Environ Monit Assess (2010) 171:671–679
DOI 10.1007/s10661-010-1312-z

Mercury concentrations in tidal marsh sparrows and their use as bioindicators in Delaware Bay, USA

Sarah E. Warner · W. Gregory Shriver · Margaret A. Pepper · Robert J. Taylor

Received: 23 July 2009 / Accepted: 15 January 2010 / Published online: 5 February 2010

Abstract Mercury (Hg) contamination from industrial sources is pervasive throughout North America and is recognized by the US Environmental Protection Agency as a health hazard for wildlife and humans. Avian species are commonly used as bioindicators of Hg because they are sensitive to contaminants in the environment and are relatively easy to sample. However, it is important to select the appropriate avian species to use as a bioindicator, which should be directly related to the project objectives. In this study, we tested the utility of two tidal marsh sparrows, Seaside (*Ammodramus maritimus*) and Saltmarsh (*Ammodramus caudacutus*) sparrows, as bioindicator species of the extent of Hg contamination in tidal marshes along the Delaware Bay. To determine the possibility of using one or both of these species, we estimated sparrow blood Hg burden in five Delaware watersheds. We found no difference in Hg concentrations between species ($F_{1,133} < 0.01$, $P = 0.99$), but Saltmarsh Sparrows had limited sample size from each site and were, therefore, not appropriate for a Delaware Bay-wide Hg indicator. Seaside Sparrows, however, were abundant and relatively easy to sample in the five watersheds. Seaside Sparrow blood Hg levels ranged from 0.15 to 2.12 ppm, differed among drainages, and were greatest in two drainages distant from the Delaware Bay shoreline ($F_{4,95} = 2.51$, $P = 0.05$). Based on a power analysis for Seaside Sparrow blood Hg, we estimated that 16 samples would be necessary to detect differences among sites. Based on these data, we propose that Seaside Sparrows may be used as a tidal marsh Hg bioindicator species given their habitat specificity, relative abundance, widespread distribution in marsh habitats, ease of sampling, and limited variation in blood Hg estimates within a sampling area. In Delaware Bay, Saltmarsh Sparrows may be too rare (making them difficult to sample) to be a viable tidal marsh Hg bioindicator.

Keywords *Ammodramus* · Bioindicators · Delaware Bay · Mercury · Tidal Marsh

S. E. Warner · W. G. Shriver (✉) · M. A. Pepper
Department of Entomology and Wildlife Ecology, University of Delaware, Newark, DE 19717, USA
e-mail: gshriver@udel.edu

R. J. Taylor
Trace Element Research Lab, Texas A&M University, College Station, TX 77843, USA

Introduction

Mercury (Hg) is widespread in the environment, originating from non-point and point sources such as coal-fired plants, industrial boilers, incinerators, and chlorine-manufacturing plants (NWF 2005; USEPA 1997, 2000). In 2004, 44 US states had fish consumption advisories due to Hg-contaminated landscapes (Driscoll et al. 2007). The northeast has especially high levels of Hg (Driscoll et al. 2007; Evers et al. 2007), and contamination in Delaware is pervasive and widely acknowledged by the United States Environmental Protection Agency (USEPA 2000), the Delaware Department of Natural Resources and Environmental Control (DNREC 2008), and the National Oceanic and Atmospheric Administration (NOAA 2001). The combined emissions from seven polluting industries in Delaware totaled 691 kg/year in 2002 (DNREC 2002). Given the Hg inputs and the extent of potential Hg methylation in Delaware, increasing our understanding of the distribution of Hg contamination is necessary to prioritize areas for potential restoration and to determine the effects of this persistent heavy metal on Delaware's natural heritage.

Once deposited in the environment, microbial processes convert elemental Hg to methylmercury (MeHg), which can be toxic to organisms (National Academy of Sciences 2000; Scheuhammer et al. 2007; USEPA 1997). Methylmercury bioaccumulates in animals and biomagnifies up food webs (Burgess 2005; Chen et al. 2009; Cumbee et al. 2008). Horne et al. (1999) showed a positive relationship between Hg in salt marsh sediment and Hg in marsh benthic invertebrates, and Cristol et al. (2008) indicated that invertebrates low on the food web had decreased levels of Hg compared to invertebrates higher up the food web. The transformation of elemental Hg to biotoxic MeHg is especially efficient in wetlands where sulfate reducing bacteria in soil in combination with other interactions makes the environment favorable to Hg methylation (Compeau and Bartha 1985). Nearly 30% of Delaware is classified as estuarine or palustrine wetland (Tiner 2001).

Birds have been used as indicators for a number of environmental contaminants such as DDT, pesticides, and heavy metals and are frequently used in toxicology research (Furness and Greenwood 1993; Novak et al. 2006; Rattner et al. 2008). Birds are particularly useful bioindicators because many are habitat-specific, sensitive to toxins, and high on the food chain (Brasso and Cristol 2007; Burger 1993; Evers et al. 2008; Gochfeld et al. 1996; Mason et al. 2005; Rimmer et al. 2005; Thompson et al. 1991). Birds uptake Hg from the environment primarily through their diet; therefore, Hg in the blood can be used to identify an individual's exposure via short-term dietary uptake (Bearhop et al. 2000) and correlates with levels found in internal tissues (Kenow et al. 2007).

Mercury accumulation affects insectivorous birds, not just piscivorous birds like loons, herons, and some waterfowl as previously documented (Cristol et al. 2008). Passerines that have been shown to carry significant levels of Hg include Bicknell's Thrush (*Catharus bicknelli*) 0.46 ug/g (Rimmer et al. 2005), Saltmarsh Sparrows (*Ammodramus caudacutus*) 1.26 ppm, Nelson's Sparrows (*A. nelsoni*) 0.74 ppm (Shriver et al. 2006), and female Tree Swallows (*Tachycineta bicolor*) 3.56 ppm (Brasso and Cristol 2007). The effects from Hg toxicity include disruptions to neurological systems (Evers et al. 2008), embryonic development (below 1.0 ppm in eggs) (Heinz 2003), and organ biochemistry (Hoffman et al. 2005), which can negatively influence reproductive success and, therefore, reduce fecundity. For example, elevated Hg levels in the fish-eating Common Loon (*Gavia immer*) have negative effects on reproductive success involving reduced egg production (Barr 1973) and abnormal incubation behavior (Evers et al. 2008).

Tidal marsh breeding sparrows are specialists and can be used as indicator species for coastal marsh integrity due to their specific habitat requirements (Post and Greenlaw 1994). Seaside (*Ammodramus maritimus*) and Saltmarsh sparrows are predominantly insectivorous and are tidal marsh obligates. The specific habitat requirements of these sparrows make them sensitive to habitat alterations such as marsh ditching (Austin 1983; Greenlaw 1992), water table manipulations (Walters 1992), rising sea levels (Shriver and Gibbs 2004), fire management (Curnutt et al. 1998; Taylor 1983; Werner 1975), and possibly, Hg contamination (Shriver et al. 2006). Seaside and Saltmarsh sparrows breed sympatrically, have similar diets, are site-tenacious, complete their entire annual cycle in salt marsh ecosystems, are long lived, and are relatively easy to sample (Greenlaw and Rising 1994; Post 1974; Post and Greenlaw 1994, 2006). These characteristics make them potential candidates to inventory and monitor contaminants in tidal marsh ecosystems (Golden and Rattner 2003).

Previous research on Hg toxicity in piscivorous avian species inhabiting and nesting in the Delaware Bay has shown relatively high levels of Hg. Rattner et al. (2008) indicated that although Hg levels were below threshold levels in Osprey (*Pandion haliaelus*) blood (0.58 ppm) and feathers (2.76 ppm), populations in the Delaware Bay may be susceptible to Hg contamination. Golden et al. (2003) sampled blood from nestling Black-crowned Night Herons (*Nycticorax nycticorax*) on Pea Patch Island in the Delaware Bay and found mean Hg concentrations at 0.14 ppm. Estimating Hg concentrations in piscivorous avian species provides valuable information about accumulation in aquatic food webs, but presently, there are no estimates of Hg accumulation in terrestrial food webs associated with Delaware Bay. Here, we sampled two obligate salt marsh passerine sparrows from five drainages distributed along the Delaware Bay to estimate blood Hg concentrations. Our objectives were to determine the utility of tidal marsh sparrows as Hg bioindicators by (1) comparing blood Hg levels between sexes and species, (2) estimating species-specific variation in Hg levels among drainages, and (3) determining the number of Hg measurements needed to estimate the Hg levels at a site within a desired level of precision.

Methods

We sampled sparrow blood (June–July 2006 and 2007) for Hg from five drainages along Delaware Bay (Table 1). Bird blood has been shown to be a suitable matrix to indicate the current Hg burden in wild birds (Eagles-Smith et al. 2008; Kahle and Becker 1999) and Rimmer et al. (2005) found that total Hg and MeHg in four species of insectivorous passerines had a nearly 1:1 ratio, and we assumed these sparrows follow these patterns. The five drainages included Smyrna River (39°21′07.46″ N, 75°33′03.81″ W), Duck Creek (39°15′46.69″ N, 75°25′17.67″ W), Green Creek (39°12′53.38″ N, 75°26′10.15″ W), Broadkill River (38°48′52.02″ N, 75°13′35.58″ W), and Cedar Creek (38°54′20.71″ N, 75°18′23.71″ W). These drainages were located in two marsh types: North Atlantic coastal plain brackish tidal marsh (Smyrna River) and Northern Atlantic coastal plain tidal salt marsh (Duck Creek, Green Creek, Broadkill River, and Cedar Creek) (Westervelt et al. 2006). Vegetation at the North Atlantic coastal plain brackish tidal marsh site was dominated by Chairmaker's Bulrush (*Schoenoplectus americanus*), Saltmeadow Cordgrass (*Spartina patens*), Smooth Cordgrass (*Spartina alterniflora*), Big Cordgrass (*Spartina cynosuroides*), and High-tide Bush (*Iva frutescens*), and Groundsel Bush (*Baccharis halimifolia*) (Westervelt et al. 2006). Vegetation at the Northern Atlantic coastal plain tidal salt marsh sites was dominated by Saltmeadow Cordgrass, Smooth Cordgrass, and Salt Grass (*Distichlis spicata*) (Westervelt et al. 2006).

Sparrows were captured using mist nets and fitted with a US Fish and Wildlife Service identification band. Blood samples were drawn from all individuals using 50-μl heparinized capillary tubes to collect approximately 20–50 μl of blood from the cutaneous ulnar vein. Capillary tubes were immediately placed in a cooler with ice and frozen at −15°C within 8 h. Samples were sent to the Texas A&M Trace Element Research Laboratory, College Station, Texas to determine blood Hg levels. Samples were analyzed for Hg by combustion/trapping/cold-vapor atomic absorption using EPA Method 7473 (USEPA 1998). After thawing, samples were expressed from the tubes, weighed to the nearest 0.1 mg, and transferred to tarred, combusted nickel boats. The boats were then loaded into the autosampler carousel of a Milestone DMA 80 Hg analyzer and sequentially introduced into the instrument's combustion chamber. Samples were heated in a tube furnace at 850°C under a stream of oxygen, and combustion products were passed through a catalyst and then through a gold-coated sand column where Hg atoms were trapped. Following thermal desorption, the oxygen gas stream carried Hg vapor through two atomic absorption cells that quantified Hg over the range 0.001–0.700 μg. Instrument calibration utilized certified reference materials as standards; calibration was monitored after every 10 samples and at the end of the analysis by analyzing a check standard and a blank.

Table 1 Seaside and Saltmarsh sparrow blood Hg from five Delaware Bay, USA drainages, 2006–2007

Drainage	Distance	Seaside Sparrow Hg			Saltmarsh Sparrow Hg		
		N	Mean (SE)	Range	*N*	Mean (SE)	Range
Green Creek	3.3	18	0.60 (0.06)	0.33–1.47	3	0.47 (0.05)	0.39–0.55
Smyrna River	4.8	21	0.57 (0.10)	0.15–2.12	3	0.40 (0.08)	0.25–0.52
Duck Creek	1.7	32	0.45 (0.06)	0.18–1.99	11	0.54 (0.04)	0.37–0.75
Broadkill River	1.8	14	0.43 (0.03)	0.22–0.63	12	0.47 (0.02)	0.37–0.60
Cedar Creek	0.5	15	0.31 (0.03)	0.18–0.56	6	0.44 (0.10)	0.19–0.83

Drainage name, distance from the shoreline (km), sample size (n), mean (±SE) (ppm), and range (ppm) blood Hg are provided

Laboratory quality control samples included a method blank, certified reference material, a duplicate sample, and a spiked sample with each batch of 20 or fewer samples. The Hg detection limit was 0.0042 ppm, and the reference material recoveries averaged 101 ± 3.14% (mean ± 1 SD; $n = 16$). Sample spike recoveries averaged 97 ± 2.74% (mean ± 1 SD; $n = 16$). Precision, estimated as the coefficient of variation (SD/mean) at a concentration of ~0.010 ppm was 1.2% ($n = 16$). Blanks were all below the Hg detection limit.

Mercury levels were tested among all five drainages for Seaside Sparrows and three drainages for Saltmarsh Sparrows (excluding two due to small sample size; Table 1). We used one-way ANOVA to test for blood Hg differences (1) between males and females for each species, (2) between species, and (3) among drainages (Zar 1999). Due to the exploratory objectives of this research, alpha = 0.10 for all tests and SPSS version 16.0 was used for all analyses (SPSS 2008).

We conducted a power analysis using our Seaside Sparrow data to estimate the number of blood samples that would be required to detect Hg levels present within a 10% accuracy of the true Hg concentrations at a site of interest. Seaside Sparrows were chosen over Saltmarsh Sparrows because of their greater sample size and more abundant distribution throughout Delaware Bay. The sample size equation ($n = (Z\alpha)^2 (s)^2/(B)^2$) (Elzinga et al. 2006) was used to calculate the initial sample size, where n = the uncorrected sample size, $Z\alpha$ = the standard normal coefficient, s = the standard deviation, and B = the precision level desired expressed as half the acceptable confidence interval width (Kupper and Hafner 1988). In this case, we wanted the confidence interval width to be within 10% of the sample mean, so $B = (0.10 \times \text{mean Hg level})$.

Results

We captured and drew blood from 100 adult Seaside Sparrows (males = 59, females = 40, unknown = 1) and 35 adult Saltmarsh Sparrows (males = 25, females = 10). We did not detect a difference in the blood Hg levels between male and female Seaside Sparrows ($F_{1,97} = 0.07$, $P = 0.77$) and did not detect a difference in blood Hg levels between male and female Saltmarsh Sparrows ($F_{1,33} = 1.20$, $P = 0.28$, Table 1). There was no difference in blood Hg levels between species ($F_{1,133} < 0.00$, $P = 0.99$).

Seaside Sparrow blood Hg levels differed among drainages ($F_{4,95} = 2.512$, $P = 0.047$, Table 1). Seaside Sparrows in the Green Creek drainage had 1.9 times greater blood Hg levels than sparrows in the Cedar Creek drainage ($P = 0.06$) and Seaside Sparrows in the Smyrna River drainage had 1.8 times greater blood Hg levels compared to sparrows in the Cedar Creek Drainage ($P = 0.09$). Because the sample sizes for Saltmarsh Sparrow in two of the drainages were small (Green Creek $n = 3$ and Smyrna River $n = 3$), we only tested for differences among the three drainages with large enough sample sizes, and no difference in blood Hg levels were detected (Duck Creek, Broadkill River Creek, and Cedar Creek; $F_{2,26} = 1.10$, $P = 0.35$). The results of our power analysis estimated that it would require 16 Seaside Sparrow blood Hg samples to detect differences among sites.

Discussion

We detected a difference in Seaside Sparrow blood Hg among the five Delaware Bay drainages. Two drainages (Green Creek and Smyrna River) had sparrows with greater blood Hg concentrations than what was detected at the Cedar Creek drainage. These results indicated that Seaside Sparrow blood Hg concentrations were site-specific, and we could detect differences among sites with the sample sizes we obtained. Given that avian blood samples provide estimates of total Hg and MeHg from foraging areas within a specific season (Rimmer et al. 2005), we assume that these differences reflect Hg ingested at these breeding sites and therefore local availability.

Distance from the Delaware Bay shoreline may explain patterns in the blood Hg levels detected. The Smyrna River and Green Creek drainage sites were located farther from the shoreline (>3 km), and Seaside Sparrows at these sites had at least 1.8 times greater blood Hg levels than Seaside Sparrows sampled at the Cedar Creek site (0.5 km from the shoreline). Seaside Sparrows had Hg levels ranging from 0.15 to 2.12 ppm, and some individuals approached or exceeded blood Hg levels (1.0 ppm) that may cause potential detrimental effects (Evers and Duron 2006). Saltmarsh Sparrows had Hg levels ranging from 0.19 to 0.83 ppm, within the blood Hg ranges of sparrows sampled at marshes in Maine (Shriver et al. 2006).

The elevation, tidal pulse, and point source pollution need further testing and could be influencing Hg methylation and pollution at sites along the Delaware Bay. In addition, Hg from freshwater inflows where MeHg concentrations can be high in the surface water (Hall et al. 2008) might increase Hg to the site and could explain why sites distant from the shore had higher levels of Hg concentrations. Regardless of the potential causes for the differences we detected in sparrow blood Hg among the marshes, these data provide support for the potential to use Seaside Sparrows as indicators of the extent of Hg bioaccumulation in tidal marshes.

Assessing ecosystem condition is increasingly important for both human and wildlife health and estimating the extent of contaminants in specific habitats is an important step in this process (Burger and Gochfeld 2001). Developing biomonitoring protocols to identify and track contaminant loads requires the identification of effective and efficient indicator species (Golden and Rattner 2003). Because bird species accumulate toxins through dietary exposure, concentrations in various tissues (blood, feathers, eggs, organs) can be estimated and may provide an accurate measure of the fate of Hg. Contaminant burdens in birds are presently being used worldwide as ecological endpoints to inventory and monitor contaminants in many ecosystems. For example, American Dippers (*Cinclus mexicanus*), an aquatic bird that occurs on fast-flowing streams of NW North America (Kingery 1996), has been proposed as a bioindicator of selenium levels in coal mine-affected streams (Wayland et al. 2006) and the closely related Eurasian dipper (*Cinclus cinclus*) has been used as an indicator of stream quality in Europe for many years (O'Halloran et al. 2003; Ormerod and Tyler 1987, 1990). Also, the Red-billed chough (*Pyrrhocorax pyrrhocorax*), a grassland bird dependent on soil invertebrates, has been proposed as a species that could be used as a bioindicator of soil condition (Bignal and Curtis 1989), specifically the extent of bacterial resistance to antibiotics related to agricultural manuring in Spain (Blanco et al. 2009).

For US Atlantic estuaries, Golden and Rattner (2003) developed a species utility and vulnerability ranking index for the purpose of indentifying species that may be appropriate bioindicators. They ranked 24 terrestrial vertebrates based on primary dietary preference, longevity, geographic occurrence, ease of collection, and exposure potential. Double-Crested Cormorant (*Phalacrocorax auritls*), Osprey (*P. haliaelus*), Great Blue Heron (*Ardea herodias*), and Common Tern (*Sterna hirundo*) scored the highest as Hg bioindicator species for US Atlantic estuarine habitats (Golden and Rattner 2003). Clapper Rails (*Rallus longirostris*) were used as bioindicators for Hg and polychlorinated biphenyl in a Georgia estuarine marsh because of their site fidelity characteristics and consistent diet on certain food items (Cumbee et al. 2008). Common Loons have been used as Hg bioindicators in freshwater lakes (Burgess and Meyer 2008), and Cliff Swallow (*Petrochelidon pyrrhonota*) eggs and nestlings have recently been used to identify environmental Hg contamination in Cache Creek watershed, California (Hothem et al. 2008).

The utility of bioindicators to provide relevant information about ecological condition or levels of contamination is dependent on their sensitivity, natural variability, and direct link to stressors (Burger and Gochfeld 2001). A good bioindicator should be relatively easy to use to address management questions or to test hypotheses about the system in question. Bioindicators should also be widespread in the habitat being proposed for monitoring and exhibit a home range within that ecosystem (Golden and Rattner 2003). Sampling the blood of birds is an ideal indicator of site contamination if the species is habitat-specific and limited to a narrow geographical area. Based on these criteria, we think Seaside Sparrow blood Hg could be used as an environmental monitoring tool for Hg contamination in tidal marsh habitats of Delaware Bay and possibly other areas where Seaside Sparrows are abundant and fit these criteria. Seaside Sparrows in Delaware Bay are abundant, widely distributed, marsh specific for nesting and foraging activities, and relatively easy to sample. In addition, Seaside Sparrow blood Hg concentrations differed among drainages, and we could detect these differences among sites with as few as 16 blood samples. Due to the lower abundance of Saltmarsh Sparrows, this species may be too infrequently encountered to provide an efficient bioindicator in Delaware Bay tidal marshes. Shriver et al. (2006), however, estimated and compared Saltmarsh Sparrow blood Hg concentrations among five salt marshes in Maine, USA, suggesting that where these sparrows are more abundant, they may provide valuable information about the Hg concentrations in salt marshes.

The sample size estimations presented here provide necessary information to assist in the design of a sampling strategy to identify and monitor Hg hotspot areas in tidal marshes of Delaware Bay. Given an estimated cost of $60/sample to determine total Hg concentration in Seaside Sparrow blood, the analytical chemistry expense at each site to detect differences in Seaside Sparrow Hg levels would be approximately $960. Based on our experience sampling for this species, we estimate that it would take two field technicians, including transportation, 1 week to adequately sample each marsh (approx. $1,100/marsh for field expenses). With 15 watersheds dominated by brackish or salt marsh habitat surrounding Delaware Bay (http://water.usgs.gov/GIS/huc_name.html), an initial assessment to identify Hg hotspots at the watershed scale could be implemented for a reasonable expense. The next step in the bioindicator testing process is to correlate the extent of Hg in the marsh sediment and arthropod community with the Seaside Sparrows foraging within that site. This would require determining sparrow prey items and the extent of Hg within them. Our results do not provide the complete picture, but we think that they are compelling enough to warrant more intensive study that will directly link the extent of Hg within a marsh to Seaside Sparrow blood Hg.

Acknowledgements We would like to thank the University of Delaware, College of Agriculture and Natural Resources for financial and institutional support and the US Fish and Wildlife Service staff at Bombay Hook and Prime Hook National Wildlife Refuges for logistical support. J. Bowman, R. Greenberg, and B. Rattner, and an anonymous reviewer provided valuable comments on early versions of this manuscript and are warmly acknowledged. We thank E. Kehas, Z. Loman, V. Shiavi, and M. Sieges for field support.

References

Austin, L. O. Jr. (1983). The seaside sparrow assemblage: A review of its history and biology. In T. L. Quay, J. B. Funderburg, D. S. Lee Jr., E. F. Potter, & C. S. Robbins (Eds.), *The seaside sparrow, its biology and management* (pp. 13–17). Raleigh: North Carolina State Biological Surveys.

Barr, J. F. (1973). *Feeding biology of common loon (Gavis immer) in oligotrophic lakes of the Canadian Shield*. PhD. Thesis, University of Guelph, Ontario, Canada.

Bearhop, S., Ruxton, G. D., & Furness, R. W. (2000). Dynamics of mercury in blood and feathers of Great Skuas. *Environmental Toxicology and Chemistry, 19*, 1638–1643.

Bignal, E., & Curtis, D. J. (1989). *Choughs and land-use in Europe*. Scottish Chough Study Group, Argyll.

Blanco, G., Lemus, J. A., & Grande, J. (2009). Microbial pollution in wildlife: Linking agricultural manuring and bacterial antibiotic resistance in Red-billed Choughs. *Environmental Research, 109*, 405–412.

Brasso, R. L., & Cristol, D. A. (2007). Effects of mercury exposure on the reproductive success of tree swallows (*Tachycineta bicolor*). *Ecotoxicology, 17*, 133–141.

Burger, J. (1993). Metals in avian feathers: Bioindicators of environmental pollution. *Review of Environmental Toxicology, 5*, 203–311.

Burger, J., & Gochfeld, M. (2001). On developing bioindicators for human and ecological health. *Environmental Monitoring and Assessment, 66*, 23–46.

Burgess, N. M. (2005). Mercury in biota and its effects. In M. B. Parsons, & J. B. Pervical (Eds.), *Mercury, sources, measurements, cycles, and effects* (pp. 235–258). Ottawa: Mineral Association of Canada.

Burgess, N. M., & Meyer, M. W. (2008). Methylmercury exposure associated with reduced productivity in Common Loons. *Ecotoxicology, 17*, 83–91.

Chen, C. Y., Dionne, M., Mayes, B. M., Strup, S., & Jackson, B. P. (2009). Mercury bioavilability and bioaccumulation in estuarine food webs in the Gulf of Maine. *Environmental Science and Technology, 43*, 1804–1810.

Compeau, G. C., & Bartha, R. (1985). Sulfate-reducing bacteria: Principal methylators of mercury in anoxic estuarine sediment. *Applied and Environmental Microbiology, 50*, 498–502.

Cristol, D. A., Brasso, R. L., Condon, A. M., Fovargue, R. E., Friedman, S. L., Hallinger, K. K., et al. (2008). The movement of aquatic mercury through terrestrial food webs. *Science, 320*, 335–335.

Curnutt, J. L., Mayer, A. L., Brooks, T. M., Manne, L., Bass, O. L., Fleming, D. M., et al. (1998). Population dynamics of the endangered Cape Sable Seaside Sparrow. *Animal Conservation, 1*, 11–21.

Cumbee, J. C., Gaines, K. F., Mills, G. L., Garvin, N., Stephens, W. L., Novak, J. M., et al. (2008). Clapper Rails as indicators of mercury and PCB bioavailability in a Georgia saltmarsh system. *Ecotoxicology, 17*, 485–494.

Delaware Department of Natural Resources and Environmental Control [DNREC] (2002). Delaware toxics release inventory report. <http://www.serc.delaware.gov/reports.shtml>. Accessed 18 Nov 2008.

Delaware Department of Natural Resources and Environmental Control [DNREC] (2008). <http://www.fw.delaware.gov/Fisheries/Pages/Advisories.aspx>. Accessed 15 Oct 2008.

Driscoll, C. T., Han, Y.-J., Chen, C. Y., Evers, D. C., Lambert, K. F., Holsen, T. M., et al. (2007). Mercury contamination in forest and freshwater ecosystems in the northeastern United States. *BioScience, 57*, 17–28.

Eagles-Smith, C. A., Ackerman, J. T., Adelsbach, T. L., Takekawa, J. Y., Miles, A. K., & Keister, R. A. (2008). Mercury correlations among six tissues for four waterbird species breeding in San Francisco Bay, California, USA. *Environmental Toxicology and Chemistry, 27*, 2136–2153.

Elzinga, C. L., Salzer, D. W., Willoughby, J. W., & Gibbs, J. P. (2006). *Monitoring plant and animal populations*. Malden: Blackwell.

Evers, D. C., & Duron, M. (2006). *Developing an exposure profile for mercury in breeding birds of New York and Pennsylvania, 2005*. Report BRI 2006-11 submitted to The Nature Conservancy. BioDiversity Research Institute, Gorham, ME.

Evers, D. C., Han, Y.-J., Driscoll, C. T., Kammen, N. C., Goodale, M. W., Lambert, K. F., et al. (2007). Biological mercury hotspots in northeastern United States and southeastern Canada. *Bioscience, 57*, 29–43.

Evers, D. C., Savoy, L. J., DeSorbo, C. R., Yates, D. E., Hanson, W., Taylor, K. M., et al. (2008). The adverse effects of environmental mercury loads on breeding Common Loons. *Ecotoxicology, 17*, 69–81.

Furness, R. W., & Greenwood, J. D. (1993). *Birds as monitors of environmental change*. London: Chapman & Hall.

Gochfeld, M., Belant, J. L., Shukla, T., Benson, T., & Burger, J. (1996). Heavy metals in laughing gulls: Gender, age, and tissue differences. *Environmental Toxicology and Chemistry, 15*, 2275–2283.

Golden, N. H., & Rattner, B. A. (2003). Ranking terrestrial vertebrate species for utility in biomonitoring and vulnerability to environmental contaminants. *Review of Environmental Contaminant Toxicology, 176*, 67–136.

Golden, N. H., Rattner, B. A., McGowan, P. C., Parsons, K. C., & Ottinger, M. A. (2003). Black-crowned night-herons (*Nycticorax nycticorax*) in Chesapeake and Delaware bays. *Environmental Contamination and Toxicology, 70*, 385–393.

Greenlaw, J. S. (1992). Seaside sparrow, *Ammodramus maritimus*. In K. J. Schneider, & D. M. Pence (Eds.), *Migratory nongame birds of management concern in the northeast* (pp. 211–232). Newton Corner: US Fish and Wildlife Service.

Greenlaw, J., & Rising, J. (1994). Sharp-tailed sparrow (*Ammodramus caudacutus*). In A. Pool (Ed.), *The birds of North America online*. Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online.

Hall, B. D., Aiken, G. R., Krabbenhoft, D. P., Marvin-DiPasquale, M., & Swarzenski, C. M. (2008). Wetland as principle zones of methylmercury production in southern Louisiana and the Gulf of Mexico region. *Environmental Pollution, 154*, 124–134.

Heinz, G. H. (2003). Embryotoxic thresholds of mercury: Estimates from individual mallard eggs. *Archives of Environmental Contamination and Toxicology, 44*, 257. doi:10.1007/s00244-002-2021-6.

Hoffman, D. J., Spalding, M. G., & Frederick, P. C. (2005). Subchronic effects of methylmercury on plasma and organ biochemistries in great egret nestlings. *Environmental Toxicology and Chemistry, 254*, 3078–3084.

Horne, M. T., Finley, N. J., & Sprenger, M. D. (1999). Polychlorinated biphenyl- and mercury-associated alterations on benthic invertebrate community structure in a contaminated salt marsh in southeast Georgia. *Archives of Environmental Contamination and Toxicology, 37*, 317–325.

Hothem, R. L., Trejo, B. S., Bauer, M. L., & Crayon, J. J. (2008). Cliff swallows *Petrochelidon pyrrhonota* as bioindicators of environmental mercury, Cache Creek Watershed, California. *Archives of Environmental Contamination and Toxicology, 55*, 111–121.

Kahle, S., & Becker, P. H. (1999). Bird blood as bioindicator for mercury in the environment. *Chemosphere, 39*, 2451–2457.

Kenow, K. P., Meyer, M. W., Hines, R. K., & Karasov, W. H. (2007). Distribution and accumulation of mercury in tissues of captive-reared Common Loon (*Gavia immer*) chicks. *Environmental Toxicology and Chemistry, 26*, 1047–1055.

Kingery, H. E. (1996). American Dipper (*Cinclus mexicanus*). In A. Poole (Ed.), *The birds of North America online*. Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online.

Kupper, L. L., & Hafner, K. B. (1988). How appropriate are popular sample size formulas? *The American Statistician, 43*, 101–105.

Mason, R. P., Abbot, M. L., Bodaly, R. A., Bullock, O. R., Driscoll, C. T., Evers, D., et al. (2005). Monitoring the response to changing mercury deposition. *Environmental Science and Technology, 39*, 14A–22A.

National Academy of Sciences Committee on the Toxicological Effects of Methylmercury, Board on Environmental Studies and Toxicology, National Research Council (2000). *Toxicological effects of methylmercury*. Washington, DC: National Academy Press.

National Oceanic and Atmospheric Administration (NOAA) (2001). Magnitude and extent of contaminated sediment and toxicity in Delaware Bay. NOS ORCA 148 Technical Report. Centers for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Sciences, Silver Spring, Maryland, USA.

National Wildlife Federation (NWF) (2005). Mercury in the mid-atlantic: Are the states meeting the challenge. 2005 Mid Atlantic Mercury Report Card <http://www.nationalwildlifefederation.org/wildlife/pdfs/MercuryMidAtlantic.pdf> Accessed 18 Nov 2008.

Novak, J. M., Gaines, K. F., Cumbee, J. C., Mills, J. L. Jr., Rodriguez-Navarro, A., & Romanek, C. S. (2006). The Clapper Rail as an indicator species of estuarine marsh health. *Studies in Avian Biology, 32*, 270–281.

O'Halloran, J., Irwin, S., Harrison, S., Smiddy, P., & O'Mahony, B. (2003). Mercury and organochlorine content of Dipper (*Cinclus cinclus*) eggs in south-west Ireland: Trends during 1990–1999. *Environmental Pollution, 123*, 85–93.

Ormerod, S. J., & Tyler, S. J. (1987). Dippers (*Cinclus cinclus*) and grey wagtails (*Motacilla cinerea*) as indicators of stream acidity in upland Wales. In A. W. Diamond, & F. L. Filion (Eds.), *The value of birds* (pp. 191–208). Cambridge: International Council of Bird Preservation, ICBP Technical Publication No. 6.

Ormerod, S. J., & Tyler, S. J. (1990). Environmental pollutants in the eggs of Welsh dippers *Cinclus cinclus*: A potential monitor of organochlorine and mercury contamination in upland rivers'. *Bird Study, 37*, 171–176.

Post, W. (1974). Functional analysis of space-related behavior in the Seaside Sparrow. *Ecology, 55*, 564–575.

Post, W., & Greenlaw, J. S. (1994). Seaside Sparrow (*Ammodramus maritimus*). In A. Poole (Ed.), *The birds of North America Online*. Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online.

Post, W., & Greenlaw, J. S. (2006). Nestling diets of coexisting salt marsh sparrows: Opportunism in a food-rich environment. *Estuaries and Coasts, 29*, 765–775.

Rattner, B. A., Golden, N. H., & Toschik, P. C. (2008). Concentrations of metals in blood and feathers of nestling ospreys (*Pandion haliaetus*) in Chesapeake and Delaware Bays. *Archives of Environmental Contamination Toxicology, 54*, 114–122.

Rimmer, C. C., Mcfarland, K. P., Evers, D. C., Miller, E. K., Aubury, Y., Busby, D., et al. (2005). Mercury concentrations in Bicknell's Thrush and other insectivorous passerines in montane forests of northeastern North America. *Ecotoxicology, 14*, 223–240.

Scheuhammer, A. M., Meyer, M. W., Sandheinrich, M. B., & Murray, M. W. (2007). Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio: A Journal for the Human Environment, 36*, 12–18.

Shriver, W. G., & Gibbs, J. P. (2004). Projected effects of sea-level rise on the population viability of Seaside Sparrows (*Ammodramus maritimus*). In H. R. Akcakaya, et al. (Eds.), *Species conservation and management: Case studies*. Oxford University Press: Oxford.

Shriver, W. G., Evers, D., Hodgman, T. P., MacCulloch, B. J., & Robert, J. T. (2006). Mercury in sharp-tailed sparrows breeding in coastal wetlands. *Environmental Bioindicators, 1*, 129–135.

SPSS (2008). *Statistical software version 16.0 for windows*. Chicago: SPSS.

Taylor, D. L. (1983). Management of the Cape Sable Sparrow. In T. L. Quay, J. B. Funderburg, D. S. Lee Jr., E. F. Potter, & C. S. Robbins (Eds.), *The Seaside Sparrow: Its biology and management* (pp. 147–152). North Carolina Biological Survey Occasional Paper 1983–5.

Thompson, D. R., Hamer, K. C., & Furness, R. W. (1991). Mercury accumulation in Great Skuas (*Catharacta Skua*) of known age and sex and its effects upon breeding and survival. *Journal of Applied Ecology, 28*, 672-684.

Tiner, R. W. (2001). *Delaware's wetlands: Status and recent trends*. Hadley: US Fish and Wildlife Service.

US Environmental Protection Agency (1997). *Mercury study report to Congress*. Washington, DC: USEPA. Executive Summary 1:1-98. EPA-452/R-97-003.

US Environmental Protection Agency (1998). *SW-846 Method 7473. Mercury in solids and solutions by thermal decomposition, amalgamation, and atomic absorption spectrophotometry*. Washington, DC: USEPA.

US Environmental Protection Agency (2000). *Mercury research strategy*. Technical report: EPA/600/R-00/073, United States Environmental Protection Agency, Office of Research and Development, Washington, DC.

Walters, M. J. (1992). *A shadow and a song: The struggle to save an endangered species*. Post Hills: Chelsea Green.

Wayland, M., Kneteman, J., & Crosley, R. (2006). The American Dipper as a bioindicator of Selenium contamination in a coal mine-affected stream in

West-Central Alberta, Canada. *Environmental Monitoring and Assessment, 123*, 285–298.

Werner, H. W. (1975). *The biology of the Cape Sable sparrow*. Report to USDI Fish and Wildlife Service Everglades National Park, Homestead.

Westervelt, K., Largay, E., Coxe, R., McAvoy, W., Perles, S., Podniesinski, G., Sneddon, L., & Walz, S. K. (2006). *A guide to the natural communities of the Delaware Estuary: Version 1*. NatureServe. Arlington, Virginia. Retrieved from: http://www.delawareestuary.org/pdf/ScienceReportsbyPDEandDELEP/GuideNaturalComm_v1.pdf.

Zar, J. H. (1999). *Biostatistical analysis*. Upper Saddle River: Prentice Hall.