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Assessment of Mercury in Maine's Interior Bald Eagle Population

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Assessment of Mercury in Maine's Interior Bald Eagle Population

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by:

Christopher R. DeSorbo [1, 2], Charles S. Todd [3], Steven E. Mierzykowski [4],
David C. Evers [2] and William Hanson [5]

[1] Antioch New England Graduate School, [2] BioDiversity Research Institute, [3] Maine Department of Inland Fisheries and Wildlife, [4] U.S. Fish and Wildlife Service, [5] Next Era Energy Resources

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EXECUTIVE SUMMARY

Mercury pollution is prevalent in the northeastern U.S. due to a combination of high rates of atmospheric deposition from Midwest sources and an abundance of habitats in the Northeast that effectively produce methylmercury from mercury inputs. Ongoing research has documented elevated mercury levels in a variety of aquatic and terrestrial fish and wildlife in Maine. High mercury burdens have been linked to negative effects on behavior, physiology, and fledging success in birds. In this study, mercury exposure and the potential for reproductive impacts in freshwater-feeding bald eagles (*Haliaeetus leucocephalus*) in Maine were investigated.

Between 2001 and 2006 (primarily 2004-2006), eaglet blood and shed adult feathers were collected from freshwater-based bald eagle nest territories throughout Maine. Tissues were analyzed for mercury to obtain insights on short-term and chronic exposure in eaglet and adult age classes, respectively. Nonviable and abandoned eggs were also collected and analyzed for mercury. Mercury patterns between habitats and among watersheds, relationships between mercury exposure and eagle productivity were evaluated. Temporal mercury trends were determined by comparing results in the present study to data collected in a previous U.S. Fish and Wildlife sponsored study (Welch 1994).

Over the course of the study, blood was collected from 304 eaglets from 150 inland nest territories. All eaglets were marked with rivet-style numbered leg bands from the Bird Banding Laboratory and with rivet-style red, 2-digit, horizontally-coded auxiliary leg bands. Eaglet blood mercury concentrations ranged from 0.08 – 1.62 parts-per-million, ppm (mean 0.53 ppm wet weight, n = 150). Eaglets reared in lake habitats (mean 0.56 ppm, n = 115 territories) had higher mercury concentrations than those reared in river habitats (mean 0.44 ppm, n = 35 territories). Blood mercury levels in lake-based Maine eaglets were higher than concentrations reported in other regions of North America, and similar to populations with known point-source pollution origins (e.g., mercury mines, dredging).

Shed adults feathers were collected from 103 nest territories. Mercury exposure in adult bald eagle feathers ranged from 7.5 - 93.0 ppm dry weight (mean 38.3 ppm). Mercury concentrations in shed adult feathers were higher at nest territories in lake habitats (mean 40.6 ppm, n = 79) than river habitats (mean 30.5 ppm, n = 24). Mean feather mercury concentrations in both habitats, particularly lakes, were higher in comparison to many North American populations studied by other researchers. Similar to patterns observed in eaglet blood, mercury concentrations for Maine lake-dwelling adult eagles were higher than or comparable to other sites in North America associated with acute mercury pollution problems.

Twenty two nonviable and abandoned bald eagle eggs were collected. Mercury in eggs from 16 inland nest territories in Maine (mean 0.40 ppm fresh wet weight, range 0.09 - 0.90 ppm) was elevated compared to other eagle populations in the United States. The majority of eagle eggs collected in this study, however, contained mercury concentrations that were below levels currently associated with reduced hatching success in piscivorous wildlife.

Statistically significant negative relationships were found between eaglet blood mercury concentrations and 3-, 5-, and 10-year eagle productivity (chicks fledged/occupied nest), but the

correlation was not strong. The negative correlation between mercury and productivity was most pronounced at lakes, where mercury concentrations were highest. This relationship may suggest a portion of Maine's eagle population may be experiencing some reproductive impacts due to mercury exposure despite continuous population growth. No relationships were detected between adult feather mercury concentrations or egg mercury concentrations and eagle productivity. Relationships between eaglet blood mercury concentrations and productivity in this study may be confounded by exposure to organic contaminants such as PCBs.

Mean eaglet blood mercury levels varied among 10 watersheds, with the St. Croix River watershed containing the highest levels, and inland Midcoast Maine containing the lowest levels. Limited sample sizes within habitat types and watersheds precluded rigorous statistical comparisons. Within the majority of watersheds, eaglet blood mercury concentrations were higher at lakes compared to rivers. However, several watersheds did not fit this pattern and require further explanation. Eaglet mercury exposure data were often consistent with findings in other biota (i.e., common loons, fish) used in other studies to delineate several areas of significant mercury concern (i.e., biological mercury hotspots) in the state.

Eaglet blood mercury concentrations at inland nest territories sampled in 1991-1992 and again in the present study (2004 – 2006) were compared to evaluate potential temporal changes in mercury concentrations available to eagle nestlings. Statistical analyses suggest a possible effect of time period on bald eagle blood mercury concentrations, but significant differences were not detected between the two sampling periods within lake and river habitat types. Comparisons suggested that an increase in mercury uptake in birds reared in river habitats over the time interval. Small sample sizes limit the ability to draw robust conclusions between the two datasets.

Recommendations for further research and management needs include identifying and linking point source databases in the state with bald eagle territories exhibiting elevated mercury levels, periodic monitoring of bald eagles at 10 to 15 year intervals, and additional sampling in watershed basins where there is limited mercury exposure data.

KEYWORDS: bald eagle, *Haliaeetus leucocephalus*, mercury, Maine

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LIST OF ACRONYMS/ABBREVIATIONS

AK	Alaska
ANC	acid neutralizing capacity
ANOVA	analysis of variance
AZ	Arizona
BC	British Columbia
BRI	BioDiversity Research Institute
cm	centimeter
DDE	dichlorodiphenyl dichloroethylene
DDT	dichlorodiphenyl trichloroethane
DEQ	Division of Environmental Quality (USFWS)
DMA	direct mercury analysis
DOC	dissolved organic carbon
dw	dry weight
F	Fahrenheit
FPL	Florida Power and Light
fww	fresh wet weight
GIS	Geographic Information System
Hg	mercury
HUC	hydrologic unit code
MD	Maryland
MEDIFW	Maine Department of Inland Fisheries and Wildlife
ME	Maine
MEDEP	Maine Department of Environmental Protection
MEFO	Maine Field Office (USFWS)
MeHg	methylmercury
MI	Michigan
mL	milligrams per liter (parts-per-million)
µg/g	micrograms per gram (parts-per-million)
NH	New Hampshire
OH	Ohio
OR	Oregon
p	probability
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
ppm	parts-per-million
SD	standard deviation
TCDD-TEQ	dioxin toxic equivalents
TERL	Trace Element Research Laboratory
U.S.	United States
USFWS	U.S. Fish and Wildlife Service
WI	Wisconsin
ww	wet weight

PREFACE

This report summarizes mercury concentrations in bald eagle blood, feather, and eggs collected from inland nest territories in Maine. Analytical work for this project was completed under U.S. Fish and Wildlife Service Analytical Control Facility Catalog Numbers 5100015 (Purchase Order 94420-06-Y590), 5100018 (Purchase Order 94420-06-Y686), and 5100022 (Purchase Order 94420-06-Y712). This work was conducted in support of the Master's thesis of Christopher DeSorbo (DeSorbo 2007). USFWS project coordinator was Steve Mierzykowski.

Questions, comments, and suggestions related to this report are encouraged. Written inquiries should refer to Report Number FY07-MEFO-3-EC and be directed to:

Steve Mierzykowski
U.S. Fish and Wildlife Service
1168 Main Street
Old Town, ME 04468

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This report complies with the peer review and certification provisions of the Information Quality Act (Public Law 106-554, Section 515).

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1. Introduction

Bald eagle (*Haliaeetus leucocephalus*) populations became locally extirpated throughout much of North America during the mid 1900s due to a combination of human persecution, habitat loss, and perhaps most notably, the impacts of DDT (dichlorodiphenyl trichloroethane; see review in Buehler 2000). Subsequent legislation banning the use of DDT, and legal protection for eagles and their habitats has resulted in strong population recoveries in many North American populations to the extent that the U.S. government removed the bald eagle from the federal Endangered Species List in 2007. Population recoveries are not uniform throughout the U.S, however, and lingering environmental contaminants, especially organic compounds, may continue to limit population productivity and recovery in some portions of the bald eagle's breeding range (Anthony *et al*. 1993, Bowerman *et al*. 2002, Elliott and Harris 2002, Bowerman *et al.* 2003).

Maine's bald eagle population is clearly expanding, but the 8% annual growth rate is well below the 13.4% rate of increase observed in the continental U.S. from 2006 to 2007 (Suckling and Hodges 2007). Population growth rate and productivity of Maine eagles are typically less than in other major populations. Causes for these deficiencies in Maine compared to other regions remain unknown. One commonly proposed explanation is that environmental contaminants such as mercury (Hg) and organic compounds may contribute to lowered nesting success, overall productivity, and slowed recovery rates.

Findings from previous studies are generally consistent in the conclusion that coastal (i.e., marine-influenced) and interior (i.e., freshwater-feeding) bald eagle populations in Maine face different contaminant challenges. Coastal populations tend to accumulate higher concentrations of organic compounds such as polychlorinated biphenyls (PCBs), while exposure to mercury in coastal populations is often below levels of concern (Welch 1994, Matz 1998). Conversely, Maine's interior bald eagle population displays some of the highest tissue mercury concentrations in the country (Welch 1994, DeSorbo 2007, DeSorbo and Evers 2007). Since the last effort to evaluate contaminants in bald eagles nesting in Maine's interior (Welch 1994), inland populations have greatly expanded and, consequently, the opportunities for sampling. Similarly since the earlier study by Welch (1994), knowledge of the extent of mercury exposure on high trophic level wildlife species in the region has greatly increased (Evers and Clair 2005) along with public concern regarding mercury contamination.

This study documents current exposure of bald eagles in interior Maine to mercury and examines productivity relationships. Concurrent USFWS studies to document concentrations of organochlorine compounds such as dioxin, dioxin toxic equivalents (TCDD-TEQ), PCBs, dichlorodiphenyl dichloroethylene (DDE), and emerging contaminants such as polybrominated diphenyl ether (PBDE) in eggs and liver tissue have recently concluded and final reports are in preparation (Mierzykowski *et al*. 2008, Mierzykowski *et al*. 2009). These concurrent studies indicate that organochlorine contamination in eggs from some inland nest territories or livers in some individuals occasionally exceed suggested toxicity thresholds (Elliott and Harris 2002, Henny and Elliott 2007). The present study, however, only describes the exposure and potential for negative effects of mercury in Maine's interior bald eagle population.

Numerous studies have demonstrated that fish, piscivorous, and even insectivorous wildlife throughout Maine are exposed to elevated levels of mercury via their diet (Evers and Clair 2005). Primary sources of mercury in Maine and other regions of the northeastern U.S. are considered to be atmospheric (Miller *et al*. 2005, VanArsdale *et al*. 2005, Evers *et al*. 2007), although several significant mercury point sources are known in the state. Once mercury is deposited on the landscape, it can be transformed to the most toxic organic form, methylmercury (MeHg), which readily biomagnifies in the foodweb to tertiary predators such as bald eagles. Not all regions or habitats produce MeHg from atmospheric deposition at the same rate. Differences in soil and water chemistry parameters (i.e., pH, dissolved organic carbon [DOC], acid neutralizing capacity [ANC]) and landcover characteristics (i.e., wetland acreage) play a significant role in MeHg production (Munthe *et al*. 2007, Driscoll *et al*. 2007, Evers *et al*. 2007). Maine's interior landscape contains an abundance of habitat characteristics that effectively produce MeHg from airborne mercury. This fact, in combination with west to east wind patterns and numerous mercury sources in the northeastern and midwestern U.S., is largely considered the cause for notably high mercury concentrations in fish and wildlife in Maine. At present, there is no federal standard for mercury emissions at the national level in the U.S., and some states still do not effectively regulate industrial mercury emissions. Therefore, studies investigating mercury exposure and potential impacts on wildlife are important in informing pollution policy decisions at the state, regional, and national levels.

2. Study Objectives

The objectives of this study were to:

a) Determine the current dietary exposure of freshwater-feeding bald eagle nestlings to mercury.

b) Determine mercury residues in adult bald eagle feathers and nonviable eggs at inland breeding territories.

c) Determine if mercury exposure might be limiting the recovery of Maine's bald eagle population by analyzing relationships between tissue mercury concentrations and productivity.

d) Establish baselines of mercury bioavailability to inland eaglet and adult bald eagles in Maine's major watersheds.

e) Evaluate potential for changes in mercury bioavailability to freshwater-feeding bald eagles over the last 14 years.

3. Study Area

All known bald eagle nest territories located in predominantly freshwater river and lake (also referred to as "inland") habitats throughout Maine were considered for sampling in this study (Figure 1). Nesting territories ranged widely in habitat characteristics including land ownership, potential for disturbance, and longevity of eagle residency.

4. Methods

4.1 Eagle Productivity and Occupancy Surveys. Seasonal nest occupancy and reproductive status was documented through ongoing aerial surveys using fixed-wing aircraft conducted by MEDIFW and USFWS biologists (MEDIFW 2004). Surveys of traditional nests and searches for new locations began in late-March/early April to determine nest occupancy and breeding activity. Interim checks of occupied nests during May identified nests with successful hatching, estimates of bald eagle nestling (also referred to as eaglets) ages, and occasional encounters with nonviable or abandoned eggs. Eagle territories were considered occupied if a pair of eagles was present within the territory during aerial surveys and/or active nesting was documented by observations of eaglets, eggs, shell fragments, or an adult eagle in incubation posture (MEDIFW 2004). Active nests were surveyed again in June/July to determine territory productivity (number chicks fledged / occupied nest; Postupalsky 1974). Older eaglets counted during late-season surveys were assumed to have fledged. Abundance and productivity of Maine's eagle population have been monitored since 1962 (MEDIFW 2004).

4.2 Tissue Selection. Tissues chosen for mercury analysis in this study include eaglet whole blood, shed adult feathers, and nonviable or abandoned eggs. Adults tending eaglets typically feed their young prey items caught near the nest, primarily from adjacent waters (Todd *et al*. 1982). Therefore, mercury exposure in eagle tissues generally represents mercury contamination in the aquatic foodweb local to the nest. The efficacy of using bird tissues to reflect mercury concentrations in the local prey base has been demonstrated (DesGranges *et al*. 1998, Evers *et al*. 2004, Burgess and Hobson 2006).

Mercury concentrations in eaglet blood are a suitable surrogate for short-term mercury exposure in adults. Weech (2003) found a strong relationship between eaglet blood and adult blood mercury concentrations from birds at the same nests in British Columbia ($R^2 = 0.91$, $p = 0.004$, $n = 7$; see also Welch 1994, Weech *et al*. 2006). Wood *et al*. (1996) found similar relationships between adult and eaglet feathers in Florida. Whole blood has a high protein turnover rate and mercury levels in blood reflect exposure to mercury via recent diet (Hobson and Clark 1994, Bearhop *et al*. 2000, Fournier *et al*. 2002, Evers *et al*. 2005).

Adult feathers reflect a coarse measure of the chronic, lifetime body burden of mercury in adults and mercury exposure during the time of feather formation (Burger 1993, Wolfe *et al*. 1998, Bearhop *et al*. 2000, Henny *et al*. 2002). Feathers can reflect 70-93% of the total body burden of mercury in birds (Burger 1993). Because bald eagles molt their flight feathers during the prolonged breeding season (Palmer *et al*. 1988, Buehler 2000), feather mercury concentrations are more likely to reflect exposure from their breeding grounds compared to species that undergo a full remigial molt on the ocean (i.e., common loons). Mercury concentrations in shed adult feathers are likely influenced by uncontrolled influences of age (bioaccumulation with age in some individuals chronically exposed to mercury over time), adults' exposure to mercury and accumulation during the winter or before ice-out at breeding lakes, and other factors. Mercury concentrations in adult eagle feathers followed a similar gradient of mercury as that observed in fish flesh among Great Lakes subregions, thus supporting the use of feathers to monitor mercury patterns in aquatic habitats (Bowerman *et al*. 1994).

Eggs may be the most sensitive life stage to toxic impacts in birds. Eggs reflect a combination of current dietary mercury exposure and chronic mercury accumulation in adult eagles. The extent to which bird eggs reflect mercury originating from diet versus body reserves varies by species, and depends on a variety of factors including the number of eggs laid, latitude, body condition, and food availability at the time of egg laying (Hobson *et al.* 1997). Evers *et al*. (2003) found that 80% of variability in common loon egg mercury could be explained by mercury levels in recent diet; similar assessments are lacking for bald eagles. The collection of unhatched eggs, as was conducted in this study, has a high potential for a sampling bias toward eggs with higher environmental contaminant concentrations.

4.2.1 Indexing blood mercury - background and use in analyses. Several field- and laboratory-based studies show that bird blood and feather mercury concentrations change in relation to physiological processes, especially feather development and molt (DesGranges *et al*. 1998, Frederick *et al*. 2002, Fournier *et al*. 2002, Fevold *et al*. 2003, Kenow *et al*. 2003). This fact is of particular concern when interpreting and making comparisons of blood or feather mercury concentrations among developing eaglets, especially those in different stages of feather development. Researchers have addressed this issue in other species by developing a weight- or morphometric-based index of mercury concentrations in an attempt to standardize mercury comparisons among nestlings of different ages (and therefore size and feather development). Evers *et al*. (2004) indexed mercury concentrations by chick weight in common loons. Similarly, blood mercury concentrations in Florida wading birds were indexed by culmen length based on relationships developed in laboratory dosing experiments (Spaulding *et al*. 2000, Heath and Frederick 2005). No similar index has been developed to compensate for differing age, weight or stage of development in nestling bald eagles, and no studies have adequately evaluated the extent to which physiological processes can influence blood mercury concentrations.

For analyses comparing mercury levels to productivity in this study, eaglet blood mercury concentrations are presented using three different blood profiles: (a) blood Hg (no index), (b) Hg / weight (x 1000) in grams and (c) Hg / age (x 100) in days. All three of these indices are used in statistical comparisons with productivity. However, only non-indexed blood Hg measures are compared to literature.

4.3 Sampling Strategy. Collecting tissues at bald eagle nesting territories at lakes and rivers within interior Maine was the focus because wildlife feeding in freshwater habitats in Maine are at a higher mercury risk compared to marine-influenced sites (Welch 1994, Evers *et al*. 2005, Evers *et al*. 2008). Additionally, marine and estuarine habitats are less comparable to inland populations due to differences in diet, trophic level, contaminant burdens, seasonal residency, and other factors (Todd 1979, Todd *et al*. 1982, Matz 1998).

Nests were visited during summers of 2001-2006, with the bulk of sampling occurring between 2004 and 2006. Sampling during 2001-2003 primarily targeted sites within the Kennebec River watershed in western Maine. Sampling from 2004 to 2006 was statewide. Sampling efforts were prioritized to: (1) sample two to three nests per watershed, (2) sample regions/watersheds in which mercury exposure was not documented in previous eagle studies, and (3) resample territories from which historical eagle blood mercury baselines existed (1991-1992; Welch 1994). Visits to sample eaglets targeted birds at approximately 5-6 weeks of age.

4.4 Eaglet Blood Sampling. Tree climbers ascended bald eagle nest trees using traditional arborist techniques (i.e., gaff and lanyard). Eaglets from each nest were captured by the climber, placed separately into a canvas bag, and lowered to the ground for processing and banding. Whole blood was taken from the brachial vein of each eaglet (7-10 mL) using 23.75 inch butterfly needles attached to heparinized evacuated test tubes. Samples were labeled and placed into protective cases, transported from the field in ice-filled coolers, and were frozen at 30°F within 10 hours. Eaglets were weighed, and morphometrics were taken (i.e., lengths of bill, culmen, footpad, tarsus, eighth primary) during processing. Eaglet age was determined following methods described in Bortolloti (1984). All eaglets were marked with rivet-style numbered leg bands from the Bird Banding Laboratory in Laurel, MD, and with rivet-style, red auxiliary leg bands (ACRAFT, Edmonton, Alberta, Canada).

4.5 Adult Feather Sampling. Shed adult feathers (mostly primaries, but also secondary tail, and body) were collected opportunistically from within and below eagle nests to gain insights on chronic mercury exposure in adults as in Bowerman *et al*. (1994) and Evans (1993). One whole feather in good condition was selected for analysis from each nest territory. Shed feathers were prioritized for analysis in the following order: primaries, secondaries, tail, and other (i.e., body). Several studies have found similar mercury concentrations among feather types (Evans 1993, Bowerman *et al*. 1994, Wood *et al*. 1996), and within individual feathers (Berg *et al*. 1966, Evans 1993, Dauwe *et al*. 2003, but see Weech 2003). Mercury concentrations in feathers collected in multiple years in the same territory were averaged.

4.6 Egg Sampling. Non-viable or abandoned eggs observed during aerial surveys or discovered during eaglet sampling visits were collected opportunistically from all nests. Eggs were processed by USFWS personnel within ten days of collection. Eggs were measured (length, breadth, weight) and scored at the equator with a stainless steel scalpel. Volume was determined from egg length and breadth measurements. Egg contents were placed in chemically clean jars, weighed, and frozen. Analytical results were adjusted on a fresh wet weight basis to account for moisture loss following egg laying (Stickel *et al*. 1973).

4.7 Relationships between Eagle Productivity and Mercury Exposure. Relationships between bald eagle productivity and tissue mercury concentrations were evaluated by comparing 3-year (2004-2006), 5-year (2001-2006), and 10-year (1997-2006) productivity to mercury concentrations for all tissues sampled (e.g., eaglet blood, adult feather, egg).

4.8 Establishing Mercury Baselines in Maine Watersheds. Baselines of mercury concentrations in eaglet blood and shed adult feathers were established by summarizing mercury data within inland portions of 10 Maine watersheds. Major watersheds were delineated by a combination of HUC-8 and HUC-10 GIS coverages used in Maine statewide eagle monitoring efforts (MEDIFW, unpublished data). Egg mercury data were not used in watershed comparisons due to limited sample sizes.

4.9 Temporal Mercury Patterns. Potential for changes in bioavailability of mercury to eaglets were evaluated by comparing eaglet blood mercury concentrations sampled during the present

study to those documented during 1991-1992 period (Welch 1994). Analyses, data summaries, and discussions in this report are taken from DeSorbo (2007).

4.10 Laboratory Analyses and QA/QC. Eaglet blood samples were homogenized and analyzed for total mercury using Direct Mercury Analysis (DMA) at the Texas A&M Trace Element Research Laboratory (TERL) in College Station, Texas. Adult feathers were analyzed using DMA at the Savannah River Ecology Laboratory, Aiken, South Carolina. All feathers were cleaned and lipid extracted prior to analysis. The distal 5 cm of one shed feather per territory was analyzed following techniques outlined in Evans (1993) and Bowerman *et al*. (1994). Egg samples were homogenized at the laboratory and an aliquot analyzed for total mercury using cold vapor atomic absorption (CVAA) at Laboratory and Environmental Testing, Inc., Columbia, Missouri.

All analyses in this study used quality assurance and quality control (QA/QC) procedures including procedural blanks, duplicates, spike recoveries, and certified reference material (Natural Research Council of Canada; dogfish muscle tissue [DORM-2] and dogfish liver tissue [DOLT-2, DOLT-3]). All QA/QC results used in this study were deemed acceptable by the USFWS Analytical Control Facility. Detection limits were approximately 0.02 µg/g for eggs and 0.0025 µg/g for blood and feathers.

4.11 Statistical Analyses. Tissue mercury concentrations were averaged in territories within (i.e., siblings averaged) and between sampling years. The sibling closest to 42 days of age was selected for temporal analyses. Normality of datasets was determined by visual inspections of distributions, normal quantile plots, and a goodness-of-fit test. Means were compared using a t-test or ANOVA for normally-distributed datasets; means for non-normally distributed data were compared using a Wilcoxon test. Mercury data was log-transformed for temporal comparisons. Productivity-mercury relationships were analyzed using a Spearman Rank Correlation test for non-normal datasets, and a Pearson Correlation test for datasets with a normal distribution. Mean eaglet blood mercury concentrations between early (1991-1992) and late (2004-2006) time periods were tested for differences using three-way analysis of variance (ANOVA) with eaglet blood mercury concentration as the dependent variable and independent variables of time period, habitat type (lacustrine, riverine), territory nested within habitat, and the interaction between time period and habitat (DeSorbo 2007). Least-squares geometric means of eaglet blood mercury concentrations were calculated (to adjust for unbalanced sample sizes) for each time period and habitat type, and they were compared using Bonferroni pairwise comparisons.

All statistical tests were performed using JMP version 4.0.0 Statistical Software (SAS 2001), except for temporal analyses, which were conducted using SYSTAT 10 software (SPSS Inc., Chicago, IL). All statistical tests were considered significant at $p < 0.05$. Arithmetic means and standard deviations are presented in text, figures, and tables unless otherwise noted.

5. Results and Discussion

5.1 Mercury Exposure – Eaglet Blood. Blood samples were collected from 304 eaglets (235 from lakes; 69 from rivers) at 150 nesting territories in interior Maine over the 2001-2006 period (Figure 1). During the bulk of the sampling period (2004-2006), eaglet sampling generally

represented 80-95% of the chick-producing inland nesting territories annually. Blood mercury concentrations in eaglets ranged from 0.08 µg/g to 1.62 µg/g (Table 1). The mean blood mercury concentrations in eaglets was higher at lake compared to river habitats ($p = 0.021$, Wilcoxon Test). This mercury exposure pattern is consistent with those reported by Welch (1994) and Evers *et al*. (2005): lake > river > estuarine > marine. A variety of factors may contribute to higher mercury concentrations in eagles feeding on lakes versus those emphasizing river resources. In comparison to rivers, lakes in our study area are more likely to exhibit water chemistry parameters favoring methylmercury production, such as low pH, high DOC, and low acid neutralizing capacity (Chen *et al.* 2005). Significant water level fluctuations, which are more common on lakes in our study area, have been linked to increased methylmecury production at some sites (i.e., Verta *et al*. 1986, Morrison and Therien 1995, Evers *et al.* 2007). Additionally, various land cover characteristics linked to increased methylmercury production, such as wetland cover, are likely more common at lakes compared to rivers in this study (see discussion in DeSorbo 2007).

5.1.1 Geographic comparisons for eaglet blood mercury. Eaglet blood mercury concentrations for Maine lake and river habitats (0.56 µg/g lake, 0.44 µg/g river; Table 1) are notably elevated compared to levels in most inland eagle populations, including South Carolina (0.11 µg/g; Jagoe *et al*. 2002), Florida (0.13 µg/g; Wood *et al*. 1996), Washington (0.23 µg/g; Wiemeyer *et al*. 1989), and a mean representing regions of New York, excluding the Catskill region (0.26 µg/g; DeSorbo *et al*. 2008) (Figure 2).

Bald eagle nestlings in Maine's river habitats had blood mercury concentrations most similar to those reported for eaglets in the Columbia River Estuary (0.47; Anthony *et al*. 1993). The Columbia River Estuary was once considered one of the more industrialized and polluted regions in the U.S. due to combined influences of industrialization, hydroelectric dams, and dredged river sediments. Populations there are exposed to several contaminants in addition to mercury (e.g., PCBs, DDE, dioxin), many of which were previously blamed for low eagle productivity (0.56 young / occupied nest) in the region.

Eaglets in Maine's lake habitats had blood mercury concentrations most comparable to those reported from the Delaware / Catskill Region of New York (0.52 µg/g; DeSorbo *et al*. 2008) and Pinchi Lake British Columbia, Canada (0.57 µg/g; Weech *et al*. 2006). The Catskill region of New York is subject to high rates of atmospheric mercury deposition (Miller *et al*. 2005, VanArsdale *et al*. 2005), and was noted as an area of concern in a recent study delineating biological mercury hotspots in the northeastern U.S. and Canada (Evers *et al.* 2007). Pinchi Lake, B.C. is associated with cinnabar mercury deposits and mercury mining. Mean eaglet blood mercury concentrations at other lakes in the Canada study ranged from 0.20 – 0.42 µg/g. Mean mercury concentrations within several Maine watersheds were similar or exceeded those found at sites such as Pinchi Lake, B.C. (i.e., Saint John River = 0.55 µg/g, the Penobscot River = 0.66 µg/g, and the Saint Croix River = 0.70 µg/g). Watershed baselines are summarized later in this report.

Only Wiemeyer *et al*. (1989) reported blood mercury concentrations higher than those reported in Maine lakes and at Pinchi Lake, B.C., Canada; however, eaglets in that study are inappropriate comparisons to studies such as the present study targeting 6-week old eaglets due to differences

in eaglet age at the time of sampling. Several studies have demonstrated a dramatic influence of the feather molt on circulating blood mercury levels in developing nestlings (Frederick *et al*. 2002, Fournier *et al*. 2002, Kenow *et al*. 2003, Fevold *et al*. 2003, Condon and Cristol 2009). It can be inferred from these studies that eaglet blood mercury concentrations will increase after feather development slows or is completed in regions where mercury is elevated in the aquatic foodweb. Mercury concentrations in eaglets sampled in the Wiemeyer study from south-central Oregon (mean 1.20 µg/g, 7 – 11 weeks of age) and Montana (mean 1.50 µg/g, sampled after fledging) are likely to be higher due to this advanced sampling age combined with higher potential for mercury exposure in that region. Significant portions of the western U.S. and Pacific Canada are considered to lie within a "mercuriferous belt" of parent material that extends throughout that region (Jonasson and Boyle 1972, Wiemeyer *et al*. 1989). Mercury is likely made more bioavailable due to anthropogenic activities (e.g., mining, dredging) and other factors in these regions. In comparison, much of the mercury in biota from the northeastern U.S. originates from atmospheric sources (Miller *et al*. 2005, VanArsdale *et al*. 2005, Evers *et al*. 2007).

5.1.2 Adverse effect thresholds for mercury in eaglet blood. Adverse effect thresholds have not been established for mercury in bald eagle blood. The majority of studies documenting adverse effect thresholds in birds are specific to adult age classes, which are inappropriate comparisons to developing nestlings. Kenow *et al*. (2007) measured 0.66 µg/g blood mercury in 5-week old common loon chicks dosed with 0.4 µg/g mercury. That study suggested mercury exposure at 0.4 µg/g (the mercury concentration found in loon prey at low pH lakes) caused suppression of antibody-mediated immunity in loon chicks, and reduced variability in antibody response. Common loons and bald eagles likely differ in their sensitivities to mercury (Scheuhammer *et al*. 2008). Findings in this study may provide some insights on adverse effect thresholds in bald eagles.

5.2 Mercury Exposure – Adult Feather. Shed adult eagle feather mercury concentrations at 103 inland nesting territories ranged 7.5 to 93.0 µg/g (dw) (Table 2). Significantly higher mercury concentrations at lake compared to river habitats were detected ($p < 0.023$, Wilcoxon test). Feather mercury concentrations were highly variable in both habitat types. Differences are likely strongly influenced by variations in age among sampled individuals (i.e., bioaccumulation with age). Concentrations of mercury evident in adult bald eagle feathers in this study indicates a portion of the Maine population, particularly in lake habitats, is bioaccumulating mercury in their bodies to levels associated with adverse effects in other species such as common loons (i.e., Evers *et al*. 2008). Evers *et al*. (2008) reported that loons containing feather mercury concentrations >30 µg/g displayed a 10% annual increase in feather mercury. The findings of the Evers study and those reported here suggest that a portion of the eagle population in Maine may be accumulating mercury in their bodies at a rate that exceeds their natural mechanisms for elimination (i.e., feather molt, demethylation in liver and kidneys).

5.2.1 Geographic comparisons for adult bald eagle feather mercury. Mean mercury concentrations in bald eagle feathers from river (30.5 µg/g, n = 24) and lake (40.6 µg/g, n = 79) habitats in Maine are higher than many geographic comparisons in the United States and Canada (Figure 3). For comparisons in this study, feathers from captive birds, and populations in Alaska were considered to have background levels (8.1 µg/g). Populations in the Great Lakes (mean

21.1 µg/g, range: 3.6 – 48 µg/g) were considered elevated in Bowerman *et al*. (1994). Adult bald eagle feathers from eagles in Maine river habitats were most similar to freshwater-feeding bald eagles throughout inland New York (30.9 µg/g; DeSorbo *et al*. 2008). Similar to patterns observed in eaglet blood, mercury concentrations in feathers from Maine lakes were comparable to those found at Pinchi Lake; however, samples sizes of this tissue type in the Canada study were limited. A portion of sampled adult eagles in Maine have bioaccumulated mercury concentrations in their tissues to levels comparable to those found in various raptors in Sweden where alkylmercuric compounds were applied directly to the landscape (Berg *et al*. 1966, Westermark *et al*. 1975).

5.2.2 Adverse effect thresholds for mercury in adult bald eagle feathers. Adverse effect thresholds for mercury have not been established in bald eagle feathers. Scheuhammer (1991) suggested background mercury levels in raptors may range from 1 – 5 µg/g, and investigations of toxic effects may be warranted in birds when feather mercury concentrations exceeded 20 µg/g. Evers *et al.* (2008) reported mercury concentrations ≥ 40 µg/g in feathers was associated with increased asymmetry in bilateral flight feathers in common loons in the Northeastern U.S.; a population considered to be experiencing negative effects of mercury. The ability of birds to develop symmetric bilateral characters is considered an indirect measure of fitness (Clarke 1995). Berg *et al*. (1966) suggested 60 µg/g or less in feathers could cause sterility, but effects related to other contaminants (i.e., organochlorine compounds) are suspected to have influenced productivity (Bowerman *et al*. 1994). The high regional variability in mercury concentrations in adult feathers, as well as a lack of adverse effect thresholds for bald eagle feathers currently limits powerful interpretations of potential adverse impacts on adult bald eagles.

5.3 Mercury Exposure - Egg. Twenty-two abandoned or nonviable bald eagle eggs were collected from 16 territories during 2004-2006 (Table 3). Means at lake (0.42 µg/g, fww) and river (0.33 µg/g, fww) sites were not statistically compared due to limited river sample sizes.

5.3.1 Geographic comparisons for eagle egg mercury. Mercury concentrations in Maine eagle eggs in this study are higher than most available geographic comparisons in the continental U.S. (Wiemeyer *et al*. 1984, 1993). Wiemeyer *et al*. (1984, 1993) reported the following mercury concentrations in bald eagle eggs collected throughout the U.S (all concentrations in µg/g, fww): 0.06 (OH), 0.17 (OR), 0.13 (WI), 0.18 (AZ), and 0.41 (ME). Most other efforts to evaluate mercury concentrations in bald eagle eggs in Maine reported generally similar mean mercury levels compared to those documented in this study (Wiemeyer *et al*. 1984, 1993, Welch 1994). It would be inappropriate to make conclusions about spatial or temporal mercury trends in Maine by comparing egg mercury concentrations in this study to others without further controlling for habitat type.

5.3.2 Adverse effect thresholds for mercury in eagle eggs. Suggested adverse effect thresholds for mercury in bird eggs range from 0.50 to 1.3 µg/g. Wiemeyer *et al*. (1984, 1993) considered 0.50 µg/g to be the adverse effect threshold for eagles based on those established in mallards (*Anas platyrhynchos*) (Heinz 1979). However, assessments of mercury levels in hatching success in Wiemeyer's studies were noted to be highly confounded by other compounds, particularly DDE. More recently, others have proposed adverse effect thresholds of 0.80 µg/g in several wading bird species (Henny *et al*. 2002) and mallards (Heinz and Hoffman

2003). Eggs of different species differ in their sensitivity to mercury and piscivorous species may be more adapted to mercury compared to species with terrestrial-based diets (G. Heinz, pers. comm.). In a methylmercury egg dosing experiment with several bird species, two species of raptors – American kestrel and osprey - exhibited the highest sensitivity to mercury with LC_{50}s less than 0.25 µg/g (Heinz *et al*. 2009). However, they cautioned that injected mercury was more toxic to eggs than the same amount of mercury deposited naturally by the mother.

Evers *et al*. (2008) established an adverse effect threshold of 1.3 µg/g in common loons, which was similar to thresholds developed independently for the same species (Burgess and Meyer 2008). Limited evidence in Maine may suggest adverse effect thresholds for bald eagle eggs may be lower than those suggested for common loons (DeSorbo 2007). In this study, seven eggs representing five nesting territories (26%) exhibited mercury concentrations exceeding 0.50 µg/g, two eggs (two territories; 10%) exceeded 0.80 µg/g, and no territories exceeded 1.3 µg/g. If the adverse effect threshold for mercury in bald eagle eggs lies between 0.80 µg/g and 1.3 µg/g, it seems likely that some bald eagle eggs in Maine may occasionally fail to hatch as a result of elevated mercury concentrations.

5.4 Relationships between Bald Eagle Productivity and Tissue Mercury Concentrations.

5.4.1 Eaglet blood mercury vs. productivity. Weak (correlation coefficient range: -0.12 to -0.35) but statistically significant correlations were detected between mean 3-, 5-, and 10-year productivity (young fledged / occupied nest) and eaglet blood mercury concentrations (Tables 4 and 5). In general, blood mercury concentrations displayed a significant negative correlation with productivity in lake and river habitat types combined (Table 4) and exclusively lake habitats (Table 5). This relationship has not been detected in other eagle populations, and few populations of wild birds (Scheuhammer *et al*. 2007, Burgess and Meyer 2008, Evers *et al*. 2008). No eaglet blood mercury indices were significantly correlated with productivity in river habitats ($p > 0.05$). The majority of significant relationships detected between eaglet blood mercury and productivity retained significance after excluding territories with less than three years nest occupancy in 3, 5, and 10-year categories (noted by superscripts in Tables 4 and 5), suggesting that territories with few years occupancy are not strongly influencing relationships between productivity and mercury. Blood mercury indices that accounted for differences in chick age or weight generally resulted in stronger correlation coefficients and greater significance, potentially suggesting these variables are important.

5.4.2 Adult feather mercury vs. productivity. Mean adult shed feather mercury concentrations were not significantly correlated with 3-year ($p = 0.79$, $r = -0.027$), 5-year ($p = 0.87$, $r = -0.017$), or 10-year ($p = 0.58$, $r = 0.057$) productivity in a dataset of combined habitat types (Spearman Rank Correlation). No significant relationships were detected between shed feather mercury concentrations and 3-year ($p = 0.48$, $r = -0.21$), 5-year ($p = 0.51$, $r = -0.17$) and 10-year ($p = 0.45$, $r = -0.23$) productivity in lake habitats. No significant relationships were detected between shed feather mercury concentrations and 3-year ($p = 0.23$, $r = 0.29$), 5-year ($p = 0.41$, $r = 0.18$) and 10-year ($p = 0.6$, $r = 0.11$) productivity in lake habitats.

5.4.3 Egg mercury vs. productivity. Mean territory egg mercury concentrations were not related to mean 3-year ($p= 0.98$, $r = 0.007$), 5-year ($p = 0.98$, $r = 0.005$), or 10-year ($p = 0.98$, $r =$

-0.007) productivity means in the dataset of combined habitat types (Spearman Rank Correlation). No significant relationships were detected between egg mercury concentrations and 3-year ($p = 0.48$, $r = -0.21$), 5-year ($p = 0.51$, $r = -0.17$) and 10-year ($p = 0.45$, $r = -0.23$) productivity in lake habitats. A limited sample size of eggs in river habitats ($n = 3$) precluded assessments of relationships between mercury and productivity in river habitats.

5.5 Spatial Comparisons: Mercury among Watersheds. This study establishes mercury baselines for nestling eagle blood and shed adult feathers within watershed units in Maine. Watershed mercury data was not statistically compared for this report due to limited sample sizes in several watersheds (see DeSorbo 2007 for limited watershed mercury comparisons). Sampling opportunities were limited in some watersheds (i.e., southern Midcoast, inland Penobscot Bay area, Cobscook Bay) due to few active nesting territories and poor nesting success during 2004-2006 nesting seasons.

5.5.1 Watershed baselines: eaglet blood mercury. Mean eaglet blood mercury concentrations within watersheds ranged from 0.24 µg/g to 0.70 µg/g in lake habitats, and 0.30 µg/g to 0.58 µg/g in river habitats (Figure 4). The highest mean eaglet blood mercury concentrations occurred within the Saint Croix and Penobscot River Basins, and the lowest mean was for inland lakes within Midcoast Maine (Figure 5). Limited sample sizes in most watershed-habitat groups preclude robust evaluations or comparisons of eaglet blood mercury concentrations among watersheds in river habitats. Limited data from river habitats within watersheds suggested rivers within the Kennebec River watershed had lower mean blood mercury concentrations compared to others, while mercury concentrations in the remaining four watersheds ranged from 0.42 µg/g to 0.57 µg/g.

Patterns suggesting eaglet blood mercury concentrations are higher at lakes compared to rivers were evident within the Kennebec, Penobscot, and St. Croix watersheds. This pattern was not evident in the Androscoggin and Downeast watersheds; however, river sample sizes were limited in those regions. Given the variety of factors influencing higher mercury exposure at lakes discussed previously, the lack of differences between eaglet blood mercury concentrations at lake and river habitats in the Androscoggin and Downeast watersheds is peculiar. It is unknown whether apparent similarities in mercury exposure within these watersheds reflects additional mercury inputs into some rivers, increased mercury retention or production at some sites, or other factors.

5.5.2 Watershed baselines: adult feather mercury. Adult feather mercury concentrations in lake habitats within watersheds ranged from 30.7 µg/g to 70.7 µg/g, while means at rivers ranged from 13.2 µg/g to 30.2 µg/g (Table 6; note small sample sizes). Standard deviations were high within habitats in all watersheds, ranging from 12.1 µg/g to 34.4 µg/g (see earlier discussion regarding factors influencing mercury concentrations in adult feathers). It is currently premature to make comparisons of mean adult feather mercury concentrations among watersheds due to limited sample sizes. Consistent with habitat patterns observed in eaglet blood in this study, mean adult feather mercury concentrations were higher in lake versus river habitats where both habitat types were represented.

Watershed mercury patterns observed in adult feathers (Figure 6) did not closely mirror patterns observed in eaglet blood (Figure 5). For example, means and standard deviations for mercury concentrations in adult eagle feathers within the Kennebec and Penobscot River basin watersheds were similar, while mean eaglet blood mercury concentrations between these two watersheds differed significantly ($p < 0.05$; DeSorbo 2007). This finding suggests adults in all Maine watersheds are accumulating mercury in their bodies over time despite differences in immediate dietary exposure to mercury. Dissimilar patterns between eaglet blood mercury and adult feather mercury are likely influenced by the high variability of mercury among shed adult eagle feathers.

To what extent chronic mercury burdens could interfere with productivity of Maine's inland bald eagle population remains unknown. Barr (1986) suggested increased mercury concentrations could lessen territory fidelity in common loons; effects such as this would be difficult to detect on Maine's generally unmarked eagle population. Chronic mercury burdens in adult eagles are also likely influenced by eagle age (i.e., mercury accumulation with age), the number of years adults remain on territory, in addition to the habitat and watershed in which they feed (DeSorbo 2007). Changes in age structure or rapid territory turnovers may influence mercury exposure in adult bald eagle tissues.

5.6 Temporal Mercury Trends. Twenty-one territories (59 territory-years) were sampled for eaglet blood in both 1991-1992 (early period hereafter) and 2004-2006 (late period hereafter) (Figure 7). One nest (territory #14; Damariscotta Lake, Damariscotta), was detected as an outlier and excluded from further analyses. Major changes in the availability of alewife prey between the 1991 and 2005 sampling periods (Tom Squiers, Maine Dept. Marine Resources, pers. com.) supported exclusion of this territory. Log-transformed mercury data were normally distributed. Eaglet blood mercury concentrations were significantly higher in the late period compared to the early period (3-way ANOVA, $n = 59$, $R^2 = 0.65$; time period, $p = 0.034$). Habitat type also had a strong influence on mercury exposure in eaglets ($p \leq 0.0001$). There were no indications that any interactions between habitat and time period ($p = 0.15$) or differences among territories ($p = 0.89$) influenced blood mercury concentrations in eaglets.

Significant differences were not detected in least-squares geometric means of eaglet blood mercury concentrations between time periods within lacustrine ($p = 0.50$) or riverine ($p = 0.125$) habitat types (Table 7; Bonferroni pairwise comparisons). Comparisons indicated significantly higher blood mercury concentrations at lakes vs. rivers in both early ($p \leq 0.001$) and late ($p \leq 0.001$) periods.

The temporal comparisons do not suggest evidence of declining bioavailability of mercury among freshwater-feeding bald eagles based on nesting habitats in Maine since 1992. The 3-way ANOVA analysis in this study that pooled habitat types and included several variables suggests mercury concentrations in eaglet blood may have increased between the two periods. However, temporal differences were not significant in pairwise comparisons of eaglet blood mercury concentrations within the two habitat types.

The ability to detect large-magnitude changes in mercury in the environment using birds and fish as biomonitors has been demonstrated (e.g., Berg *et al*. 1966, Westermark *et al*. 1975, Hrabik and Watras 2002, Frederick *et al*. 2002, Odsjo *et al*. 2004, Evers *et al*. 2007). Declines in

mercury emissions may not always reflected in biota due reflecting the overarching influence of site-specific factors influencing the transport, methylation, retention, and bioaccumulation of mercury that vary among sites (Effler 1996, Wiener *et al*. 2003, Driscoll *et al*. 2007, Evers *et al*. 2007, Munthe *et al*. 2007).

The suggestion of the analysis in this study that mercury bioavailability to bald eagles may have increased between the two time periods studied is contrary to patterns observed in atmospheric deposition and other measures. Data collected at four atmospheric monitoring stations located throughout Maine indicate a 1.7% - 1.8% annual decline in wet atmospheric deposition over the approximate period of 1996 - 2007 (David Gay, Maine Deposition Network, pers. com, http://nadp.sws.uiuc.edu/). Long-term mercury deposition trends indicated by analysis of sediment cores in New Hampshire, Vermont, and Maine also suggest evidence of declines in atmospheric deposition (Kamman and Engstrom 2002, Kamman *et al*. 2005a). Interpretations of limited temporal analyses of mercury patterns in fish in northeastern North America (generally collected 1981 – 2003) are unclear, with mercury increases evident at some sites and decreases in others, and no apparent temporal trend overall (Kamman *et al*. 2005b; N. Kamman, pers. com.). Similar patterns of increasing mercury concentrations at some sites and decreases at others were found in eaglet blood mercury levels this study, and have been similarly noted elsewhere in other species (e.g., Johansson *et al*. 2001, Frederick *et al*. 2002, Rasmussen *et al*. 2007). It is possible that declines in dry and wet mercury deposition at the scale suggested by atmospheric monitoring may not be of a sufficient magnitude or duration in order to be detected in aquatic biota.

Limited sample sizes reduce our certainty in drawing powerful conclusions based on this temporal mercury dataset. The suggestion that mercury concentrations in eaglet blood have increased over the study period are of particular relevance to inland eagle populations in Maine because mercury levels are higher in Maine compared to many other populations, and adverse effect thresholds are lacking for this species with regard to mercury. Short-term growth of eagle nesting numbers inland is not grounds to speculate that mercury contamination is not a long-term limiting factor for eagle recovery in interior Maine. The substantial mercury datasets developed during this study will enable more robust evaluations of temporal mercury trends in Maine in the future.

6. Summary and Management Recommendations

6.1 Summary. This study indicates bald eagles in Maine continue to accumulate mercury, sometimes in significant amounts. Specific findings of this study include:

● Prevalence of mercury in eaglet blood indicates mercury is being ingested and accumulated via the diet, which in inland Maine is primarily fish.

● Analysis of mercury in adult feathers indicates a portion of adult bald eagles in Maine are accumulating mercury to or beyond levels associated with adverse impacts in other species such as common loons. Annual accumulation of mercury in some adults may outpace natural mechanisms of elimination that provide protective effects from adverse impacts.

● Analyses of mercury in abandoned and nonviable bald eagle eggs suggests eggs in inland Maine may occasionally fail to hatch due to mercury.

● Mercury concentrations in adult and eaglet tissues from inland Maine, particularly at lakes, are higher than most geographic comparisons, and often most similar to regions associated with notable mercury pollution problems.

● Lacking adverse effect thresholds for this species in all tissues analyzed limit our ability to fully assess the extent of exposure within the inland population.

● Findings of a weak, but statistically significant negative correlation between eaglet blood mercury and productivity in this study suggest mercury may be slowing the recovery of bald eagles in interior Maine despite evidence of overall population growth at the statewide level (8% annual growth rate; Todd and Matula 2008).

● Baselines of mercury exposure in 10 inland Maine watersheds were established through this study. While further sampling is needed to adequately assess mercury in some watersheds-habitat combinations, analyses suggest mercury exposure is highest in the Saint Croix River and the Penobscot River Basins, and is the lowest in Midcoast region lakes and river habitats within the Kennebec River Basin.

● Comparisons of mercury concentrations in eaglet blood between sampling conducted in this study (2004-2006) to those sampling previously in 1991 and 1992 by Welch (1994) did not suggest bioavailability of mercury to eagles has declined between early and late periods. Rather, this limited dataset suggests mercury may have increased between the two periods, particularly in river habitats. These findings are contrary to evidence of temporal mercury trends suggested by atmospheric monitoring. Small sample sizes limit our ability to make strong conclusions from this dataset; however, and those indications emphasize the importance of long-term mercury monitoring in biota.

● Laboratory dosing studies have established that mercury increases in the blood of developing eaglets after the completion of feather development due to the cessation of this excretory route for ingested mercury. This fact may be of importance for a portion of eaglet eagles in inland Maine that continue to be exposed to high mercury levels via their diet during and after fledging. It is at this stage that the neurotoxicological effects of mercury may be most evident. However, our study does not document juvenile survival beyond fledging.

● The potential effects of chronic mercury burdens in adult bald eagles is of concern for Maine's inland population, particularly those dwelling at lakes in high-risk regions. Mercury has been implicated in negatively affecting territorial fidelity, and such impacts would be very difficult to detect in Maine's generally unmarked bald eagle population. The fact that mercury has been found to negatively affect productivity, behavior, and physiology of other piscivorous wildlife in Maine (i.e., common loon) should raise concerns regarding the potential effects of mercury on bald eagles and other piscivorous wildlife in the region.

6.2 Management Implications and Recommendations. Evidence of continuing population expansion in Maine's bald eagles, the 2007 removal of the bald eagle from the federal Endangered Species List, and the pending proposal to delist bald eagles from the Maine State list (Todd and Matula 2008), should not obviate management or policy significance of the findings of this study.

Maine's eagle population has significant biological relevance to populations in other regions. Maine is the stronghold for bald eagles breeding in the Northeastern U.S. The state's population constitutes 71% of the resident totals for New England and New York (M.J. Amaral, USFWS, pers. comm.) Over time, Maine's bald eagle population may increasingly contribute to recruitment in neighboring areas.

Information gathered on contaminant burdens in Maine's bald eagles used to evaluate potential health risks to eagles in this study have been used to assess: (1) geographic contaminant patterns (e.g., biological mercury hotspots, Evers *et al.* 2007), and (2) temporal contaminant patterns in Maine (DeSorbo 2007). Contaminant assessments in bald eagles can also be used to evaluate potential toxicological risks to other piscivores (e.g., Evers *et al*. 2007).

The banding of 304 eaglets during this study will have long-term utility for learning about Maine's bald eagle population. These color-banded, known-aged individuals can provide additional insights on behavior, dispersal, and contaminant uptake (i.e., resampling blood/feather tissues) over time.

The following recommendations are based on findings in this study of mercury in the inland bald eagle population of Maine.

6.2.1 Regulating mercury inputs - Findings in this study are consistent with others indicating mercury is prevalent throughout many of Maine's freshwater habitats, often at levels that meet or exceed those recorded for other regions in North America. Given the persistent nature of mercury, and a general abundance of habitats in Maine that can effectively produce methylmercury from mercury inputs (Evers *et al*. 2007, 2008), proactive steps should be taken to control both point and nonpoint source mercury inputs into the landscape at local, regional, national, and global levels.

Point sources: Point sources (legacy and current) still contribute mercury to Maine ecosystems. Examples of point sources include chemical plants, paper mills, landfills, tanneries, power plants, and waste incinerators. Compared to many states, Maine has a particularly aggressive regulatory policy towards reducing local and state mercury emissions and mercury in the waste stream. The extent of mercury pollution and potential for adverse impacts on wildlife is currently being investigated in some locations (e.g., the former Holtra-Chem chlor-alkali plant on the Penobscot River in Orrington, ME). However, there is currently no comprehensive, spatially-explicit database of potential and known mercury sources to Maine's waterways. Such a resource would improve researchers' ability to interpret spatial mercury patterns observed in water, fish and wildlife throughout the state.

Nonpoint sources: The primary source of mercury to the northeastern U.S. is considered to be atmospheric (Evers and Clair 2005, Miller *et al*. 2005, VanArsdale *et al*. 2005, Driscoll *et al*. 2007, Evers *et al*. 2007). At present, there is currently no standard for mercury emissions at the federal level, and some U.S. states still do not regulate mercury emissions. Therefore, ineffective or nonexistent mercury emission policies in states "upwind" may result in significant mercury inputs into Maine's landscape.

Recommendation - Point and Nonpoint Sources: Many state and federal agencies have developed separate comprehensive, spatially-explicit databases of potential and known mercury sources. These databases should be linked to existing wildlife mercury databases to identify specific current or legacy point sources that may be affecting biota. Atmospheric transport and marked mercury residues in Northeast biota should be major considerations during the development or re-authorization of environmental policy and legislation.

6.2.2 Conduct long-term mercury monitoring studies to evaluate temporal contaminant trends - Findings from this study do not demonstrate any significant reduction of mean dietary exposure to mercury since 1992 as measured in eaglet blood. Limited comparisons from a subset of riverine samples in this study suggest mercury bioavailability to eagles may have increased over the period, and temporal mercury patterns may vary regionally. Due to the marked expansion of eagle nesting territories inland in recent years, mercury exposure indicated by adult feathers may not yet reflect the full potential of prolonged chronic exposure. This consideration provides strong justification for periodic monitoring given the notable persistence of mercury in the environment.

Recommendation - Monitoring: Periodic sampling of eaglets, shed adult feathers, and nonviable or abandoned eggs at approximately 10 - 15 year intervals in Maine is recommended to monitor temporal trends in mercury and other contaminants of concern. Parallel efforts to periodically monitor mercury concentrations in fish and other piscivores are also recommended. Long-term programs to monitor bioavailability of heavy metals and organic pollutants to high trophic level predators such as bald eagles are established in midwestern U.S. states (i.e., Bowerman *et al*. 2002, Roe 2004), and can serve as a template for long-term monitoring programs in Maine. The establishment of such monitoring programs is particularly relevant in northeastern U.S. states given knowledge of west to east patterns of atmospheric transport of airborne pollutants (Miller *et al*. 2005, VanArsdale *et al*. 2005).

6.2.3 Refining mercury baselines and evaluations of mercury risk to wildlife in Maine's watersheds. This study and related Master's thesis (DeSorbo 2007) are the first to compare mercury concentrations in lake- and river-feeding bald eagles among discrete hydrological units (major watersheds) within Maine. The present study design has been used as a basis for a similar mercury assessment in New York (DeSorbo *et al*. 2008). Findings from the present study suggest bioavailability of mercury to eagles in some watersheds, such as lake habitats in the Saint Croix and Penobscot River watershed basins, may exceed levels of concern. Spatial variations in mercury exposure are a potential consideration for state and federal regulators when issuing discharge permits and impoundment licenses. While sampling intensity and geographic coverage in this study are substantial given annual available sampling opportunities, increased sample sizes of lake and river habitats within some major watersheds are needed to properly

assess spatial- and habitat-based mercury patterns throughout Maine. This information would be valuable in designating regions in which mercury is most prevalent and wildlife populations may be at higher risk to adverse mercury effects, as well as determining which areas can serve as reference regions in future toxicological investigations. In some large watersheds, evaluations of mercury at a level of higher resolution (i.e., subdrainage level) are appropriate (i.e., DeSorbo and Evers 2007).

Recommendation – Baselines and Risk: Additional sampling efforts in lake and river habitats in watersheds in which habitat-specific sample sizes limit statistical comparisons is recommended. Specifically, increasing sample sizes of mercury baselines in Southern Maine (Saco, Presumpscot, Androscoggin), river samples in the Downeast and Saint Croix watersheds, and northernmost portions of the state (St. John Basin) would be valuable. A target sample size of 12 nests per river basin (6 nests per habitat type) is recommended. Continued recovery and range expansion of Maine's eagle population should improve future sampling opportunities.

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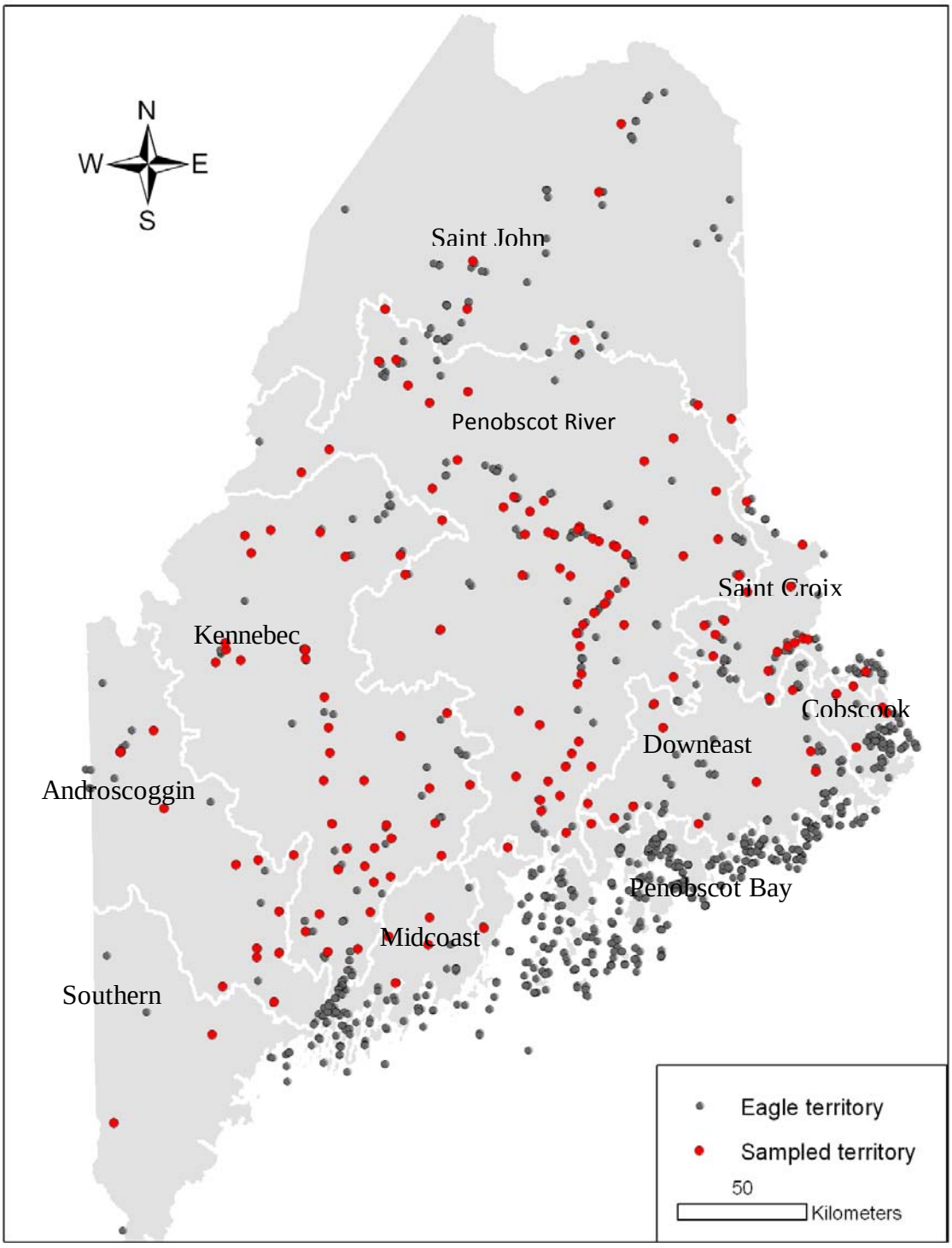
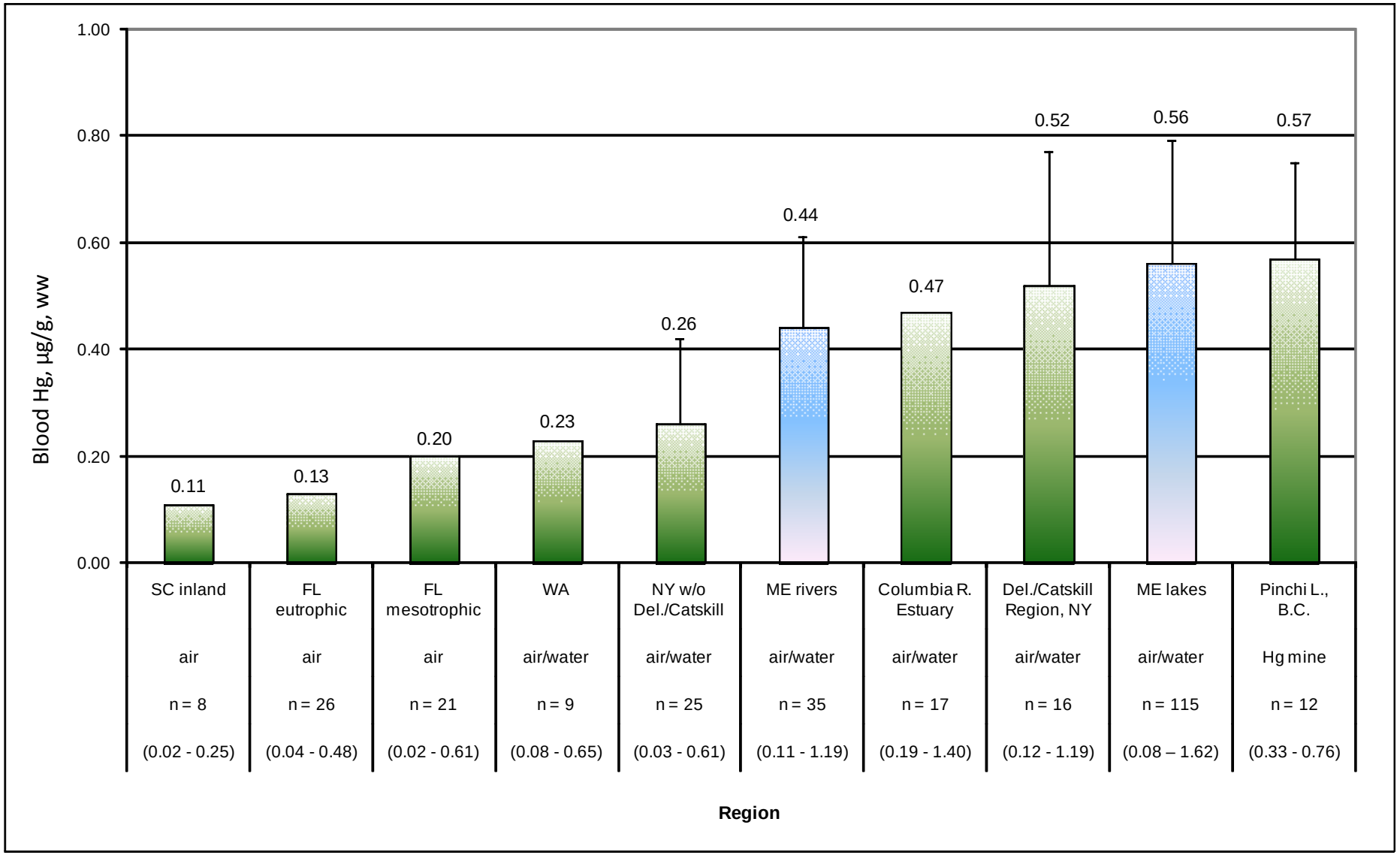


Figure 1. Bald eagle nest territories sampled for eaglet blood (n = 150) in ten major watersheds in interior Maine, 2001 - 2006. Watershed boundaries delineated in white.

Figure 2. Blood mercury concentrations in eaglets from Maine and geographic population comparisons.



Means over each bar. Error bars represent standard deviations and were not available all regions. Sample sizes represent number of territories. Siblings and repeat sampling between years are averaged/nest. Regions from left to right: South Carolina inland (Jagoe et al. 2002; range reflects inland and marine nests), Florida eutrophic and mesotrophic lakes (Wood et al. 1996); Washington State (Wiemeyer et al. 1989); NY w/o Catskills = nests sampled throughout NY state, excluding those in the Catskills Region. Maine Maine rivers, this study; Columbia River Estuary (Anthony et al. 1993) a site associated with extensive Hg point source pollution inputs likely exacerbated by numerous anthropogenic activities (e.g., dredging, hydroelectric dams); Delaware / Catskill region, NY, (DeSorbo et al. 2008; an area considered an area of concern to Hg due to increased Hg deposition); Maine lakes, this study; Pinchi Lake, BC, Canada, (Weech et al. 2006; a site associated w/ a Hg mine.

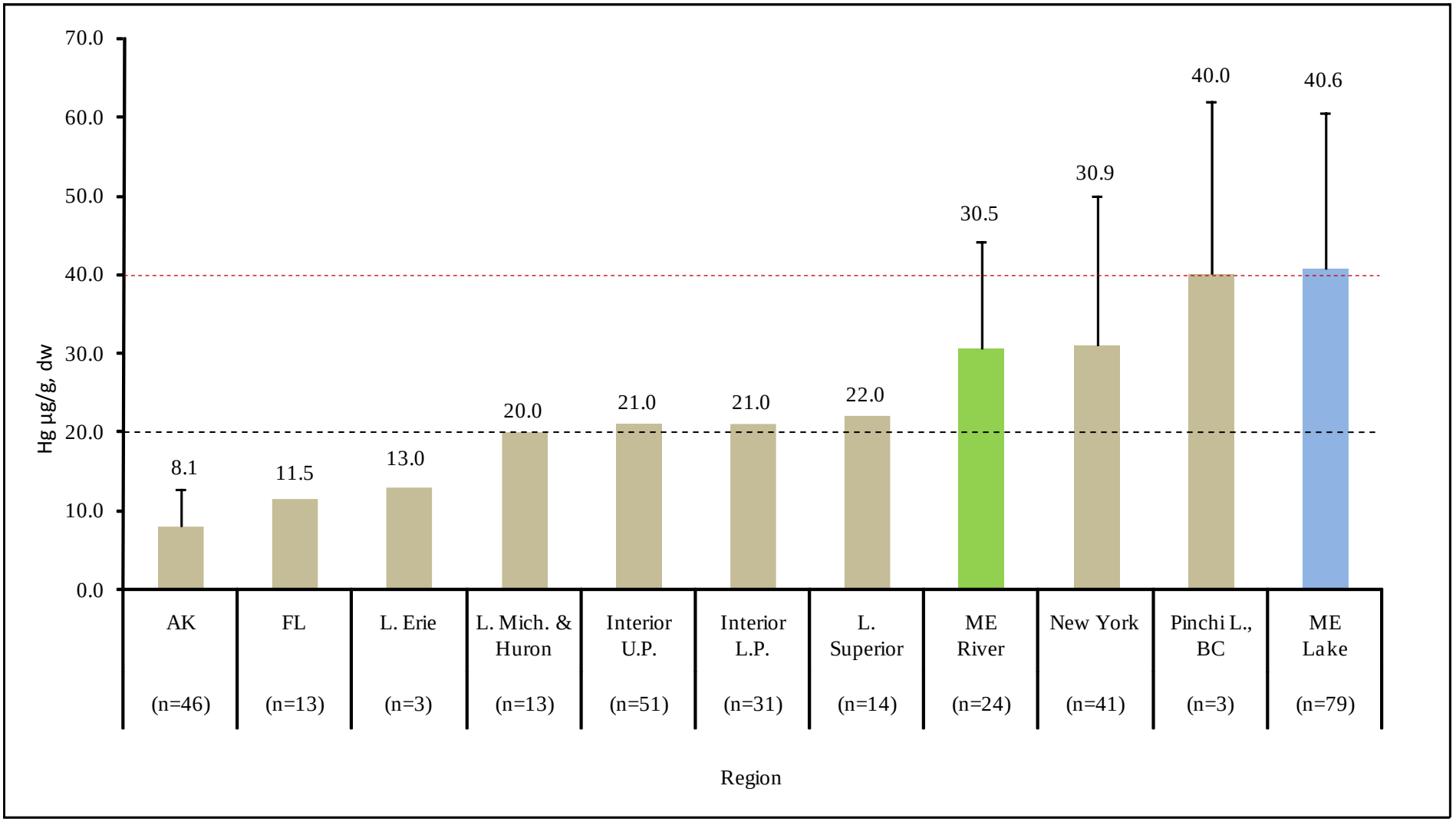
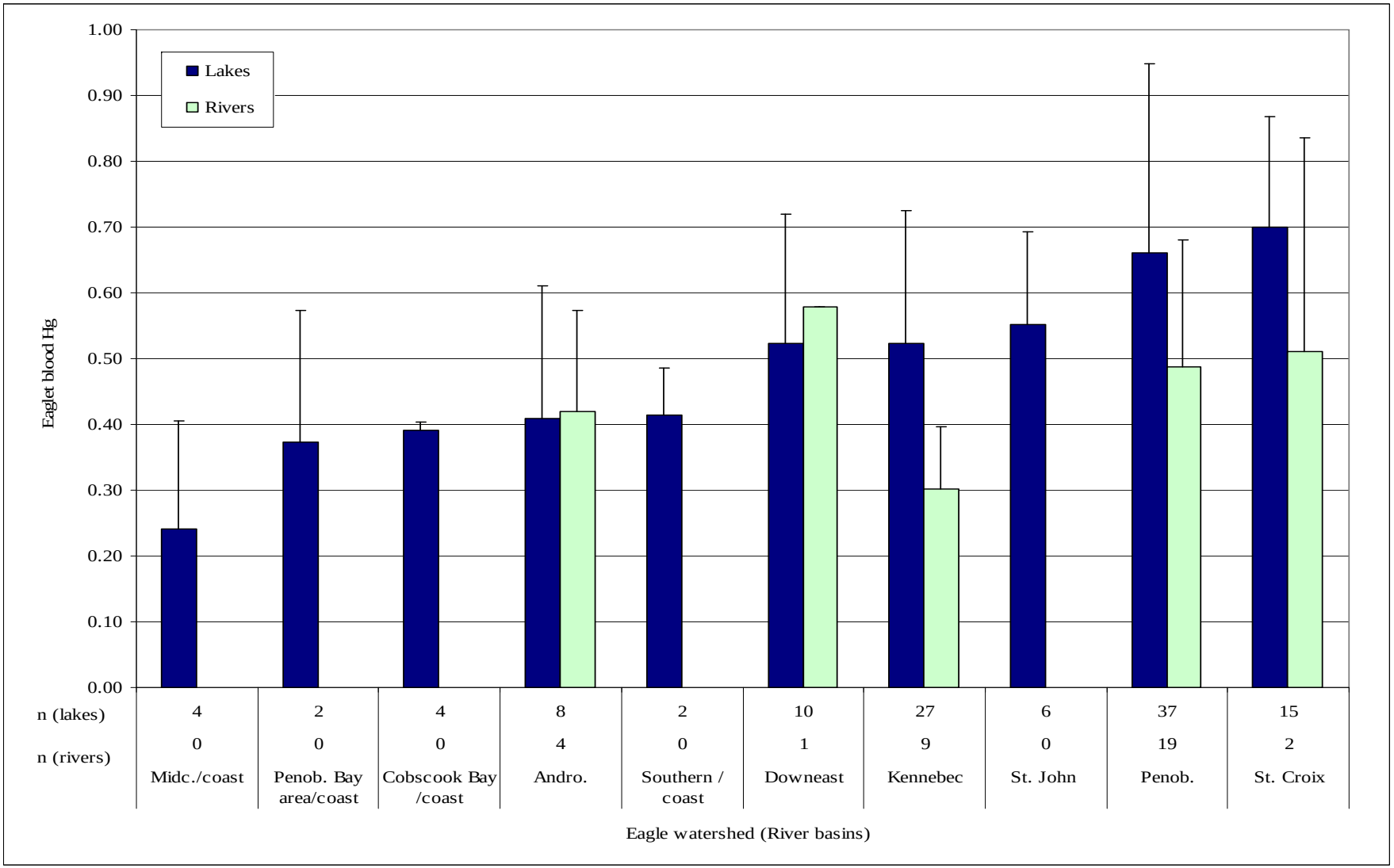


Figure 3. Mercury concentrations in adult bald eagle feathers in Maine and geographic comparisons throughout North America.

Means over bars. Error bars (SD) given when available. Sample sizes (no. territories) in parentheses. Lower dotted line at level at which Scheuhammer (1991) suggests toxic investigations on bird populations should be investigated. Upper dotted line represents level at which: (1) Evers *et al*. (2008) found evidence of links between Hg and flight feather symmetry in adult common loons, in population shown to display reproductive impacts from Hg, and (2) Spaulding *et al*. (2000) detected negative effects in juvenile egrets dosed with 0.5 µg/g Hg. Comparison populations include: AK, (Evans 1993, Alaska, range: 1 – 20 µg/g); Florida (Wood *et al*. 1996; range: 2.01-34.7 µg/g). All Midwest comparisons from Bowerman *et al*. (1994): Lake Erie, range: 9-19 µg/g; Lake Michigan/Huron: range: 7.2 – 40 µg/g; Interior Upper Penninsula, Michigan, range: 0.2 – 66 µg/g; Interior Lower Penninsula, Michigan, range 6.1-62 µg/g; Lake Superior, Wisconsin, range, 5.9 – 38 µg/g; Maine river (this study); New York, (DeSorbo *et al*. 2008; range 5.7 – 77.9 µg/g); Pinchi Lake, BC, (Weech *et al*. 2006; range 24 – 65 µg/g; Hg mine point source); Maine Lakes (this study).

Figure 4. Eaglet blood mercury exposure in 10 Maine watersheds.

Eaglet blood mercury levels (µg/g, ww) averaged for siblings and between years at repeat sample sites (2001-2006; primary sampling 04-06).



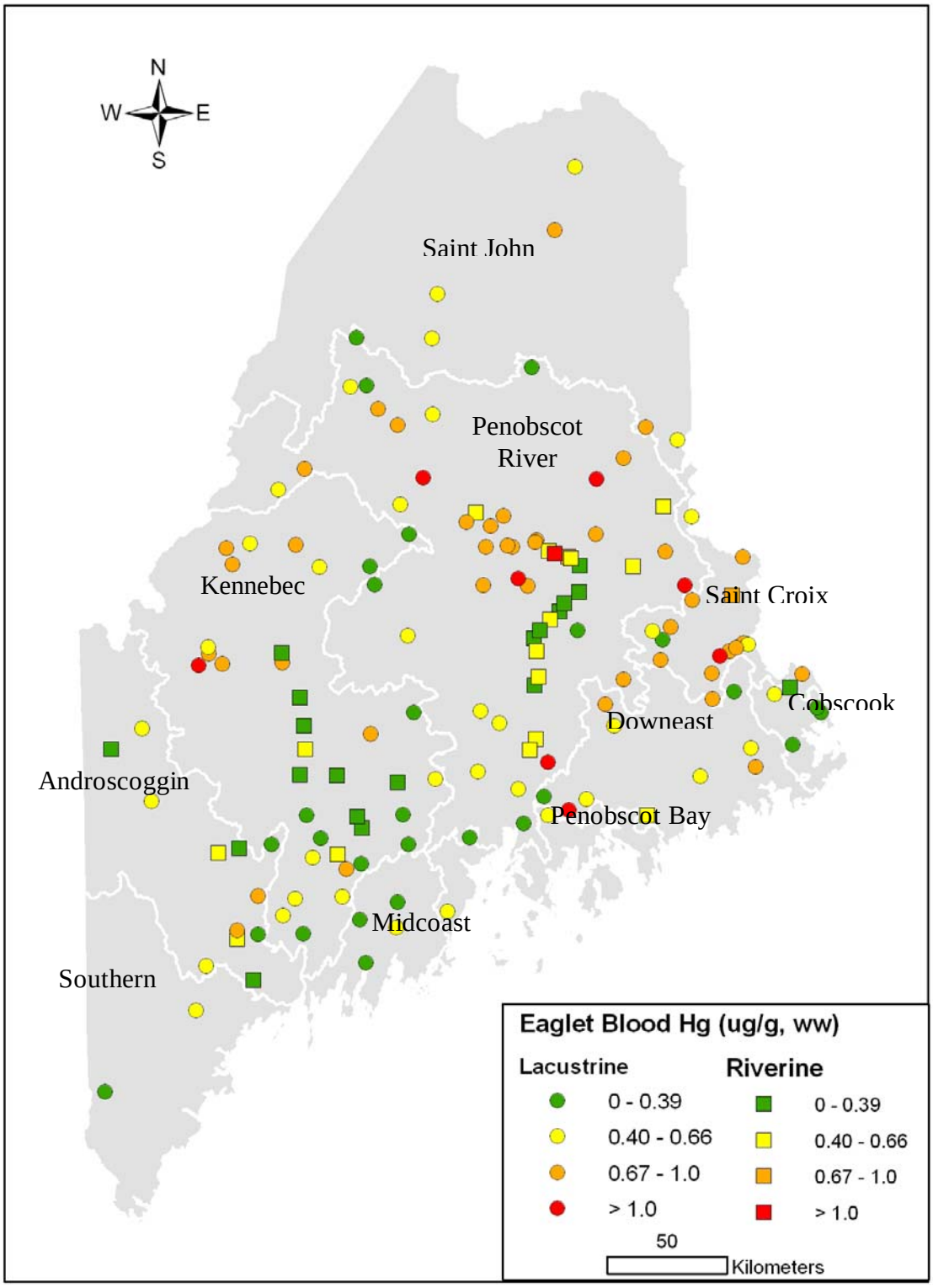


Figure 5. Map of mean blood mercury concentrations in eaglets sampled in ten major watersheds in interior Maine, 2001-2006 (n = 150 territories). Watershed boundaries delineated in white

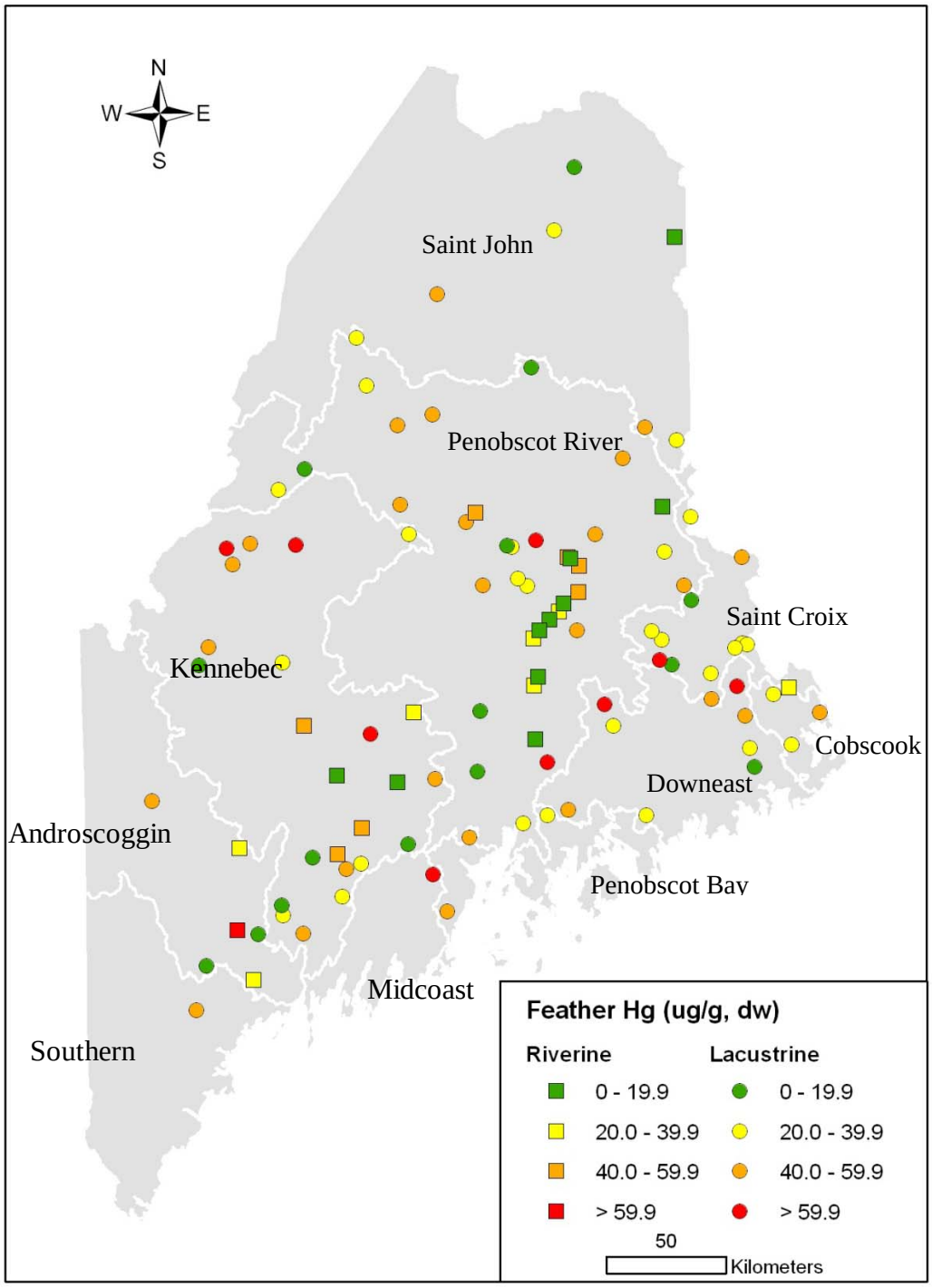


Figure 6. Map of feather mercury concentrations in shed adult bald eagle feathers collected from 103 nesting territories in ten major watersheds in interior Maine, 2001-2006.

Table 1. Mean blood mercury concentrations (µg/g, wet weight) in eaglets sampled in two habitat types in Maine.

Habitat Type	n	Blood Hg [a]	SD	Range [b]
Lacustrine	115	0.56	0.24	0.08 - 1.62
Riverine	35	0.44	0.18	0.11 – 1.19
BOTH	150	0.53	0.24	0.08 - 1.62

[a] Means and sample sizes reflect territory averages (i.e., siblings averaged / nest; nests sampled in multiple years averaged).
[b] Range reflects Hg concentrations in individual eaglets.

Table 2. Mean mercury concentrations (µg/g dry weight) in shed adult bald eagle feathers collected in two habitat types in Maine.

Habitat type	n [a]	Mean [b]	SD	Range
Lacustrine	79	40.6	20.0	7.5 – 93.0
Riverine	24	30.5	13.7	13.2 – 59.2
BOTH	103	38.3	19.2	7.5 – 93.0

[a] Denotes sample size of distinct bald eagle nesting territories.
[b] Habitat means are significantly different ($p = 0.023$, Wilcoxon test). Mercury concentrations for multiple feathers (collected in different years) were averaged at 29 territories. At total of 134 individual feathers were analyzed.

Table 3. Mean mercury concentrations (µg/g fresh wet weight) in bald eagle eggs collected in two habitat types in Maine, 2004-2006.

Habitat type	n [a]	Mean [b]	SD	Range
Lacustrine	13	0.42	0.25	0.09 – 0.90
Riverine	3	0.33	0.14	0.17 – 0.44
BOTH	16	0.40	0.24	0.09 – 0.90

[a] Denotes sample size of distinct bald eagle nesting territories.
[b] Means not statistically compared due to limited riverine sample size. Mercury concentrations were averaged within a clutch (territory #412, 2005; territory #141, 2006) and at territories sampled in multiple years. At total of 22 individual eggs were analyzed. All individual egg Hg concentrations were within ranges noted in table.

Table 4. Relationships between 3-, 5-, and 10-year productivity measures and 3 indexes of mean eaglet blood mercury concentrations (µg/g wet weight) at freshwater nesting territories (lake and river habitats combined).

Hg index	3-yr productivity	5-yr productivity	10-yr productivity
Hg (no index)	r = -0.13 (0.11) [a]	r = -0.31 (0.0001) [a]	r = -0.26 (0.0014) [a]
Hg/age	r = -0.21 (0.017) [a]	r = -0.34 (0.0001) [a]	r = -0.33 (0.0001) [a]
Hg/weight	r = -0.16 (0.052) [a]	r = -0.29 (0.0004) [a]	r = -0.28 (0.0006) [a]

Spearman's Rho correlation coefficient and significance (in parentheses) for eaglet blood Hg exposure vs. 3-, 5-, and 10-year productivity (young fledged/occupied nest).

[a] Relationships remained or became significant at p = 0.05 after removing territories occupied <3 years from 3-, 5-, and 10-year datasets.

Table 5. Relationships between 3-, 5-, and 10-year productivity measures and 3 indexes of eaglet blood mercury concentrations (µg/g wet weight) in lake nesting territories.

Hg index	3-yr productivity	5-yr productivity	10-yr productivity
Hg (no index)	r = -0.12 (0.20)	r = -0.32 (0.0004) [a]	r = -0.25 (0.0068) [a]
Hg/age	r = -0.23 (0.022) [a]	r = -0.35 (0.0003) [a]	r = -0.34 (0.0005) [a]
Hg/weight	r = -0.16 (0.09) [a]	r = -0.31 (0.0007) [a]	r = -0. 30 (0.0012) [a]

Spearman's Rho correlation coefficient and significance (in parentheses) for eaglet blood Hg exposure vs. 3, 5, and 10-year productivity (young fledged/occupied nest).

[a] Relationships remained or became significant at p = 0.05 after removing territories occupied <3 years from 3-,5-,10- yr datasets.

Table 6. Mercury concentrations (µg/g dry weight) in adult bald eagle feathers collected in two habitat types within 10 Maine watersheds.

	Lacustrine			Riverine		
Watershed	n	Mean	SD	n	Mean	SD
Saint John River basin	5	30.7	13.8	1	13.2	
Cobscook Bay area coastal waters	3	36.0	17.7			
Saint Croix River basin	12	37.6	19.2	2	13.6	17.2
Penobscot River basin	24	40.1	18.3	14	30.2	13.5
Kennebec River basin	19	40.9	22.8	5	34.9	19.3
Downeast river basins	8	43.0	20.6	1	34.5	.
Androscoggin River basin	4	46.2	34.3	2	31.0	3.4
Penobscot Bay area	2	51.6	12.1			
Southern river basins	1	57.0				
Midcoast river basins	1	70.7				

Table is sorted by increasing feather Hg in lacustrine sites.

Table 7. Least-squares geometric means of eaglet blood mercury concentrations (µg/g, wet weight) in two habitats and time periods.

Period	Lacustrine	Riverine
1991-1992	0.62 (0.57-0.67; 15) [a]	0.26 (0.23-0.29; 6)
2004-2006	0.67 (0.61-0.73; 15)	0.39 (0.34-0.46; 6)

[a] Asymmetric upper and lower standard errors and sample sizes given in parentheses. Between-period differences within each habitat type were not significant at $p < 0.05$ (Bonferroni paired comparisons). Means within rows were significantly different (see text).