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CONCENTRATIONS OF TRACE ELEMENTS IN EGGS AND BLOOD OF SPECTACLED AND COMMON EIDERS ON THE YUKON–KUSKOKWIM DELTA, ALASKA, USA

JAMES B. GRAND,*† J. CHRISTIAN FRANSON,‡ PAUL L. FLINT,† and MARGARET R. PETERSEN†
†U.S. Geological Survey, Biological Resources Division, Alaska Biological Science Center, 1011 E Tudor Road, Anchorage, Alaska 99503
‡U.S. Geological Survey, Biological Resources Division, National Wildlife Health Center, 6006 Schroeder Road, Madison, Wisconsin 53711

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Abstract—We examined the relations among nesting success, egg viability, and blood and egg concentrations of As, Cd, Pb, Hg, and Se in a threatened population of spectacled eiders (*Somateria fischeri*) and a sympatric population of common eiders (*S. mollissima*) on the Yukon–Kuskokwim Delta, Alaska, USA, during 1995 and 1996. During the early breeding season, males and females had mean Se concentrations in their blood of 19.2 μg/g and 12.8 μg/g wet weight, respectively. Blood Se concentrations of females were correlated with egg concentrations. During brood rearing, blood Se levels were higher in adult females than in ducklings. Blood concentrations of Pb in spectacled eider females were higher than in common eider females captured at hatching, but blood concentrations of Se were similar. Trace element concentrations were not related to nest success or egg viability. We submit that nest success and egg viability of spectacled eiders are not related to concentrations of the trace elements we measured. Because blood Se concentrations declined rapidly through the breeding season and were not related to nest success or egg viability, we suggest that spectacled eiders are exposed to high concentrations of Se during winter that pose little threat to this population.

Keywords—Eider Trace elements Reproduction Selenium Lead

INTRODUCTION

Spectacled eiders (*Somateria fischeri*) are medium-sized sea ducks that nest in coastal areas adjacent to the Bering Sea in western and northern Alaska, USA, and adjacent to the Chukchi Sea in Russia. Populations of spectacled eiders breeding in western Alaska have declined substantially in recent years [1]. As a result of this trend, the breeding population has been listed as threatened under the provisions of the Endangered Species Act [2]. Recent studies have examined survival and productivity of spectacled eiders breeding on the Yukon–Kuskokwim Delta (YKD), Alaska, USA [3–5]. Studies of spectacled eider nesting ecology have found relatively high numbers of inviable eggs (i.e., eggs that did not hatch because of infertility or embryonic mortality) and exposure to trace elements has been linked to poor reproductive success in birds [6–11]. Liver samples collected from a small sample of eiders were found to contain high concentrations of Se, and feathers of spectacled eiders had Se concentrations of up to 64 μg/g dry weight [12,13]. Exposure to Se may impair survival of embryos and ducklings and is potentially lethal to adult waterfowl [7,8,14]. Additionally, Pb poisoning resulting from ingestion of lead shot has been shown to influence annual survival of eiders and may influence reproductive success as well [3,4]. The combination of these results resulted in speculation that exposure to trace elements may influence population dynamics of spectacled eiders. However, the effects of trace elements on spectacled eiders are largely speculative because researchers frequently document exposure to trace elements in eiders and other marine birds, but for most species the effects on reproduction in the wild are poorly understood [15–18].

Our goal was to determine the effects of selected trace elements on the reproductive success of spectacled eiders. Our objectives were to compare the levels of trace elements in viable and inviable eggs; to compare levels of five trace elements in the blood of breeding spectacled eiders among time periods, sex, and age groups; to compare levels and detection rates of trace elements in blood of spectacled eiders to those for sympatric nesting common eiders (*Somateria mollissima*); and to examine relationships between trace metal levels and reproductive success of females.

MATERIALS AND METHODS

This study was conducted along the lower Kashunuk River drainage (61°20′N, 165°35′W) on the outer coastal fringe of the Yukon Delta National Wildlife Refuge, Alaska, USA, during 1995 and 1996. The study area was previously described in detail [19]. During 1995, we collected eggs from spectacled eider nests for trace metal analysis. Each egg was classified as viable or inviable by candling in the field. During 1996, spectacled eiders and common eiders were captured and blood samples were collected during three time periods, late May (laying and incubating), late June and early July (hatching), and late July and early August (brood rearing). Techniques used to capture eiders and their young also have been described [3]. All birds were marked with U.S. Fish and Wildlife Service metal tarsus bands and weighed to the nearest 10 g. We took blood samples by jugular or brachial venipuncture. Samples were transferred immediately from plastic syringes to sodium heparinized, evacuated glass tubes and frozen as soon as possible. Samples remained frozen until analysis.

Nests were monitored weekly to determine their fates. We used three classes of nest fate: abandoned after nest trapping or other observer activities, unsuccessful because of predation or flooding, and successful (hatching at least one egg). Egg viability and stage of incubation were determined by candling in the field [20]. All inviable eggs were collected when detected; additionally a sample of viable eggs was collected at 0 to 21 d of incubation. Eggs were frozen whole until they

* To whom correspondence may be addressed (grandjb@auburn.edu).

Table 1. Mean ($\bar{x}$) (and standard error [SE]) detectable concentrations (μg/g wet wt) of As, Hg, Pb, and Se in eggs of spectacled eiders nesting along the lower Kashunuk River (AK, USA) in 1995

	Egg condition								
	Viable (n = 8)			Inviable (n = 12)			Total		
Metal	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$	SE
As	3	0.10	0.013	10	0.11	0.01	13	0.11	0.01
Se	8	0.26	0.16	10	0.25	0.07	18	0.26	0.08
Pb	8	1.15	0.07	12	1.01	0.06	20	1.07	0.05
Hg	8	0.07	0.01	12	0.07	0.01	20	0.07	0.01

could be thawed and contents transferred into acid-washed glass jars. Concentrations of As, Cd, Pb, and Se in blood and eggs were determined by graphite furnace atomic absorption spectrophotometry and total Hg concentration was determined by cold-vapor reduction absorption spectrophotometry [21–23]. Eggs were analyzed for methyl Hg by electron-capture gas chromatography [24]. All analyses were performed at Hazleton Environmental Services (Madison, WI, USA). Lower limits of detection (on a wet-wt basis) were 0.07 to 0.10 μg/g for As, Cd, and Pb; 0.01 μg/g for Hg; and 0.14 to 0.20 μg/g for Se. Mean percent recoveries from spiked samples and standard reference materials, respectively, were 86 and 92 for As, 109 and 95 for Cd, 111 and 107 for Pb, 99 and 106 for Hg, and 93 and 93 for Se. The average moisture and lipid contents of 20 eggs were 66% and 18%, respectively. All results are given in μg/g wet weight, uncorrected for percent recoveries.

Statistical analyses

We compared mean concentrations of all five trace elements simultaneously by using multivariate analysis of variance (MANOVA) on the rank-transformed data. When differences were detected, we used univariate analysis of variance on the ranks to determine which trace elements differed among groups. Likewise, we used Spearman rank correlations to examine the relations among trace elements in eggs and blood of females captured during late laying or early incubation. We used a two-way MANOVA with females as blocks to examine variation in blood levels of trace elements within females among periods. Controlling for variation among individuals in this manner is equivalent to using a repeated-measures design, and allowed us to include data from females that were sampled one to three times in a single analysis. We used analysis of covariance on the log-transformed levels to estimate the daily decline in blood Se while controlling for variation among individuals. We estimated half-time, the time to reduce trace element concentration to 50% of the initial observed level, with the formula ln(0.5)/ln(1 − rate of decline). Daily mass loss and daily decline in blood concentration of Se was calculated with the formula

$$r = \left(\frac{x_2}{x_1}\right)^{1/t}$$

where r is the proportional rate of decline in a parameter, x_1 is the parameter value at time 1, x_2 is the parameter value at time 2, and t is the time (days) between measurements. We used a two-way MANOVA on rank-transformed data with females as blocks to examine variation in blood levels of trace elements among females with different nesting fates and between females laying inviable eggs (one or more inviable eggs in the clutch) and those laying only viable eggs. Similarly, we used MANOVA on ranks with females as blocks to compare levels of trace elements between viable and inviable eggs.

RESULTS

In 1995, we collected 20 eggs from six different nests, including 12 eggs that were inviable and 8 eggs that were developing. In 1996, we collected 110 blood samples from 73 spectacled eiders and 11 common eiders for laboratory analysis. Adult female spectacled eiders were sampled during laying or in early incubation only (n = 24), hatching only (n = 5), during laying or in early incubation and again at hatching (n = 20), at hatching and again during brood rearing (n = 2), and during all three sampling periods (n = 2). Adult male spectacled eiders (n = 10) were sampled while females were laying or in early incubation. Spectacled eider ducklings (n = 10) were sampled from broods of females that were not sampled or were in mixed broods with several adult females present. Adult female common eiders (n = 11) were sampled only at hatching. In 1996, we also collected 50 eggs (19 viable and 31 inviable) from 24 spectacled eider nests during early incubation. Of the eggs collected in 1996, 47 came from nests of 21 females from which blood samples also were collected.

Blood and egg concentrations

In 1995, trace element concentrations did not differ between eggs that were viable and those that were not (MANOVA, $F_{4,15}$ = 1.76, p = 0.19; Table 1). However, some indication was found that As levels were higher in inviable eggs because detectable levels were found in 27% of viable eggs and 45% of inviable eggs. Methyl Hg was not detected in eggs collected in 1995.

In 1996, concentrations of trace elements varied between adult female spectacled eiders captured during laying and early incubation and adult male spectacled eiders captured during a similar time period (MANOVA, $F_{5,50}$ = 2.94, p = 0.02; Table 2). Further analysis revealed that only concentrations of Se differed between males and females ($F_{1,54}$ = 7.85, p = 0.01; Table 2). Rank concentrations of As ($F_{1,54}$ = 0.88, p = 0.35), Cd ($F_{1,54}$ = 0.21, p = 0.65), Pb ($F_{1,54}$ = 2.98, p = 0.09), and Hg ($F_{1,54}$ = 1.18, p = 0.28) were similar between males and females.

Concentrations of trace elements also varied between adult female spectacled eiders and ducklings captured at about 30 d after hatching (MANOVA, $F_{5,8}$ = 4.02, p = 0.04). Concentrations of Se in blood differed between ducklings and brood-rearing females ($F_{1,13}$ = 19.2, p = 0.0009; Table 2), but concentrations of As ($F_{1,13}$ = 2.19, p = 0.16), Cd ($F_{1,13}$ = 0.38, p = 0.55), Pb ($F_{1,13}$ = 2.33, p = 0.15), and Hg ($F_{1,13}$ = 0.48, p = 0.50) were similar.

Likewise, trace element concentrations also varied between adult female spectacled eiders and common eiders captured

Table 2. Number (percent), mean concentration (μg/g wet wt), and standard error (SE) of blood samples containing detectable levels of As, Cd, Hg, Pb, and Se from spectacled eiders (SPEI) and common eiders (COEI) by sex (male [M], female [F]), age (after second year [ASY], ducklings [LOC]), and time period (incubating [I], hatch [H], brood rearing [B]) in the lower Kashunuk River (AK, USA) study area, 1996. The minimum detection level was 0.01 μg/g for Hg; 0.10 μg/g for As, Cd, and Pb; and 0.20 μg/g for Se

				As			Cd			Se			Hg			Pb		
Species	Sex	Age	Period	*n* (%)	Mean	SE	*n* (%)	Mean	SE	*n* (%)	Mean	SE	*n* (%)	Mean	SE	*n* (%)	Mean	SE
SPEI	M	ASY	I	1 (10)	0.11	—	0	—	—	10 (100)	19.26	2.18	10 (100)	0.14	0.01	9 (90)	0.14	0.01
SPEI	F	ASY	I	10 (22)	0.15	0.01	1 (2)	0.21	—	46 (100)	12.79	0.78	46 (100)	0.14	0.01	38 (83)	0.74	0.22
COEI	F	ASY	H	3 (22)	0.12	0.01	0	—	—	11 (100)	7.29	0.65	11 (100)	0.15	0.04	9 (82)	0.14	0.01
SPEI	F	ASY	H	6 (21)	0.14	0.01	1 (3)	0.10	—	29 (100)	9.03	0.56	29 (100)	0.14	0.03	26 (90)	2.02	1.19
SPEI	F	ASY	B	0	—	—	0	—	—	4 (100)	4.32	0.50	4 (100)	0.15	0.04	3 (75)	1.02	0.69
SPEI	—	LOC	B	4 (60)	0.14	0.01	1 (10)	0.27	—	10 (100)	1.96	0.28	10 (100)	0.15	0.03	6 (60)	0.14	0.01

on nests at hatch ($F_{5,34} = 2.49$, $p = 0.05$). In this case, concentrations of Pb in blood differed between species ($F_{1,38} = 6.30$, $p = 0.02$), and rank concentrations of As ($F_{1,38} = 0.11$, $p = 0.74$), Cd ($F_{1,38} = 0.37$, $p = 0.54$), Se ($F_{1,38} = 2.28$, $p = 0.14$), and Hg ($F_{1,38} = 1.72$, $p = 0.20$) were similar.

We detected Cd, Pb, As, Hg, and Se in 0, 16, 64, 82, and 100%, respectively, of eggs ($n = 50$; Table 3). Concentrations of As, Pb, and Hg in eggs were not correlated with blood concentrations in laying females ($n = 47$; $r = -0.14$, 0.14, -0.05; $p = 0.35$, 0.36, 0.76), but concentrations of Se in eggs were positively correlated with blood levels in females ($n = 47$, $r = 0.46$, $p = 0.001$).

Dynamics of selenium in blood

Repeated measurements of trace element concentrations in adult female spectacled eiders varied among periods (MANOVA, $F_{10,40} = 9.473$, $p = 0.001$; Table 2). Closer inspection revealed that rank concentrations of As ($F_{2,24} = 2.26$, $p = 0.13$), Cd ($F_{2,24} = 0.56$, $p = 0.58$), Pb ($F_{2,24} = 1.81$, $p = 0.18$), and Hg ($F_{2,24} = 2.34$, $p = 0.12$) did not vary among periods. However, concentrations of Se in blood changed among periods ($F_{2,24} = 82.96$, $p < 0.01$; Table 2) and average concentrations of Se were highest among females captured during laying and early incubation. The log-transformed blood concentration of Se declined during the period from laying through brood rearing ($F_{1,78} = 49.55$, $p < 0.01$, $R^2 = 0.93$; Fig. 1). The average daily decline in blood Se was 1.9 ± 0.2% per day (Fig. 2) yielding a half-life estimate for Se of approximately 37 d (95% CI 33–41 d). The rate of decline in Se concentration was negatively correlated with mean daily mass loss (Fig. 1).

Nest success, egg viability, and impact of trace elements on condition and nest success

Trace element concentrations in blood were not different among females that abandoned their nests, those that nested successfully, and those that were unsuccessful ($n = 9$, 22, and 15; $F_{12,76} = 0.85$; $p = 0.60$), nor did trace element concentrations in blood differ between females laying all viable eggs and those that laid at least one inviable egg ($F_{5,49} = 1.13$, $p = 0.36$; Table 3). After we controlled for variation among nests (females), trace element concentrations did not differ in viable versus inviable eggs ($F_{4,22} = 0.78$, $p = 0.55$; Table 3).

DISCUSSION

Selenium

Selenium is known to cause mortality and teratogenic effects in water birds [25]. Levels of Se in the blood of spectacled eiders in early incubation and at hatch were similar to or greater than levels that were associated with mortality among mallards (*Anas platyrhynchos*) in experimental studies [26–28]. Blood Se concentrations in the eiders that we sampled also were greater than levels found in sympatric emperor geese (*Chen canagica*) or common eiders nesting in the Baltic Sea [15,29,30]. Although Hg or As [31,32] may interact to alleviate the toxic effects of Se, the concentrations of Hg and As in the blood samples we examined were quite low and were not correlated with Se levels.

Blood Se levels of adult females may have been lower than those of adult males during laying and early incubation, because females deposited Se in eggs. Furthermore, we speculate that the high metabolic costs of egg laying and incubation resulted in increased excretion rates. Concentrations of Se in

Table 3. Mean detectable concentrations (μg/g wet wt) of As, Cd, Hg, Pb, and Se in blood and eggs of spectacled eiders nesting along the lower Kashunuk River (AK, USA) in 1996

	Eggs						Females					
	Viable (n = 19)			Inviable (n = 31)			All eggs viable (n = 38)			With inviable eggs (n = 8)		
Metal	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$	SE
As	10	0.13	0.02	22	0.15	0.02	8	0.14	0.01	2	0.17	0.04
Cd	—	—	—	—	—	—	1	0.21	—	0	—	—
Se	19	1.42	0.09	31	1.20	0.05	38	13.30	0.88	8	10.36	1.34
Pb	4	0.09	0.01	4	0.14	0.04	31	0.79	0.27	7	0.55	0.24
Hg	15	0.06	0.01	26	0.06	0.01	38	0.14	0.02	8	0.10	0.01

eggs are sensitive to dietary changes and probably reflect recent exposure [33]. Despite high concentrations of Se in blood, we found no measurable differences between viable or inviable eggs or the females that laid them, and no evidence of poor condition or mortality among females early in the nesting season when blood Se levels were highest.

Spectacled eiders eliminated Se at a rapid rate, indicating that the greatest exposure occurred prior to their arrival on the YKD. Additionally, blood Se concentrations of 30-d-old ducklings were much lower than those for adult females, suggesting that food items on the YKD were not a significant source of Se. We propose that the rapid decline in blood Se concentrations for adult female spectacled eiders indicated that high Se concentrations are accumulated from the invertebrates they consumed at sea during winter. This is similar to the hypothesis used to explain Se exposure of emperor geese. At the time of hatching, blood Se levels in adult female spectacled eiders and common eiders were similar, suggesting similar exposure to Se sources. Although the wintering ranges of common eiders and spectacled eiders do not overlap, both species winter in the Bering Sea and feed primarily on benthic and epibenthic marine invertebrates. The bioaccumulation of Se and other trace elements in marine invertebrates is well documented [34–36].

The rate of decline in blood Se levels of adult females we observed (1.9 ± 0.2% per day, half-time 37 d) was much slower than that observed among mallards under laboratory conditions (7.1% per day, half-time 9 d) [26]. This slower rate of decline may have been due to exposure to low levels of Se on the breeding grounds, as evidenced by the observed concentrations in blood of ducklings. However, the rate of decline we observed was greater than the +1% per day and −1% per day observed in two emperor geese in the same region in western Alaska [29]. Concentrations in blood were highest among adult female spectacled eiders early in the nesting season and the rate of decline in Se concentration was negatively related to average daily mass loss between captures. Thus, females captured early were heaviest and exhibited the greatest use of stored reserves for incubation, but their blood Se concentrations declined more slowly than later-nesting females with fewer nutritional reserves.

Lead

Lead exposure in spectacled eiders and its detrimental effects on their survival on the YKD are well documented [3,5,16,37,38]. Given the high prevalence of Pb exposure in spectacled eiders on our study area and the potential effect of Pb on egg hatchability, we suspected Pb to be related to the high incidence of inviable eggs [39]. However, we found no relationships among blood Pb levels, nesting success, Pb concentrations in eggs, and egg viability.

Detectable Pb was present in at least 60% of the blood samples in every comparison group and 16% of the eggs we examined. That we found no correlation between Pb concentrations in eggs and blood is not surprising, because eggs are generally thought to be of little use in evaluating exposure of birds to Pb [17]. The mean blood Pb concentrations of females captured during laying and early incubation, hatch, and brood rearing were higher than those reported in an earlier study of spectacled eiders on the YKD [16]. Flint et al. [16] modeled the Pb exposure rate (blood Pb levels > 0.20 μg/g) of spectacled eiders through the breeding season under the assumption that the daily exposure probability of spectacled eiders to Pb was relatively constant from arrival on the YKD through departure. The high mean Pb concentration in blood of females

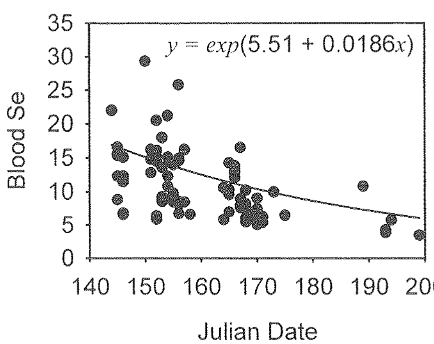

Fig. 1. Decline in Se concentrations (μg/g wet wt) in blood of adult female spectacled eiders from laying through 30 d after hatch along the lower Kashunuk River, Alaska, USA, 1996.

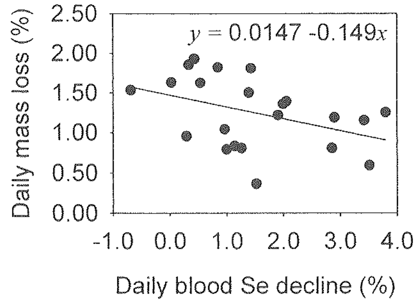

Fig. 2. Daily mass loss (%) versus the daily decline in Se concentrations (% wet wt) in the blood of spectacled eider adult females captured during laying and early incubation and then at hatch along the lower Kashunuk River, Alaska, USA, 1996 (Pearson rank correlation, r^2 = 0.20, p = 0.04).

in early incubation observed in this study suggests that most exposure occurred before the onset of incubation. This is consistent with the observations of Flint and Grand [40] on the high rate of incubation constancy and infrequent incubation breaks by females.

Cadmium

Cadmium is known to cause a number of sublethal effects in animals, but was present in less than 3% of the blood samples we examined. Furthermore, seabirds may tolerate higher levels of exposure to Cd than freshwater birds [11,41,42]. Thus, it is not likely that this trace element caused any problems in the birds we studied.

Arsenic

In controlled studies on captive mallards, As caused reduced growth rates in ducklings and eggshell thinning, but did not affect survival of young or hatching success of eggs [31]. Although As was detectable in many of the blood and egg samples, rank concentrations of As did not vary between any of the comparison groups. The concentrations of As we found in the blood of eiders were considerably lower than those attained in mallards in a study of accumulation rates [43].

CONCLUSIONS

The trace elements we examined are suspected contaminants with detrimental effects on survival and reproduction. Nonetheless, we found no evidence that the concentrations we found in blood and eggs affected nest success or egg viability of spectacled eiders. Of particular interest, we found very high concentrations of Se in the blood, but relatively low concentrations in eggs. Our results imply that some trace elements, particularly Se, are normal constituents of marine environments that are concentrated by the benthic and epibenthic invertebrates that eiders consume. Therefore, in contrast to freshwater species, eiders and other marine birds may have evolved the physiological means to eliminate these trace elements or neutralize their harmful effects. However, we only studied breeding birds, and contaminant burden accrued over winter could influence body condition in spring thereby reducing the number of birds that attempt to breed. Further investigations should examine contaminant loads in nonbreeding birds, the adaptations that allow marine birds to tolerate high concentrations of Se, and the sources of trace elements in foods consumed by marine birds of the Bering Sea and North Pacific Ocean.

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