Arch Environ Contam Toxicol 53, 442–449 (2007)
DOI 10.1007/s00244-006-0060-0

Heavy Metals and Selenium in Grebe Feathers from Agassiz National Wildlife Refuge in Northern Minnesota

Joanna Burger · Bruce Eichhorst

Received: 17 March 2006 / Accepted: 10 March 2007

Abstract Metal levels in feathers can often be used as an indicator of exposure and of potential effects in birds. In previous work at Agassiz National Wildlife Refuge, northwestern Minnesota, pied-billed grebe (*Podilymbus podiceps*) eggs had significantly higher levels of manganese and mercury and significantly lower levels of selenium than eared (*Podiceps nigricollis*) or red-necked grebes (*Podiceps grisegena*), but in 1999, pied-billed grebes had significantly higher levels of mercury, but lower levels of selenium and tin than the other grebes. This led us to examine whether these patterns held up in feathers of grebes as a function of age. The feathers of young birds represent local exposure. We collected feathers of flightless young and adult grebes from 1997 to 1999 in the marshes at Agassiz National Wildlife Refuge. Regression models indicated that year, age, or species were significant factors accounting for variations in the levels of arsenic, cadmium, chromium, lead, manganese, mercury, and selenium, depending on the metal. Overall, there were significant intraspecific differences for all metals. Pied-billed grebes had the highest levels of arsenic, chromium, and selenium, and eared grebes had the highest levels of cadmium, manganese, and mercury. Pied-billed and western grebes (*Aechmophorus occidentalis*) had the highest levels of lead. There were significant age-related differences in cadmium, chromium, and mercury for both eared and red-necked grebes, for arsenic in eared grebes, and for lead and manganese in red-necked grebes. Adults had higher levels of all metals, except young had higher levels of chromium. Mercury in the feathers of eared grebes were higher than found from other studies with a wide range of aquatic and marine birds and were above those known to cause adverse effects in laboratory studies, suggesting some cause for concern.

Keywords Mercury · Cadmium · Lead · Selenium · Grebes · Age-related · Feathers · Metals

J. Burger (✉)
Division of Life Sciences, Rutgers University, Piscataway, NJ 08854-8082, USA
e-mail: burger@biology.rutgers.edu

B. Eichhorst
Department of Biology, University of Nebraska at Kearney, Kearney, NE 68849, USA

B. Eichhorst
Department of Biology, University of North Dakota, Grand Forks, ND 58202, USA

Increasingly, governmental agencies, policy makers, managers, conservationists, and the general public are concerned about the health of the environment and require indicators that assess status and trends, not only of individual organisms, but also of populations and communities. Chemical use is increasing in our environment and might pose a threat to some species and communities. Species that live in, or forage in, aquatic environments are particularly vulnerable because of the potential for rapid movement of contaminants in water, compared to movement in terrestrial environments, and because chemicals can be stored in sediments, providing a pool for years to come. Levels of many of these chemicals are elevated in marine and coastal ecosystems because of the influx from rivers as well as runoff and direct pollution (Furness and Rainbow 1990). The threat from long-range atmospheric transport and deposition of certain substances is increasing as many chemicals, such as mercury, are transported to all regions, including relatively isolated lakes and marshes (Fitzgerald 1989; Houghton et al. 1992).

In earlier work at Agassiz National Wildlife Refuge in northwestern Minnesota (in 1994), Burger and Gochfeld (1996) showed that eared grebes (*Podiceps nigricollis*) had higher levels of all metals (except mercury) in their eggs than American coots (*Fulica americana*), Franklin's gulls (*Larus pipixcan*), black-crowned night-herons (*Nycticorax nycticorax*), and double-crested cormorants (*Phalacrocorax auritus*). This was not expected on the basis of food-chain relationships, because the grebes eat smaller fish than the latter two species. In a later study, we found that there were significant differences in levels of selenium, manganese, and mercury in eggs collected from three species of grebes in 1997, with pied-billed grebe (*Podilymbus podiceps*) having significantly higher levels of manganese and mercury and significantly lower levels of selenium than eared or red-necked grebes (*Podiceps grisegena*; Burger and Eichhorst 2005). In 1999, pied-billed grebes again had significantly higher levels of mercury and lower levels of selenium and tin than the other species. The only pattern that was significant and consistent among years was selenium: Pied-billed grebes had lower levels than the other species. Because egg data represent both local exposure, and exposure of females while on the wintering grounds and while migrating, we undertook the present study to examine whether these relationships were supported by data from feathers. Feathers of young represent local exposure because young are fed entirely from local sources (Burger 1993; Furness et al. 1986).

In this article, we examine the levels of metals in the feathers of young and adult eared and red-necked grebes and in the feathers of young pied-billed and western grebes (*Aechmophorus occidentalis*) from Agassiz National Wildlife Refuge in northwestern Minnesota in 1997, 1998, and 1999 (not all species in all years). We were interested in whether the patterns of metal exposure shown in previous studies (Burger and Gochfeld 1996) and in eggs were supported and whether there were also yearly differences. Because young grebes are provisioned by their parents entirely from local sources, age-related differences might indicate parental exposure on the wintering grounds.

Birds are useful as bioindicators of pollution (Furness 1993; Furness and Camphuysen 1997; Gochfeld 1971, 1975, 1980; Hays and Risebrough 1972; Peakall 1992; Walsh 1990). Aquatic and marine birds are exposed to a wide range of chemicals because most occupy higher trophic levels, making them susceptible to bioaccumulation of pollutants. Feathers are useful indicators of metal contamination because (1) birds sequester metals in their feathers, (2) the proportion of body burden that is in feathers is relatively constant for each metal, (3) a relatively high proportion of the body burden of certain metals is stored in the feathers (Burger 1993), and (4) there is a high correlation between levels of mercury in the diet of seabirds and levels of mercury in their feathers (Monteiro and Furness 1995). Because different species have different life-history strategies and cycles, behavior and physiology, diet, and habitat uses, their vulnerability varies (Burger and Peakall 2003). As with other animals, susceptibility often varies with age, reproductive stage, and gender (Burger 1993).

Materials and Methods

Under appropriate federal and state permits, breast feathers were collected at Agassiz National Wildlife Refuge, Marshall County, Minnesota (48°21′N, 95°57′W) from adults and flightless young of eared (1997, 1998) and red-necked grebes (1997–1999) and young of pied-billed (1998, 1999) and western grebes (1998). Young were captured by handnet, as they were still flightless, or shooting, and adults were captured with gill nets or nest traps. It was not possible to have a balanced design in all years because of differences in nesting attempts and reproductive success (young must nearly reach fledging before feathers are collected). Feathers were placed in individual envelopes, labeled for later identification, and then shipped to the Environmental and Occupational Health Sciences Institute for analysis.

Breast feathers were selected because they are considered to be more representative of exposure to metals (Burger 1993). Breast feathers were collected from young once they were fully formed, just prior to independence. Metals enter feathers during the 2–3 weeks that it takes for them to grow; then the blood supply ends and there is no further uptake of metals (Burger 1993). Thus, feathers are an archive of metal exposure in a given time period.

All feathers were analyzed in the Elemental Analysis Laboratory of the Environmental and Occupational Health Sciences Institute in Piscataway. Feathers were washed three times with acetone and then digested individually in warm nitric acid mixed with the addition of 30% hydrogen peroxide and subsequently diluted with deionized water. Mercury was analyzed by the cold vapor technique, and the other elements were analyzed by graphite furnace–atomic absorption (Burger and Gochfeld, 1991). All concentrations are expressed in nanograms per gram (ppb) on a dry-weight basis using weights obtained from air-dried specimens.

Detection limit ranges were: 0.02 ppb for cadmium, 0.08 ppb for chromium, 0.15 ppb for lead, 0.09 ppb for manganese, 0.2 ppb for mercury, and 0.7 ppb for selenium. All specimens were analyzed in batches with known standards, calibration standards, and spiked specimens. Recoveries ranged from 88% to 102%. Batches with recoveries of less than 85% were reanalyzed. The coefficient of variation on replicate, spiked samples ranged up to 10%.

Table 1 Models for differences in metal levels in feathers of grebes 1997 to 1999

	Arsenic	Cadmium	Chromium	Lead	Manganese	Mercury	Selenium
Model							
r^2	0.18	0.57	0.52	0.38	0.53	0.59	0.25
f	2.6	16.08	13.46	7.62	13.3	17.18	4.18
p	0.01	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002
Factors entering (F, p)							
Species	3.18 (0.05)	4.63 (0.01)	3.51 (0.03)	4.56 (0.0005)	NS	9.84 (0.0002)	NS
Year	4.26 (0.02)	12.3 (0.0001)	13.3 (0.0001)	6.13 (0.0003)	11.75 (0.0001)	NS	7.56 (0.0009)
Age	NS	NS	6.46 (0.01)	NS	3.24 (0.07)	24.16 (0.0001)	NS
Species x year	NS	6.88 (0.002)	NS	NS	NS	NS	2.77 (0.07)

NS = not significant

Nonparametric Wilcoxon chi-square tests were used to examine differences among species, and Duncan multiple range tests were performed to distinguish significant differences between species. Western grebes were not included in the statistical analyses because of their small sample sizes, but the metals levels were included because of the paucity of such data for this species. General linear models were constructed to determine the relative contribution of species, year, and species × year to variations in metals levels (PROC GLM; SAS 1995). Both arithmetic and geometric means are given to facilitate comparisons with other studies. We accept a probability level of 0.05 as significant, but we present all values below 0.10 to allow the reader to asses the significance for themselves.

Results

Models indicate that between 18% and 59% of the variation in individual metals was explained by species, year, age, and/or a species × year interaction; interaction variables not given in Table 1 were tested and found not to be significant for any metal. These factors explained the least variability for arsenic and the most for cadmium and mercury. Age-related differences were present for chromium and mercury and were close to significant for manganese (Table 1). Year was the most significant contributor to variation for arsenic, cadmium, chromium, lead, manganese, and selenium (Table 1). Because year was the most important variable, we present the metals levels overall (as most studies do; Table 2) and then present them by year (Table 3).

Overall, when all three years are considered together (adults and young combined), (1) eared grebe had the highest levels of cadmium, manganese, and mercury, (2) pied-billed grebe had the highest levels of arsenic, (3) pied-billed and red-necked grebes had the highest levels of chromium and selenium, and (4) pied-billed and western grebes had the highest levels of lead (Table 2). Thus, no one species had the highest levels of all metals. Because year was the most important variable entering the models for all metals (except mercury), we present the values by year for adults and young combined (Table 3).

We were able to statistically compare metal levels in feathers for adults and young only for eared and red-necked grebes (Table 4). Levels in pied-billed grebe feathers are presented only for comparison, due to the presence of only one adult. Adults generally had significantly higher levels of all metals (where there was a significant difference), except for chromium. Young grebes had significantly higher levels of chromium than did adults. In comparing levels among young birds, who have received all their exposure from the surrounding waters, pied-billed grebe young had the highest levels of arsenic, lead, and mercury, red-necked grebe young had the highest levels of cadmium and selenium, and eared grebe young had the highest levels of manganese (χ^2 tests, $p < 0.05$); there were no significant differences for chromium.

Discussion

Metal Levels in Feathers

Overall, eared grebes had higher levels of cadmium (by an order of magnitude), manganese (twice as high as any other species), and mercury (an order of magnitude) in their feathers than did other grebes. No other species patterns were as clear; although there were species differences, they were small. The differences in accumulation presumably reflect differences in diet, differences in proportions of different foods (if they eat the same foods), differences in the sizes of prey items, or differences in uptake rates.

In general, red-necked grebes eat a variety of small fish, aquatic and land insects, tadpoles, crustaceans, mollusks, and aquatic worms (Palmer 1962; Stout and Nuechterlein

Table 2 Comparison of metal levels in feathers of four grebe species (combined samples of adults and young) from 1997 to 1999

	Eared grebe	Pied-billed grebe	Red-necked grebe	Western grebe	Wilcoxon X^2 (*p*)
Sample size	50	15	37	5	
Arsenic	323 ± 57	580 ± 147	212 ± 43	213 ± 93	3.6(0.03)
	100 (A, B)	58 (A)	23 (B)	45 (B)	
Cadmium	304 ± 63	17 ± 3	58 ± 10	18 ± 5	18(0.0003)
	80 (A)	13 (B)	37(B)	15 (B)	
Chromium	1192 ± 108	1952 ± 214	2110 ± 143	1459 ± 110	31(0.0001)
	979 (B)	1811 (A)	1921 (A)	1441 (A, B)	
Lead	1640 ± 238	3559 ± 445	1713 ± 317	4481 ± 741	29(0.0001)
	1030 (B)	3242 (A)	1218 (B)	4223 (A)	
Manganese	6846 ± 683	1824 ± 246	3455 ± 503	1539 ± 472	37(0.0001)
	5428 (A)	1641 (B)	2603 (B)	1251 (B)	
Mercury	11803 ± 1477	1843 ± 403	2203 ± 358	2519 ± 102	26(0.0001)
	8420 (A)	1449 (B)	1479 (B)	2511 (B)	
Selenium	1514 ± 107	1900 ± 436	2237 ± 276	792 ± 199	10(0.02)
	1308 (A, B)	1601 (A)	1757 (A)	673 (B)	

Given are means and standard error, geometric mean (ppb dry weight mean ± SE; NS = not significant; Duncan values in parentheses; different letters indicate significant differences)

1999); eared grebes eat primarily aquatic and land insects and their larvae and less frequently take fish, amphibians, and mollusks (Cullen et al. 1999); pied-billed grebes eat primarily fish, crayfish and other crustaceans, and insects (Muller and Storer 1999); and western grebes eat primarily fish (Palmer 1962; Storer and Nuechterlein 1992). These trophic level considerations suggest that pied-billed and western grebes should have the highest levels of metals that bioaccumulate. In fact, in our study of levels in eggs, pied-billed grebes had the highest levels of mercury and manganese (Burger and Eichhorst 2005). In the present study, young pied-billed grebes had the highest levels of lead and mercury in their feathers, but not of the other metals.

The yearly variations in metal levels might be a result of differences in global exposure, water levels, and specific nesting locations. As might be expected, levels were higher in adults than in young eared and red-necked grebes for only about half the metal comparisons, perhaps reflecting longer periods of exposure and different sources (levels in adult feathers partly reflect sources from their wintering and migration grounds). The notable exception was chromium; chromium levels were significantly higher in young eared and red-necked grebes than in adults. We suggest that this difference reflects local exposure; young grebes at Agassiz are exposed to higher levels in their foods or they eat different foods than their parents. Some of these differences might be due to the draw-down patterns at Agassiz. Some of the pools at Agassiz are drawn down and the vegetation burned to open the marshes for duck nesting. For example, mercury levels are often higher after reflooding than before.

Although the one adult pied-billed grebe is not enough to make any comparisons, the results are intriguing and suggest a need for further study; the 14 young averaged higher levels than the 1 adult for arsenic, chromium, lead, manganese, and selenium. Young grebes reflect local exposure because all of their food comes from the aquatic areas surrounding their nest site. In comparing the young, young pied-billed grebes had higher levels of lead and mercury (the latter only slightly higher than eared grebe young), whereas red-necked grebe young had higher levels of cadmium, chromium, and selenium. Although the differences were not great, they should be investigated further.

Comparisons of Feather Levels with Other Species

Feathers usually provide the best tissue for a comparison with other species largely because there are more feather levels reported in the literature. Methodologically, however, these comparisons are valid only if the same feather type, age, and treatment (washing) are used. Further, the feathers of young are particularly useful because they always represent local exposure. It is instructive to compare the levels of metals found in the feathers of eared grebes and red-necked grebes, the species with sufficient sample sizes, with those of the other species at Agassiz, and elsewhere around the world.

Cadmium levels in eared grebes at Agassiz were higher than those found in American bittern (*Botaurus lentiginosus*) and were lower than those found in black-crowned night-heron or young Franklin's gulls from the same

Table 3 Comparison of metal levels in feathers of four grebe species (combined samples of adults and young) from 1997 to 1999

1997	Eared grebe	Red-necked grebe	Wilcoxon X^2 (p)
Sample size	24	5	
Arsenic	240 ± 49	19.3 ± 14.3	7.72(0.006)
	93.2	1.10	
Cadmium	630 ± 99	175 ± 16.8	5.6(0.02)
	465	171	
Chromium	665 ± 46.3	918 ± 137	4.32(0.04)
	631	882	
Lead	587 ± 69.9	484 ± 58.4	0.00(NS)
	504	470	
Manganese	9909 ± 1042	7453 ± 2204	0.48(NS)
	8905	5410	
Mercury	9999 ± 870	4150 ± 790	6.16(0.01)
	8824	3627	
Selenium	1041 ± 84.5	824 ± 226	1.92(NS)
	964	725	

1998	Eared grebe	Pied-billed grebe	Red-necked grebe	Western grebe	Wilcoxon X^2 (p)
Sample size	26	3	16	5	
Arsenic	399 ± 98	197 ± 99	169 ± 39	213 ± 93	(NS)
	106 (A)	21 (A)	26 (A)	45 (A)	
Cadmium	29 ± 6	18 ± 8	46 ± 11	18 ± 5	(NS)
	19 (A)	12 (A)	35 (A)	15 (A)	
Chromium	1679 ± 150	1420 ± 118	2223 ± 196	1459 ± 110	9(0.03)
	1447 (A)	1410 (A)	2092 (A)	1441 (A)	
Lead	2612 ± 362	3965 ± 1489	1185 ± 133	4481 ± 741	17(0.0008)
	1945 (B,C)	3487 (A,B)	1018 (C)	4223 (A)	
Manganese	4018 ± 413	1147 ± 68	3204 ± 683	1539 ± 472	9(0.03)
	3496 (A)	1145 (A)	2498 (A)	1251 (A)	
Mercury	14100 ± 2103	2966 ± 1913	2825 ± 585	2519 ± 103	13(0.004)
	8420 (A)	1937 (B)	1906 (B)	2511 (B)	
Selenium	1951 ± 147	1402 ± 264	2916 ± 549	792 ± 199	11(0.01)
	1714 (A, B)	1353 (A,B)	2190 (A)	673 (B)	

1999	Pied-billed grebe	Red-necked grebe	Wilcoxon X^2 (p)
Sample size	12	16	
Arsenic	676 ± 173	316 ± 85	(NS)
	76 (A)	54 (A)	
Cadmium	17 ± 4	32 ± 5	3(0.06)
	13 (B)	23 (A)	
Chromium	2084 ± 253	2370 ± 197	(NS)
	1928 (A)	2249 (A)	
Lead	3457 ± 458	2625 ± 659	8(0.06)
	3183 (A)	1962 (A)	
Manganese	1936 ± 274	2441 ± 331	(NS)
	1743 (A)	2152 (A)	
Mercury	1563 ± 237	1582 ± 367	(NS)
	1348 (A)	1148 (A)	
Selenium	2025 ± 540	1998 ± 203	(NS)
	1670 (A)	1860 (A)	

Given are means and standard error, geometric mean (ppb dry weight, mean ± SE; NS = not significant)

Table 4 Comparison of metal levels in feathers between adults and young in three species of grebes (1997 to 1999)

	Eared grebe		Red-necked grebe		Pied-billed grebe	
	Adult	Young	Adult	Young	Adult	Young
Sample size	45	5	14	23	1	14
Arsenic	347 ± 62	106 ± 57	144 ± 33	254 ± 66	302	600 ± 156
	120	22	30	20		51
X^2	3.6 (0.06)		NS			
Cadmium	339 ± 68	9 ± 4	93 ± 19	36 ± 8	29	16 ± 3
	111	6	71	24		12
X^2	11 (0.001)		10.3 (0.001)			
Chromium	1070 ± 91	2293 ± 523	1688 ± 164	2367 ± 190	1556	1980 ± 227
	926	2049	1565	2175		1830
X^2	6 (0.01)		5 (0.03)			
Lead	1690 ± 263	1192 ± 227	1096 ± 157	2089 ± 488	2667	3622 ± 473
	1023	1097	932	1432		3287
X^2	NS		3(0.09)			
Manganese	7151 ± 739	4098 ± 1009	5813 ± 1090	2122 ± 201	1079	1881 ± 258
	5792	3342	4402	1934		1695
X^2	NS		8 (0.004)			
Mercury	17119 ± 2115	1421 ± 285	4948 ± 373	956 ± 102	6785	1881 ± 258
	13794	1304	4824	864		1695
X^2	12 (0.0006)		20 (0.0001)			
Selenium	1557 ± 116	1267 ± 315	2200 ± 320	2259 ± 405	1333	1941 ± 466
	1343	1078	1824	1718		1622
X^2	NS		NS			

Given are means and standard error, geometric mean (ppb dry weight, mean ± SE; NS = not significant). Below are the *p*-values in parentheses

marshes (Burger and Gochfeld 1996). Similarly, for 63 studies of birds, the median cadmium concentration was 1000 ppb, which was much lower than the average in this study (Burger and Gochfeld 1996). However, the levels were an order of magnitude higher in 1997 compared to the other years, suggesting a temporal decline. Further, cadmium levels in the eared grebes in the present study were three times higher than for the 63 studies examined by Burger (1993) for feather levels overall. The relatively high levels of cadmium in the feathers of most birds at Agassiz relative to birds from elsewhere suggest potential exposure at Agassiz. The question of whether eared grebes somehow ingested sediment that had high levels of cadmium bears examination. It suggests that stomach contents should be analyzed and compared to levels found in internal tissues.

Cadmium comes from erosion of surface deposits and from anthropogenic sources, such as purification of ores in smelters and mines, as well as from commercial products (Parmeggiani 1983). Volcanism is another source of cadmium, as well as forest fires (Hutton 1987). The high levels of cadmium in the feathers of grebes are not easily accounted for by either of these sources.

Chromium levels in the feathers of grebes at Agassiz were higher than the levels reported for other species at Agassiz, but were generally lower than the average of 8800 ppb reported for feathers from 17 studies of birds (Burger 1993).

The lead levels in the feathers of eared and red-necked grebes in this study were twice as high (and those of pied-billed and western grebes were over five times higher) than those reported for young of Franklin's gulls, American bittern, and black-crowned night-heron from the same marshes (Burger and Gochfeld 1996). Further, these lead levels were at or above the median of 1600 ppb for 69 studies of birds (Burger 1993), suggesting that lead levels should be monitored at Agassiz.

Manganese levels of the grebes were within the range reported for other birds at Agassiz (Burger and Gochfeld 1996) and were generally within the range reported from 19 other studies with birds (median of 3400 ppb; Burger 1993).

Mercury levels in the feathers of adult eared grebes (mean of 17,119 ppb) were higher than those reported for all other birds at Agassiz, including Franklin's gulls, black-crowned night-herons, double-crested cormorants, and

American bitterns (Burger and Gochfeld 1996). Further, the levels in the eared grebes were higher (eight times higher) than the median value of 2100 ppb reported for 180 studies of feather levels in birds (Burger 1993). Mercury comes from the natural erosion of soils and underlying bedrock as well as from anthropogenic sources (Parmeggiani 1983).These grebes, however, might have obtained their mercury from food-chain accumulation as a result of atmospheric deposition. Further, the periodic flooding of freshwater marshes results in more mobilization of mercury from soil than normally occurs at the bottom of lakes (Hudson et al. 1994; Zillioux et al. 1993).

Selenium levels in grebe feathers were within (or slightly higher than) the range reported for other birds at Agassiz (Burger and Gochfeld 1996) and were slightly lower than the median level of 2200 ppb reported from 42 studies with birds (except for red-necked grebe; Burger 1993). There are few data reported for arsenic, and similar comparisons are not possible.

Significance

Laboratory studies have been used to identify the levels of metals that results in adverse impacts on the behavior, physiology, or reproductive success of birds. In general, mercury levels in feathers that are associated with adverse reproductive effects in birds are 5000 ppb (Burger and Gochfeld 2000; Eisler 1987). Eared grebes exceeded this level, suggesting cause for concern, given that mercury levels in eggs are also high (see Burger and Eichhorst 2005; Burger and Gochfeld 1996).

Laboratory studies have indicated that adverse effects occur at lead levels of 4000 ppb in feathers (Burger and Gochfeld 2000; Custer and Hohman 1994). Both pied-billed and western grebes averaged close to this level for sublethal effects, suggesting that these species should be monitored for possible effects. There are few controlled laboratory studies for the other metals, making it difficult to interpret the significance of these levels.

Finally, it is important to acknowledge that all field studies have methodological problems that often entail unbalanced designs. This is due to differences in nesting and breeding success often caused either by predators or inclement weather. Even so, the data are useful in understanding differences among species and age classes.

Acknowledgments Feathers were collected under appropriate state and federal permits to Eichhorst. We thank M. Anderson, G. Huschle, D. Bennett, S. Wockenfuss, G. Tischer, and B. Wikstrom for logistical support at Agassiz NWR and T. Shukla, C. Dixon, and C. Jeitner for help with the analysis. This research was a cooperative project with the US Fish and Wildlife Service, was approved by the Rutgers University Animal Review Board, and was funded by the University of North Dakota, the US Fish and Wildlife Service, the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) through the Department of Energy (AI # DE-FC01-95EW55084, DE-FG-00NT-40938), the Division of Life Sciences of Rutgers University, and NIEHS (P30ES005022).

References

Burger J (1993) Metals in avian feathers: bioindicators of environmental pollution. Rev Environ Toxicol 5:203–311

Burger J, Eichhorst B (2005) Heavy metal and selenium levels in grebe eggs from Agassiz National Wildlife Refuge in Northern Minnesota. Environ Monit Assess 107:285–295

Burger J, Gochfeld M (1991) Cadmium and lead in common terns (Aves: Sterna hirundo): relationship between levels in parents and eggs. Environ Monit Assess 16:253–258

Burger J, Gochfeld M (1996) Heavy metal and selenium levels in birds at Agassiz National Wildlife Refuge, Minnesota: food chain differences. Environ Monit Assess 43:267–282

Burger J, Gochfeld M (2000) Effects of chemicals and pollution on seabirds. In: Schreiber EA, Burger J (eds) Biology of marine birds. CRC Press, Boca Raton, FL, pp 485–525

Burger J, Peakall D (2003) Methodologies for assessing exposure to metals: speciation, bioavailability, and ecological host factors. Ecotoxicol Environ Safety 56:110–121

Cullen SA, Jehl JR Jr, Nuechterlein GL (1999) Eared grebe (Podiceps nigricollis). In: Poole A, F. Gill F (eds) The birds of North America, No. 433. The Birds of North America, Inc., Philadelphia

Custer TW, Hohman WL (1994) Trace elements in canvasback (Aytha valisineria) wintering in Louisiana, USA, 1987–1988. Environ Pollut 84:253–259

Eisler R (1987) Mercury hazards to fish, wildlife and invertebrates: a synoptic review. Biological Report 85 (1.10). US Department of Interior, Washington DC

Fitzgerald WF (1989). Atmospheric and oceanic cycling of mercury. In: Riley JP, Chester R (eds) Chemical oceanography, Vol. 10. Academic Press, New York, pp 151–186

Furness RW (1993) Birds as monitors of pollutants. In: Furness RW, Greenwood JJD (eds) Birds as monitors of environmental change. Chapman & Hall, London, pp 86–143

Furness RW, Camphuysen KCJ (1997) Seabirds as monitors of the marine environment. ICES J Marine Sci 54:726–737

Furness RW, Rainbow PS (eds) (1990) Heavy metals in the marine environment. CRC Press, Boca Raton, FL

Furness RW, Muirhead SJ, Woodburn M (1986) Using bird feathers to measure mercury in the environment: relationship between mercury content and moult. Marine Poll Bull 17:27–37

Gochfeld M (1971) Premature feather loss: a new disease of common terns. Kingbird 21:206–211

Gochfeld M (1975) Developmental defects of common terns of western Long Island, New York. Auk 92:58–65

Gochfeld M (1980) Mercury levels in some seabirds of the Humboldt Current, Peru. Environ Poll A 22:197–205

Hays H, Risebrough RW (1972) Pollutant concentrations in abnormal young terns from Long Island Sound. Auk 89:19–35

Houghton JT, Callander BA, Varney SK (1992) Climate change 1992. Cambridge University Press, Cambridge

Hudson RJM, Cherint SA, Watras CJ, Porcella DB (1994) Modeling the biogeochemical cycle of mercury in lakes: the mercury cycling model (MCM) and its application to the MTL study lake. In: Watras CJ, Huckabee JW (eds) Mercury pollution: Integration and synthesis Lewis, Boca Raton, FL, pp 473–523

Hutton M (1987) Cadmium. In: Hutchinson TC, Meema KM (eds) Lead, mercury, cadmium and arsenic in the environment. SCOPE Monograph 31, Wiley, Chichester, UK, pp 35–42

Monteiro LR, Furness RW (1995) Seabirds as monitors of mercury in the marine environment. Water Air Soil Pollut 80:831–870

Muller MJ, Storer RW (1999) Pied-billed grebe (Podilymbus podiceps). In: Poole A, Gill F (eds) The birds of North America, No. 410. The Birds of North America, Inc., Philadelphia

Palmer RS (ed) (1962) Handbook of North American birds. Yale University Press, New Haven, CT

Parmeggiani L (1983) Encyclopedia of occupational health and safety. Intern. Labor Office, Geneva

Peakall DB (1992) Animal biomarkers as pollution indicators. Chapman & Hall, London, UK

SAS (1995) SAS users' guide. SAS Institute, Cary, NC

Storer RW, Nuechterlein GL (1992) Western and Clark's grebe. In: Poole A, F. Gill F (eds) The birds of North America, No. 26. The Academy of Natural Sciences, Philadelphia/ The American Ornithologists' Union, Washington, DC

Stout BE, Nuechterlein GL (1999) Red-necked grebe (Podiceps grisegena). In: Poole A, F. Gill F (eds) The birds of North America, No. 465. The Birds of North America, Inc., Philadelphia

Walsh PM (1990) The use of seabirds as monitors of heavy metals in the marine environment. In: Furness RW, Rainbow PS (eds) Heavy metals in the marine environment. CRC Press, Boca Raton, FL, pp 183–204

Zillioux EJ, Porcella DB, Benoil JM (1993) Mercury cycling and effects in freshwater wetland ecosystems. Environ Toxicol Chem 12:2245–2264