prior to chemical analysis.

During the July nest visit to band chicks, two to three mantle feathers were plucked from the largest chick found at each nest. Ages of chicks ranged from 4 to 5 weeks based on culmen and wing length (Poole 1989; P.J.E. personal observation). Adult wing and tail feathers found in the nest were also collected from GB, SMR, and KL in 1991 only. Since females spend most of the breeding season on the nest and start molting in May, whereas males spend most of the summer foraging and arrest their molt for this period (Poole 1989), it is likely that most of the adult feathers collected were from females. In a few cases at the GB study area, feathers were collected from individuals found dead at the nest (i.e., three chicks and one adult). Mercury levels found in these feathers were not significantly different from levels in feathers from live individuals ($p > 0.05$) and, thus, these feathers were pooled with other feathers collected from GB adult ospreys and chicks, respectively. All feathers were stored in individually labeled plastic bags for mercury analysis. Collections of eggs and chick feathers from the same breeding attempt (clutch) enabled a comparison of mercury concentrations in the two tissue types.

Chemical Analysis

All chemical analyses were performed at Environment Canada's National Wildlife Research Centre in Hull, Québec. Egg contents were weighed out into glass preweighed acid-washed test tubes, freeze-dried, and then dry weights were recorded. Feathers were washed repeatedly with acetone followed by a washing using dilute Triton X-100 (1:400) then a thorough rinse with water. The feathers were freeze dried and weighed out into preweighed acid washed glass test tubes and their dry weights were recorded.

Egg and feather samples were digested with a mixture of nitric, hydrochloric, and sulfuric acids. Total mercury was analyzed by the cold vapor technique as described in Scheuhammer and Bond (1991). Results were calibrated using a variety of standard reference materials since analyses were performed immediately after each year of study. For analyses of feathers, these materials included horse kidney certified reference material (IAEA); a pool of feather samples prepared and certified as 5.72 ± 0.3 µg/g Hg; and DORM-1 (dogfish muscle) and DOLT-2 (dogfish liver) reference materials. For analyses of eggs, bovine liver obtained from the National Bureau of Standards (NBS) was used for both study years. Minimal detection limits of mercury were approx. 2.0 µg/kg. The percentage recovery for all analyses ranged from 95 to 102% for egg samples and 91 to 107% for feather samples. Residue concentrations were not adjusted for percentage recovery. Feathers were analyzed only once due to low sample weights; eggs were run three times with a standard deviation of <10%. Mercury concentrations for eggs and feathers are reported as dry weight values.

Mercury concentrations in a regular prey species of osprey were also examined to investigate spatial and biomagnification patterns observed between tissues and among areas. Yellow perch (*Perca flavescens*) were selected as the prey species of choice because mercury data were available for this species, and because it is commonly eaten by osprey (comprised up to 7% of total food items in all Great Lakes basin study areas; P.J.E. unpublished data). Yellow perch were collected by the Ontario Ministry of Natural Resources (OMNR) as part of their sport fish contaminant monitoring program and analyzed for mercury at the Ontario Ministry of the Environment and Energy (OMOEE) laboratories in Toronto, Ontario. Fish were collected using a variety of standard fish gear including trap nets, electrofishers, and seines. Collection areas were within the same areas/lakes in which osprey were known to forage (mean foraging distance is equal to approximately 2 km with a total foraging range of <1 km up to 8 km on Great Lakes; P.J.E. unpublished data). Areas and dates of collection of fish are as follows: Lake George, St. Marys River, 1989; Snug Harbour (near Dillon), Georgian Bay, 1988; and Buckhorn Lake (one of the Kawartha Lakes), 1992. The total length of the fish was recorded, and a skinless, boneless fillet of epaxial muscle was removed for methyl mercury analysis according to standard OMOEE laboratory methods (Laboratory Services Branch (LSB) Routine Method HGBIO-E3057A, May 1995). Spatial patterns in mercury were examined using yellow perch of a known age (4–5 years) in order to account for differences in fish growth rates (and thus differences in the period of contaminant exposure) among areas. Yellow perch ages were estimated by OMNR using scales (length-by-age) from fish that had been collected from the same areas or in close proximity to areas where yellow perch were collected for mercury analysis (OMNR, unpublished data).

Regardless of fish age and degree of contaminant exposure, osprey would be expected to feed on fish of a similar size (where present) at any area. Given a fish of similar size and providing it is as commonly fed upon at all areas, we would expect mercury to accumulate in osprey in a similar manner at all areas. Thus, similarities in biomagnification factors across areas for a specific tissue (i.e., eggs, feathers) might be indicative of which tissue is a better indicator of local contaminant conditions. Osprey typically feed on fish up to 30 cm in length (Ewins *et al.* 1995); yellow perch that were 20 cm long were therefore, selected as a standard size. Mercury estimates for fish of this size were provided by OMOEE using standard regression equations of mercury concentra-

tions versus total length of yellow perch specific to each area. Since mercury concentrations for fish were determined on a wet weight basis, a conversion factor to dry weight was employed. Borgmann and Whittle (1983) estimated water content in slimy sculpin (*Cottus cognatus*) and rainbow smelt (*Osmerus mordax*) to be equal to approximately 75% for the whole fish. Lean muscle would be expected to have less water and, for the purpose of converting mercury concentrations expressed as a wet weight (ww) to a dry weight (dw) in yellow perch, 70% water content was assumed. Biomagnification factors (BMF) were estimated using mercury concentrations (dry weight) measured in eggs and feathers divided by that determined for yellow perch.

Statistical Analysis

Mercury concentrations expressed on a dry weight basis for random and addled eggs were similar ($p > 0.05$) in 1991 and 1992, and data for these two egg groups were combined. For ease of comparison to avian mercury values commonly cited in the literature, wet weight values for random and addled eggs are reported in the appendix; significant differences were detected in wet weight mercury values between random and addled eggs in 1992 only ($p < 0.05$). Mercury values are reported as arithmetic means for eggs and feathers since frequency distributions were generally normal using Kolmogorov-Smirnov one-sample test for normality. Bartlett's test for homogeneity of variance revealed that variances were generally homogenous and where they were not, could made so upon log transformation of the data.

A two-way analysis of variance was used to compare mercury concentrations in each tissue among areas and years and, where appropriate, effects were pooled and a one-way analysis of variance was performed. Tukey's multiple comparison method was used to test for differences in mercury concentrations in tissues among areas when the results of the ANOVA showed significant differences. The relationship between mercury concentrations in eggs and feathers collected from the same nest and from a variety of different nests was examined using the Pearson product correlation coefficient and a general linear regression. To assess points of high influence and leverage using this model, Cook's statistic (Cook 1977) and leverage coefficients (Sokal and Rohlf 1981), respectively, were examined. Points (i.e., nests) deemed as noteworthy were determined, in the case of Cook's statistic, using the 50th percentile of the F distribution (Cook 1977); similarly, exceptional values of the leverage coefficient (h) for each nest were determined using the equation $4/N$, where N equals the total number of nests (Hoaglin and Welsch 1978; Sokal and Rohlf 1981). All statistical procedures followed SAS (1985). The level of statistical significance was defined as $p < 0.05$.

Results

Eggs

In 1991, no significant differences were detected in mean mercury concentrations in osprey eggs among the three study areas (Table 1). In 1992, however, with the inclusion of two more areas and more equitable sample sizes, significant differences in mercury concentrations among areas were detected. A comparison of mercury concentrations between 1991 and 1992 among the SMR, GB, and KL study areas revealed significant differences among areas (log-transformed data: $F_{2,41} = 5.33$, $p = 0.01$) but not between years ($F_{1,41} = 2.22$, $p = 0.14$) or for the area by year interaction ($F_{2,41} = 0.37$, $p = 0.67$). Overall for both years pooled, osprey eggs from OR had significantly higher levels of mercury than eggs from the other study areas, with the exception of GB (Table 1).

Chick and Adult Feathers

Significant differences in mean mercury concentrations in chick feathers among study areas were detected in both 1991 and 1992 (Table 2). In 1991, chick feathers from SMR had significantly higher mean mercury concentrations than feathers from GB and KL. In 1992, chick feathers from OR had significantly higher mercury concentrations than those from KL, GB, and DB. A comparison of mercury concentrations between 1991 and 1992 among SMR, GB, and KL revealed significant differences among areas ($F_{2,38} = 30.93$, $p = 0.0001$) but not between years ($F_{1,38} = 0.10$, $p = 0.76$) or for area by year interaction ($F_{2,38} = 1.80$, $p = 0.18$). Mean mercury concentration ± SD in chick feathers from DB in 1993 and 1994 were 1.78 ± 0.52 µg/g ($N = 6$) and 2.54 ± 0.23 µg/g ($N = 4$), respectively (not shown in Table 2). No significant differences in mean mercury concentrations in chick feathers at DB were detected among all three years ($F_{2,11} = 3.60$, $p = 0.063$), and so for the purpose of among-area comparisons, as in Table 2, these values were pooled. Mean mercury concentrations ± SD for chick feathers from the Atlantic coast in 1993 and 1994 were 3.47 ± 1.15 µg/g ($N = 4$) and 3.19 ± 0.78 µg/g ($N = 3$), respectively, and, similarly, since no significant difference was detected between years ($t = 0.36$, $df = 5$, $p = 0.75$) at this area, these values were also pooled. Overall for all years pooled at each area, chick feathers from OR and the SMR had significantly higher concentrations of mercury than those from GB, KL, DB, and AC. Chick feathers from DB had the lowest mean mercury concentration.

Adult osprey feathers from SMR had significantly higher mean mercury concentrations than osprey feathers from KL (log-transformed data: $F_{2,8} = 5.60$, $p = 0.03$; Table 3). Mean mercury concentrations in chick and adult feathers were significantly different among SMR, GB and KL (log-transformed data: $F_{2,29} = 17.33$, $p = 0.0001$) and also significantly different between feather types ($F_{1,29} = 47.82$, $p = 0.0001$), but not for area by feather type interaction ($F_{2,29} = 0.54$, $p = 0.59$). Mean mercury concentrations were 2.4–4.6 times higher in adult feathers than in chick feathers in 1991 (Table 3).

Fish and Biomagnification Factors

For fish of a similar age (i.e., 4–5 years), a clear spatial pattern was evident: there were significant differences in mercury levels for these fish among the three areas examined (Table 4). Furthermore, this spatial pattern was more similar to that observed for osprey chick feathers than for eggs. Mean total lengths ± SD of yellow perch, which correspond to mean mercury values in these areas, were 23.4 ± 1.5 cm at SMR; 25.5 ± 0.9 cm at GB, and 17.6 ± 1.1 cm at KL. Considering fish size, 20-cm yellow perch were approximately twice as contaminated with mercury at SMR than at other areas; this was reflected in contaminant levels measured in feathers only. All biomagnification factors were greater than 1, and ranged from 1 to 4 in eggs and from 11 to 22 in chick feathers.

An examination of the coefficients of variation revealed that mercury concentrations were approximately twice as variable in eggs than in feathers (Table 5). Mercury levels were more variable in adult feathers than in chick feathers at GB and SMR. Biomagnification factors (BMF) calculated using eggs were also more variable than those calculated using feathers (Table 5).

Table 1. Mercury concentrations (μg/g dry weight) in osprey eggs collected from nests in the Great Lakes study areas and Delaware Bay, New Jersey 1991–1992[a]

	1991				1992				1991 & 1992	
Area	n	Mean	Range	SD	n	Mean	Range	SD	Mean	SD
St. Marys River	2	0.63a	0.50–0.76	0.18	6	0.64b	0.45–1.10	0.24	0.64b	0.21
Georgian Bay	10	0.89a	0.33–2.19	0.57	7	0.61bc	0.26–1.75	0.51	0.78ab	0.55
Kawartha Lakes	13	0.53a	0.11–0.95	0.27	9	0.32c	0.15–0.78	0.20	0.44b	0.26
Ogoki Reservoir	—	—	—	—	8	1.40a	0.70–2.15	0.46	1.40a	0.46
Delaware Bay	—	—	—	—	5	0.42bc	0.19–0.71	0.21	0.42b	0.21
Among-area comparison			$F_{2,22} = 2.22$ p = 0.13				$F_{4,30} = 12.30^b$ p = 0.0001			$F_{4,55} = 8.86^b$ p = 0.0001

[a] Letters denote the results of among-areas, within-year comparison of means. Areas with a common letter did not differ significantly
[b] Log-transformed data

Table 2. Mercury concentrations (μg/g dry weight) in osprey chick feathers collected from nests in the Great Lakes study areas and New Jersey study areas 1991–1994[a]

	1991				1992				1991–1994[b]		
Area	n	Mean	Range	SD	n	Mean	Range	SD	n	Mean	SD
St. Marys River	7	7.86a	5.90–10.10	1.48	5	6.77ab	5.80–8.33	0.97	12	7.40a	1.36
Georgian Bay	8[c]	4.63b	2.60–6.80	1.61	5	4.46bc	1.57–5.66	1.76	13	4.56b	1.60
Kawartha Lakes	9	2.81b	1.10–5.00	1.46	10	3.67cd	2.66–5.18	1.02	19	3.26bc	1.29
Ogoki Reservoir	—	—	—	—	5	10.98a	7.61–17.00	3.98	5	10.98a	3.98
Delaware Bay	—	—	—	—	4	2.26d	1.81–2.73	0.49	14	2.14c	0.53
Atlantic coast	—	—	—	—	—	—	—	—	7	3.35bc	0.94
Among-area comparison			$F_{2,21} = 21.88$ p = 0.0001				$F_{4,24} = 16.13^d$ p = 0.0001			$F_{5,64} = 26.57^d$ p = 0.0001	

[a] Letters denote the results of among-areas, within-year comparison of means. Areas with a common letter did not differ significantly
[b] Data pooled for St. Marys River, Georgian Bay, Kawartha Lakes for 1991 and 1992; Ogoki Reservoir sampled in 1992 only; Delaware Bay for 1992, 1993 (n = 6) and 1994 (n = 4); Atlantic Coast for 1993 (n = 4) and 1994 (n = 3)
[c] Feathers from three dead chicks included
[d] Log-transformed data

Table 3. Mercury concentrations (μg/g dry weight) in adult osprey feathers collected from nests in the Great Lakes study areas in 1991.[a] Ratios of mean mercury concentrations in adult feathers to chick feathers for the three study areas in 1991 are also presented

Area	n	Mean	Range	SD	Adult:Chick Ratio
St. Marys River	2	28.8a	17.3–40.2	16.2	3.7
Georgian Bay[b]	5	21.1ab	7.5–47.9	15.8	4.6
Kawartha Lakes	4	6.70b	5.3–7.6	1.00	2.4

[a] Letters denote the results of among-areas comparison of means. Areas with a common letter did not differ significantly.
[b] Feather from one dead adult included

Egg-Chick Feather Comparison at the Same Nest

A significant relationship was detected between mercury levels in chick feathers and eggs collected from 24 different nests at SMR, KL, GB, and OR during 1991 and 1992 ($r = 0.46$, $p = 0.02$; Figure 2). This linear relationship was described by the equation: $[Hg_{feather}] = 4.47 \times [Hg_{egg}] + 2.35$. Upon examining this figure more closely, it appears that the high mercury values detected for two OR nests could have unequal weighting compared to the other nests and hence might be driving the linear relationship. For instance, it appears that nest OR5 exerts a higher degree of influence on the regression line (Cook's statistic, $D = 0.68$; calculated D value = 0.72; df = 2, 22), relative to all other nests (range of D values equal to 0–0.25). Nest OR3, on the other hand, exerts considerable leverage on the regression line (leverage coefficient, $h = 0.42$; calculated h value equals 0.17) relative to the other nests (range of h values equals 0.04–0.14). When these two nests are excluded from the model and nests from naturally formed lakes were analyzed, no significant relationship between mercury levels in chick feathers and eggs was observed ($r = 0.30$, $n = 22$, $p = 0.17$; regression equation: $[Hg_{feather}] = 2.59 \times [Hg_{egg}] + 2.90$). Thus, the inclusion of the two nests from OR have a major impact on the existence of a significant relationship between mercury levels in eggs and feathers.

Discussion

Spatial and Temporal Patterns of Mercury

Factors that may have contributed to the significant spatial variation in concentrations of mercury among the six study areas include point source discharges and atmospheric deposition of mercury. Soil type and underlying rock may be important in affecting background levels of mercury (Mailman 1980). Differences in chemical water parameters (such as lake pH and dissolved organic carbon), epilimnetic temperature, and morphometric lake parameters (such as lake size and the ratio of

Table 4. Mean mercury concentrations (μg/g dry weight) ± SD in osprey eggs and chick feathers collected in 1991 and 1992, and yellow perch (YP) collected in close proximity to osprey study areas.[a] Biomagnification factors (BMF) were calculated using mean concentrations in osprey tissues divided by that measured in yellow perch using the age (4–5 years) or length (20 cm) of interest

	Area			Among Area Comparison
	St. Marys River	Georgian Bay	Kawartha Lakes	
Mercury in osprey eggs	0.64 ± 0.21 ab	0.78 ± 0.55 a	0.44 ± 0.26 b	$F_{2,44} = 5.06$[b] $p = 0.0106$
Mercury in osprey chick feathers	7.40 ± 1.36 a	4.56 ± 1.60 b	3.26 ± 1.29 c	$F_{2,41} = 32.17$ $p = 0.0001$
Mercury in yellow perch (4–5 years)	0.60 ± 0.16 (7) a	0.38 ± 0.14 (4) b	0.24 ± 0.06 (14) c	$F_{2,22} = 23.85$[b] $p = 0.0001$
Estimated mercury in yellow perch (20 cm)	0.47	0.21	0.28	—
BMF eggs/$YP_{(4-5)}$	1.07	2.05	1.83	—
BMF feather/$YP_{(4-5)}$	12.33	12.00	13.58	—
BMF eggs/$YP_{(20)}$	1.36	3.71	1.57	—
BMF feather/$YP_{(20)}$	15.74	21.71	11.64	—

[a] See Materials and Methods for details. The number in parentheses denotes the number of fish sampled to estimate mean mercury concentrations. Letters denote the results of among-area comparison of means for eggs, feathers, and yellow perch of known age. Areas with a common letter did not differ significantly.
[b] Log-transformed data

Table 5. Coefficients of variation for osprey eggs, chick feathers, and adult feathers collected from nests in the Great Lakes study areas 1991–1992 and for biomagnification factors (BMF) calculated across all three sites (calculated from Table 4) using yellow perch (YP) 4–5 years of age and 20 cm in length

	Coefficient of Variation (%)		
	St. Marys River	Georgian Bay	Kawartha Lakes
Individual areas			
Eggs 1991	28.6	64.0	50.9
Eggs 1992	37.5	83.6	62.5
Chick feathers 1991	18.8	34.8	52.0
Chick feathers 1992	14.8	39.5	27.8
Adult feathers 1991	56.3	74.9	14.9
All three study areas			
BMF eggs/$YP_{(4-5)}$		31.2	
BMF feather/$YP_{(4-5)}$		6.6	
BMF eggs/$YP_{(20)}$		58.8	
BMF feather/$YP_{(20)}$		30.9	

catchment area to lake volume) may also influence concentrations of mercury detected in lakes (Suns *et al.* 1980; Håkanson *et al.* 1988; McMurtry *et al.* 1989; Bodaly *et al.* 1993). Specifically, Miskimmin *et al.* (1992) have found that changes in dissolved organic carbon, pH, and microbial respiration rates influence the rate of mercury methylation, which, consequently, increases the amount of methyl mercury available to aquatic biota.

Mean mercury concentrations reported for the St. Marys River, Georgian Bay, Kawartha Lakes, and Delaware Bay are generally similar to those detected in osprey eggs from previous North American studies. For instance, osprey eggs collected from the Lake of the Woods in 1971 in northwestern Ontario had a mean mercury concentration ± SD of 0.58 ± 0.19 μg/g dw (n = 7) (Grier *et al.* 1977). Noble and Elliott (1990) collected osprey eggs in 1965–1972 from eastern Canada, including Ontario, and reported similar mean mercury concentrations of less than 0.1 μg/g ww (see Appendix). Mean mercury levels ±SD in osprey eggs collected from nests in northern Québec were 0.18 ± 0.10 μg/g ww (n = 33) (DesGranges *et al.* 1994), similar to values reported for addled eggs from Georgian Bay in 1991 (see Appendix). One addled egg that fell out of an osprey nest at the Bay of Quinte, Lake Ontario, in 1994 contained a relatively high level of mercury (1.56 μg/g dw) compared to levels reported for other southern Ontario areas in this study (P.J.E. unpublished data). Mean mercury concentrations for random and addled osprey eggs collected from Delaware Bay in 1985–1989 were 0.09 μg/g ww (n = 7) and 0.10 μg/g ww (n = 4), respectively (Steidl *et al.* 1991a); these values are similar to our values reported for addled eggs (0.08 μg/g ww) in 1992 (see Appendix). Steidl *et al.* (1991a) also found that mean mercury concentrations for eggs from the Atlantic coast were higher [random: 0.14 μg/g ww (n = 8); addled: 0.23 μg/g ww (n = 4)] than the mean for eggs from Delaware Bay, a pattern that is similar to that observed in this study using feathers. Mercury levels were also comparable to those reported for osprey from the eastern United States in 1978 (Wiemeyer *et al.* 1988).

Mercury concentrations for osprey feathers are also similar to those found in other studies. Both osprey chick and adult feathers collected from osprey populations in northern Québec (DesGranges *et al.* 1994) had mean concentrations ±SD that fall in the range of those found in the present study [chicks: 6.96 ± 4.32 μg/g dw (n = 63); adults: 16.47 ± 12.82 μg/g dw (n = 29)]. Solonen and Lodenius (1990) reported a mean concentration ± SD equal to 4.0 ± 1.6 μg/g dw (n = 32) for half-grown to nearly fledged osprey chicks in southern Finland in the mid 1980s.

In contrast to osprey breeding areas that are located around naturally formed lakes, Ogoki Reservoir represents a unique study area in which to examine mercury contamination since the formation of reservoirs has been implicated as the cause of high mercury levels in aquatic biota. Elevated mercury concentrations observed in osprey tissues at Ogoki Reservoir are consistent with studies that have detected high mercury levels in fish (Potter *et al.* 1975; Abernathy and Cumbie 1977) and osprey populations (DesGranges *et al.* 1994) at other reservoirs.

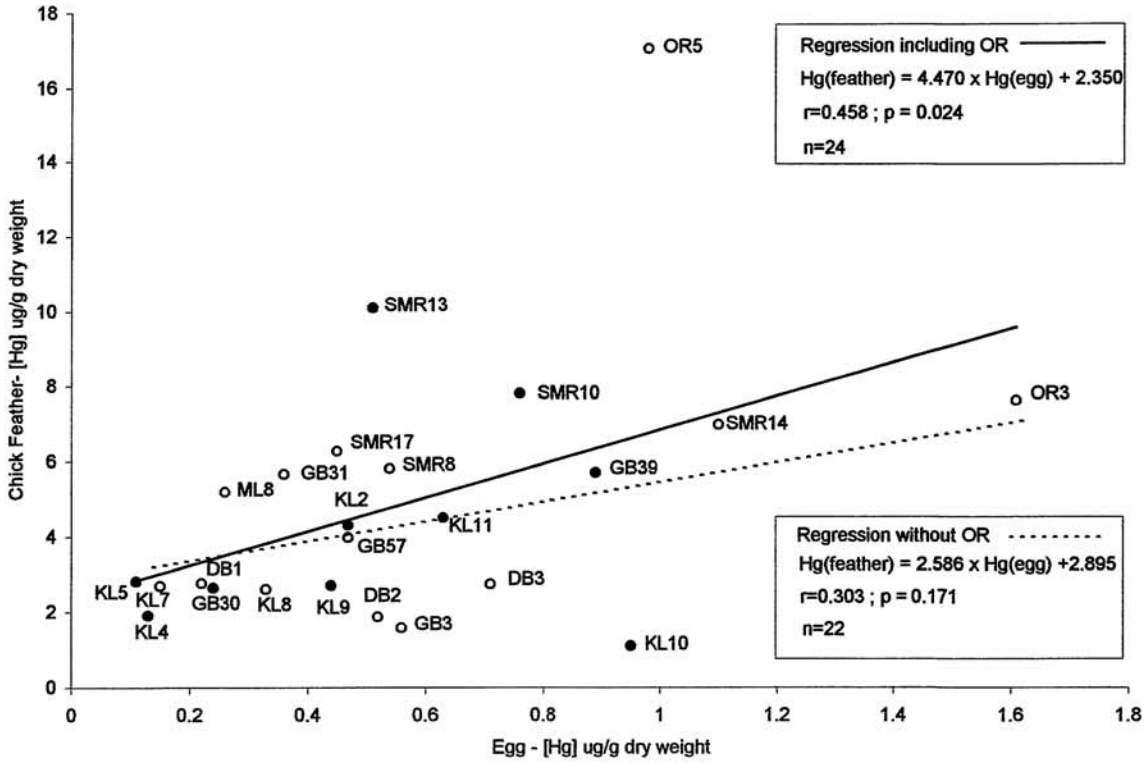

Fig. 2. A comparison of mercury levels in osprey eggs and chick feathers collected from the same nest at the Great Lakes study sites [St. Marys River (SMR), Kawartha Lakes (KL), Georgian Bay (GB) and the Ogoki Reservoir (OR)] in 1991 and 1992. Closed circles denote 1991 data; open circles denote 1992 data. Two linear relationships are described, one of which includes OR data and the other of which does not (see text for details)

In northern Québec, both osprey chick and adult feathers had significantly higher mercury levels at hydroelectric reservoir areas than at naturally formed lakes and rivers (DesGranges *et al.* 1994). It has been hypothesized that the flooding of terrestrial soils (during reservoir formation for instance) adds inorganic mercury and organic nutrients to the aquatic system which in turn elevates microbial methyl mercury production (Wright and Hamilton 1982; Bodaly *et al.* 1984). In support of this hypothesis, Bodaly *et al.* (1984) found that increases in fish mercury concentration coincided with an increase in water level immediately following diversion and subsequent flooding of the Churchill River in Manitoba. When the Ogoki Reservoir Project became operational in 1943, water levels rose 40 feet along the Ogoki River and 10 feet at Mojikit Lake, the first lake into which the river had been diverted (Bridger and Day 1976). Mercury data from larger fish species in this lake suggest that mercury levels are indeed elevated in this area and may exceed the 0.5 µg/g ww level considered safe for human consumption (IJC 1977). For example, mean methyl mercury concentrations in Mojikit Lake in 1981 for northern pike (*Esox lucius*) and walleye (*Stizostedion vitreum*) were 0.61 µg/g ww (minimum = 0.48, maximum = 0.74; n = 5) and 0.70 µg/g ww (minimum = 0.30; maximum = 1.3; n = 15), respectively (OMNR, unpublished). These mean levels are at least 1.5 times higher than mercury measured for these species at the St. Marys River, Georgian Bay and the Kawartha Lakes (OMNR, unpublished data). Mercury concentrations for fish were never examined prior to the formation of the reservoir. However, it appears that mercury levels detected in osprey eggs and feathers as well as fish sampled from the Ogoki Reservoir are elevated relative to other areas and it is likely that the presence of this reservoir accounts for the large spatial difference observed at this area relative to all other areas.

With the exception of the Ogoki Reservoir, mercury data for osprey in Great Lakes study areas (Ontario) prior to 1991 are not available. Temporal trends of mercury in other biota, such as spottail shiner (*Notropis hudsonius*), rainbow smelt, slimy sculpin, lake trout (*Salvelinus namaycush*), and herring gull (*Larus argentatus*) eggs, indicate that mercury levels have declined noticeably at many locations on the Great Lakes since the 1970s (Suns *et al.* 1985; Borgmann and Whittle 1991, 1992; Bishop *et al.* 1992; Koster *et al.* 1996). In contrast to this pattern, a comparison of mercury concentrations for two addled osprey eggs from two nests on the Ogoki Reservoir in 1971 (0.05 and 0.11 µg/g ww) (Postupalsky 1977) with the relatively high levels reported in this study suggest an increase in mercury availability. Clearly, long-term studies of mercury in ospreys are necessary, particularly at reservoirs, which are rich with dead timber following flooding and which provide attractive nesting sites for ospreys (Postupalsky 1977; DesGranges *et al.* 1994); consequently, the increase in exposure to mercury at reservoirs may be of concern.

Toxicity Associated with Mercury

Mercury concentrations in random or addled eggs in this study do not approach the critical value of greater than 0.5 µg/g wet

weight typically associated with adverse reproduction in birds (Fimreite 1971; Thompson 1996; see Appendix). Mercury concentrations in adult osprey feathers, on the other hand, exceed what is considered to be normal background levels (1–5 μg/g dw) for raptorial birds living in relatively uncontaminated habitats (Berg *et al.* 1966; Honda *et al.* 1986b). These levels do not appear to have a significant effect on breeding success at the Georgian Bay, Kawartha Lakes, and St. Marys River areas (Table 6; from Ewins 1996) as the mean number of chicks fledged per nest is usually greater than 0.8, a value considered necessary to maintain stable osprey populations (Spitzer 1980). Indeed, population numbers of osprey are increasing by 10–15% per annum in these areas (Ewins 1992; Ewins *et al.* 1995). The ban of the use of persistent organochlorine pesticides in North America as well as the presence of artificial nest structures contributes to the observed increase in breeding success observed at these study areas (Ewins 1996).

Coincident with low mercury levels in 1971, osprey nesting success at the Ogoki Reservoir was also low as only two of nine osprey pairs nesting on the Ogoki Reservoir were successful (Postupalsky 1971). A mean production of only 0.8 young fledged per nest at the Ogoki Reservoir in 1992 suggests that factors other than exposure to mercury may be limiting productivity in this area. Such factors include a limited number of nesting sites, weather conditions (i.e., strong winds that blow down nests), human disturbance, and limited food availability (Poole 1981, 1989; P.J.E. personal observations).

Ospreys nesting along the Delaware Bay side of New Jersey have been shown to experience lower reproductive success than the New Jersey Atlantic Coast population, mainly as a result of low hatching success (Steidl *et al.* 1991b). This observation has been attributed to high levels of organochlorine contaminants found in the eggs, notably DDE and PCBs (Wiemeyer *et al.* 1988; Steidl *et al.* 1991a). Predation of chicks by great-horned owls (*Bubo virginianus*) at Delaware Bay appears to be another important factor responsible for limiting productivity at this area (Steidl *et al.* 1991b). Although the Atlantic Coast New Jersey population had slightly higher levels of mercury, these levels are too low to affect productivity adversely (Steidl *et al.* 1991a; this study). Other factors that may contribute to limited population growth at Delaware Bay include low food availability and a limited number of nesting areas (K.E.C., personal observations).

Mercury in Chick vs Adult Feathers

Large differences in mercury levels between chick feathers and adult feathers (2.4 to 4.8-fold) at all areas reflect differences in age and, thus, differences in exposure to mercury (see Burger 1993 for a review). Adult birds generally have higher levels of mercury in their feathers than chicks since adults bioaccumulate mercury in their soft tissues, such as the liver, over a longer period prior to their molt (Lindberg and Odsjö 1983; Furness *et al.* 1990). The adult osprey undergoes a stepwise continuous molt such that all primaries are renewed annually (Prevost 1983). Molt is most active from July to early September and from mid-October to March. It is arrested temporarily during osprey migration in March and April and in October and November (Prevost 1983; Poole 1989). Therefore, mercury concentrations in adult primary feathers collected at the breeding area in July likely reflect levels of mercury accumulated in internal tissues since March (three months) (Furness *et al.* 1986; DesGranges *et al.* 1994). Osprey chicks, while susceptible to concentrations of mercury in the egg, are exposed to increasing levels of mercury but, at the time of feather collection, for a relatively shorter period of time spanning a few weeks of their development (Furness *et al.* 1990). Adults are also exposed to varying concentrations of mercury as a result of their migratory behavior. Ospreys from the Northeast and mid-Atlantic United States overwinter in the major water systems of South America including the Amazon (Poole and Agler 1987), where mercury used for gold-mining is being released into the aquatic environment (Martinelli *et al.* 1988). The relatively large coefficients of variation for adult feathers compared to those of chicks at St. Marys River and Georgian Bay suggests that differences in exposure are noteworthy (Furness *et al.* 1990). Other factors that might affect the magnitude of this difference include the type of adult feather selected and the time of sampling in relation to molt (Furness *et al.* 1986), since, for example, it has been shown that mercury levels progressively decrease from the first to last feathers molted as mercury is redistributed from the body tissues into the feathers (Braune and Gaskin 1987).

Eggs vs Chick Feathers as Indicators of Local Mercury Contamination

Chick feathers are better indicators of local contaminant conditions compared to eggs for a number of reasons. First, mercury patterns among areas in chick feathers were similar to those found in yellow perch of known age, whereas the same was not true for eggs. One explanation for this discrepancy is that mercury deposited in eggs may not have originated solely from the local/breeding environment: mercury may have been accumulated in the female during migration and on the wintering grounds. Although female osprey arrive on the Great Lakes breeding grounds in early April, a few weeks prior to egg laying (mean ± SD = 16.6 ± 4.6 days; n = 19 females; P.J.E. unpublished data), they may be using endogenous reserves acquired elsewhere for egg production. Second, coefficients of variation for mercury concentrations estimated using chick feathers were relatively small compared to those for eggs (Table 5). Third, the coefficient of variation for biomagnification factors estimated using chick feathers and yellow perch of a standard size was relatively small (30.9%) compared to that for eggs (58.8%; Table 5). Similarities in biomagnification factors are dependent on yellow perch being selected equally as prey items at all areas.

Finally, no significant correlation was observed between mercury concentrations in eggs and chick feathers from osprey clutches at naturally formed lakes. To our knowledge, this is the first study to examine whether a correlation exists between mercury levels in osprey chick feathers and eggs from the same clutch. Studies of herring gulls from the highly contaminated German North Sea have examined developmental changes in mercury levels in eggs, chicks, and adults (Becker and Sperveslage 1989; Lewis *et al.* 1993; Becker *et al.* 1994). Becker and Sperveslage (1989) found a significant correlation in mercury levels between eggs and whole herring gull chicks (5 days old), suggesting that, at this age, mercury levels in young chicks are dependent on levels in the egg. As herring gull chicks grow older, mercury levels in feathers grown later decrease

Table 6. Mean reproductive output at occupied osprey nests on natural and artificial structures at Great Lakes study areas and New Jersey study areas[a]

Site	Year	Nest Structure	Occupied Nests (n)	Young Fledged (n)	Young per Occupied Nest
Ogoki Reservoir	1992	Natural	15	12	0.80
St. Marys River	1991–93	Natural	78	75	0.96
		Artificial	44	57	1.30
Georgian Bay	1991–93	Natural	37	35	0.95
		Artificial	91	83	0.91
Kawartha Lakes	1991–93	Natural	85	106	1.25
		Artificial	110	133	1.21
Delaware Bay	1992–94	Artificial	28	27	1.04
Atlantic Coast	1992–94	Artificial	112	144	1.29

[a] From Ewins (1996); mean reproductive output for Delaware Bay and the Atlantic Coast are from Steidl *et al.* (1991a)

Appendix. Mean mercury concentrations (μg/g), expressed on a wet weight basis, for random and addled osprey eggs collected from nests in the Great Lakes study areas and Delaware Bay, New Jersey 1991–1992

		Random				Addled			
Year	Site	n	Mean	Range	SD	n	Mean	Range	SD
1991	St. Marys River	—	—	—	—	2	0.11	0.10–0.11	0.01
1991	Georgian Bay	6	0.11	0.08–0.15	0.03	4	0.20	0.05–0.33	0.11
1991	Kawartha Lakes	8	0.08	0.02–0.15	0.05	5	0.10	0.06–0.20	0.06
1992	St. Mary's River	3	0.09	0.08–0.10	0.01	3	0.14	0.10–0.19	0.04
1992	Georgian Bay	4	0.07	0.06–0.10	0.02	3	0.14	0.05–0.28	0.12
1992	Kawartha Lakes	3	0.03	0.02–0.04	0.01	6	0.07	0.04–0.13	0.04
1992	Ogoki Reservoir	7	0.22	0.12–0.34	0.08	1	0.34	—	—
1992	Delaware Bay	—	—	—	—	5	0.08	0.05–0.12	0.03

(Becker *et al.* 1994), indicating a gradual depletion of the body pool of mercury. Consequently, whereas a positive correlation was apparent in mercury levels between down and early-grown feathers (side and shoulder), by the time chicks are 29 days old, no relationship was detected in mercury levels between down and later-grown feathers (i.e., back feathers). They suggest that, by this stage, the sources of mercury were different and that mercury levels in down reflect levels in the egg while mercury levels in back feathers reflect levels accumulated on local feeding grounds (Becker *et al.* 1994). A similar conclusion was drawn by Lewis *et al.* (1993), who found no significant correlation in mercury levels between eggs and adult feathers of female herring gulls. The lack of correlation in mercury levels between eggs and chick feathers collected from sites with low contamination in this study indicates that the high degree of variability in mercury levels detected in these two tissues may be due to the fact that the sources of mercury contamination are different.

The inclusion of two heavily contaminated nests from Ogoki Reservoir in the regression model resulted in a significant correlation in mercury levels between osprey eggs and chick feathers. For breeding areas that are more contaminated relative to wintering areas, the influence of high levels of mercury acquired on breeding sites becomes more apparent, as high levels of mercury are deposited in eggs and chick feathers. Becker *et al.* (1993) found similar spatial patterns of mercury in common tern (*Sterna hirundo*) eggs and chick feathers at highly contaminated sites. Indeed, at highly contaminated sites, eggs may be as good as feathers as indicators of local contamination; however, more osprey data from more contaminated areas are needed to determine this conclusively. A number of factors should be considered when attempting to explain the overall variation observed in mercury levels between these tissues. Mercury levels detected in eggs and feathers are dependent on the body burden of the individual, as rates of elimination of mercury are related to the degree of contamination shown by the individual (Becker *et al.* 1994). Furthermore, there may be differences in mercury levels of osprey eggs in a single clutch. In common terns and gull eggs collected at the German North Sea coast, the first laid egg of a clutch contained up to 39% more mercury than the second and third egg (Becker 1992). In this study, where areas were relatively much less contaminated, mercury levels in feathers from the oldest osprey chick (and thus the first laid egg) were compared with mercury levels in the third osprey egg. If a similar decline in mercury levels within a single clutch is evident in osprey, this might also contribute to the variation observed in mercury levels for eggs and chick feathers.

The elimination of mercury via eggs and feathers represents two very important mechanisms in which birds can lessen the adverse effects associated with mercury exposure. The sampling of feathers is ideal for monitoring mercury bioavailability in birds because feathers can be easily collected and sampling is nondestructive and causes little or no injury to the bird. Furthermore, mercury deposited in feathers is also relatively stable over long periods of time (Appelquist *et al.* 1984; Goede and deBruin 1984) and represents, at least for chicks, local levels of exposure during the later stages of development. After feather growth is complete, mercury levels in internal tissues of chicks may continue to rise, as has been observed in adult birds (Braune and Gaskin 1987). At sites that are highly contaminated, this may be a concern and further studies are required to

assess whether mercury levels in internal tissues become hazardous at this time.

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