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COUPLING CONTAMINANTS WITH DEMOGRAPHY: EFFECTS OF LEAD AND SELENIUM IN PACIFIC COMMON EIDERS

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Abstract—We coupled intensive population monitoring with collection of blood samples from 383 nesting Pacific common eiders (*Somateria mollisima v-nigrum*) at two locations in Alaska (USA) from 2002 to 2004. We investigated annual, geographic, and within-season variation in blood concentrations of lead and selenium; compared exposure patterns with sympatrically nesting spectacled eiders (*Somateria fischeri*); and examined relationships with clutch size, egg viability, probability of hatching, and apparent survival of adult females. Lead concentrations were elevated in 3.6% of females, and all individuals exhibited elevated selenium, most (81%) at concentrations associated with death in captive waterfowl. Blood lead and selenium concentrations varied both within and among site-years and were lower than those of spectacled eiders. During incubation, blood lead concentrations in females increased significantly (possibly via re-release of stored lead from bone), whereas selenium concentrations decreased (likely because of natural excretion). Probability of a nest containing at least one nonviable egg was positively related to blood selenium in hens, but adverse effects in other life-history variables were not supported. Although reproduction appeared to be sensitive to selenium toxicity, our data suggest that high rates of nonviability are unlikely in this population and that selenium-related reductions to clutch size would be inconsequential at the scale of overall population dynamics. We conclude that Pacific common eiders and other wild marine birds likely have higher selenium tolerances than freshwater species and that interspecific differences in exposure levels may reflect differences in reproductive strategies.

Keywords—Alaska Blood Lead Selenium Pacific common eider

INTRODUCTION

Identification of measurable demographic responses to environmental stressors, such as contaminants, is critical in assessing population-level impacts to wildlife. Linking contaminants with reproduction and survival not only provides a means of estimating specific vital rate effects but also can be used to assess relative influences on overall population dynamics. However, examining demographic effects in wild populations is difficult, as it requires the coupling of nondestructive sampling with detailed, long-term, individual life-history information.

Trace elements, such as lead, selenium, mercury, and cadmium, are ubiquitous in the marine environment, and sea birds can serve as sensitive bioindicators of these elements [1,2]. Among marine birds, sea ducks (tribe Mergini) have undergone broad-scale declines across their distribution [3], and exposure to contaminants has been suggested as a potential contributing factor in these declines [3,4]. Sea ducks have long life spans, occupy high trophic positions, and may be exposed to anthropogenic inputs in both marine and terrestrial environments [4,5]. They depend on sessile, filter-feeding, benthic invertebrates as their primary food source [3,4], and these organisms are known to bioaccumulate high levels of local contaminants [6]. Furthermore, high prevalence of spent lead shot in areas with historical hunting activity, such as on some sea duck breeding grounds [5,7], may increase their susceptibility to exposure.

On the Yukon–Kuskokwim Delta (YKD) in western Alaska (USA), Pacific common eiders (*Somateria mollisima v-nigrum*) have declined by more than 90% during the past 40 years [8], and in accord with similar declines in sympatrically nesting spectacled (*Somateria fischeri*) and Steller's (*Polysticta stelleri*) eiders [8]. Although no single cause for these population declines has been identified [3], lead poisoning (via ingestion of spent shot) is a known source of mortality for nesting common and spectacled eiders on the YKD [5,9]. Furthermore, local blood selenium concentrations are within ranges associated with death in experimental mallards (*Anas platyrhynchos*) [5,10–12].

Lead is considered to be a nonessential, highly neurotoxic metal, and its effects on adult survival have been well studied [13]. Conversely, selenium is an essential trace element, which can become toxic at high concentrations [14]. Importantly, reproduction (particularly early development [15,16]) appears to be more sensitive than adult survival to elevated selenium [10,14]. Laboratory and field studies suggest that blood concentrations of both elements can be extremely dynamic [10,11,16–18], thus serving as stronger indicators of recent exposure than other tissues. Because common eiders fast during their entire incubation period [19], they offer a natural control for examining toxicokinetics and comparing exposure patterns with species that feed on their terrestrial breeding grounds (e.g., the spectacled eider [20]).

Based on high levels of lead and selenium in eiders and other sea ducks [4,5,11,12,18,21,22], combined with the need for es-

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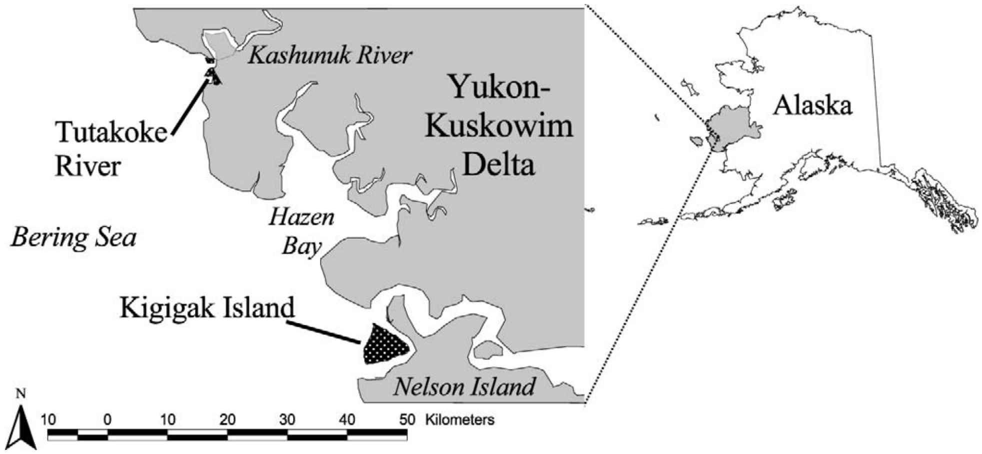

Fig. 1. Study sites (Tutakoke River and Kigigak Island) on the Yukon–Kuskokwim Delta (AK, USA) where blood samples were collected from nesting Pacific common eiders (*Somateria mollisima v-nigrum*) from 2002 to 2004.

timates of contaminant-related demographic effects, we measured blood concentrations in nesting Pacific common eiders. We evaluated spatial and temporal patterns of lead and selenium occurrence, and we quantified differences in blood concentrations among eiders at specific breeding sites and across years. In addition, we examined within-season dynamics of lead and selenium (i.e., changes across the incubation period) both within and among females, and we compared exposure patterns between sympatrically nesting common and spectacled eiders. Finally, we examined relationships between blood contaminant concentrations and life-history traits: Clutch size, egg viability, nest survival, and apparent survival of adult females.

MATERIALS AND METHODS

Sample collection

We sampled adult Pacific common eiders during the nesting period at two primary breeding sites on the YKD (Fig. 1) from 2002 to 2004: Tutakoke River (TR; 60°51′N, 165°49′W) and Kigigak Island (KI; 60°50′N, 165°50′W). Each year, we searched for nests and, once found, revisited them every 7 d until hatch or failure. We candled all eggs at each visit to assess egg viability and incubation stage. We captured females throughout incubation (day 0 = nest initiation, day 26 = hatch) using mist nets, decoys, and bow-net traps. In 2003 and 2004, we collected two samples within each season from a subset of females (n = 20) captured early (0–15 d) and late (16–26 d) in incubation. In all captures, we marked birds with U.S. Geological Survey metal and alphanumerically coded plastic leg bands, weighed individuals to the nearest gram, and collected 5 ml of blood by jugular or brachial venipuncture. All sampling was conducted following protocols approved by the University of Alaska, Fairbanks Institutional Animal Care and Use Committee. At collection, we immediately transferred 3 ml of whole blood to lithium-heparanized BD Vacutainers® (Becton, Dickinson and Company, Franklin Lakes, NJ, USA) for trace element analyses. All blood samples were frozen within a few hours of collection in liquid nitrogen vapor shippers and were maintained frozen in the laboratory at −80°C until analysis.

Trace element analyses

We analyzed blood lead and selenium concentrations using inductively coupled plasma–mass spectrometry. Mean percentage recoveries from standard reference material and spiked samples were 96 and 100%, respectively, for lead and 110 and 102%, respectively, for selenium. We report all trace element results as μg/g wet weight, uncorrected for percentage recoveries. The lower limit of detection for both lead and selenium was 0.01 μg/g wet weight. We assigned a concentration of one-half the lower limit of detection to all samples that were below detection limits in calculating group means and standard errors [11], and we report detection rates (% above the lower limit of detection) for all groups (i.e., by site, year, and sex) when rates were less than 100%.

Statistical analyses

The majority (94%) of our sample was composed of adult females, although we captured a small number of males at KI in 2003 (n = 8) and at TR in 2004 (n = 15). Because males were sampled only during the preincubation period and only in specific site-years, we analyzed them separately. Most (90%) of the females in the present study were sampled only once per year. To avoid pseudoreplication for the 20 females sampled twice within seasons (2002–2003), we randomly selected one of the paired samples for inclusion in our overall analysis of spatiotemporal variation in contaminant concentrations. Assumptions of normality within samples were not met (Shapiro-Wilk; lead: $W = 0.10$, $p < 0.01$; selenium: $W = 0.97$, $p < 0.01$) even after log-transformation (log(lead): $W = 0.98$, $p < 0.01$; log(selenium): $W = 0.76$, $p = 0.02$). Therefore, we used nonparametric statistics, unless otherwise stated, and report partial coefficients (β values) to indicate direction of relationships. Because we performed analyses on ranked concentrations, estimated β values and their associated variances were in ranked form and, thus, were not appropriately scaled for direct interpretation. We report patterns of variation as indicated by our best approximating models and means and standard errors on the original scale of the data (Table 1).

Model selection. We tested for multicollinearity among all our explanatory variables before constructing multivariate models. The original data were orthogonal, and estimated variance inflation factors by site-year were low (range, 1.01–1.19), indicating little correlation among explanatory variables. For each of our primary analyses, we created suites of hierarchical models based on biologically meaningful combinations of explanatory variables (≤5 variables/analysis). We used Akaike's Information Criterion adjusted for small sample sizes (AIC_c), model weights (w_i), sums of model weights ($\Sigma\ w_i$), and mea-

Table 1. Blood lead and selenium concentrations (μg/g wet wt) in adult Pacific common eiders (*Somateria mollisima v-nigrum*) at two breeding locations, Kigigak Island (KI) and Tutakoke River (TR), on the Yukon–Kuskokwim Delta (AK, USA), from 2002 to 2004. $\bar{x}$ = mean

			Lead				Selenium			
Location	Year	Sex	n	$\bar{x}$	SE[a]	Range	n	$\bar{x}$	SE	Range
KI	2002	F	45	0.27	0.16	0.02–7.00	45	5.77	0.25	2.10–10.50
	2003	F[b]	67	0.04	0.01	0.01–0.28	67	7.11	0.25	3.20–13.00
		M	8	ND[c]	ND	ND	8	9.88	0.58	7.50–13.00
	2004	F[b]	135	0.05	0.01	0.02–0.50	135	6.74	0.21	1.50–15.00
		M	7	0.01	0.01	0.01–0.03	7	9.53	1.26	4.60–12.70
TR	2002	F	61	0.15	0.11	0.01–6.60	61	6.62	0.24	2.20–11.20
	2003	F	2	ND	ND	ND	2	10.00	1.00	9.00–11.00
		M	3	0.01	0.01	0.01–0.03	3	9.47	0.82	8.20–11.00
	2004	F	44	0.05	0.01	0.02–0.60	50	8.71	3.51	4.00–15.70
		M	5	0.01	0.01	0.01–0.03	5	11.40	3.79	5.80–18.80

[a] SE = standard error.
[b] Percentages of samples in which trace elements were detected; lead (KI females: 2003, 48%; 2004, 94%). All other groups had 100% detection unless otherwise noted.
[c] ND = not detected.

surements of model fit ($-2\ \log(L)$ or deviance) to evaluate strength of evidence for competing models and individual explanatory variables [23]. When model-selection uncertainty was high (i.e., top model $w_i < 0.9$), we calculated model-averaged estimates [23].

Spatiotemporal variation. We hypothesized that lead and selenium concentrations would vary between study sites, among years, and within seasons, as previously observed for spectacled eiders [5,21]. Because selenium tends to be highly interactive with other elements [14], we also considered the influence of selenium on lead concentrations. We examined these interactions using separate analyses of covariance on ranked trace element concentrations [24].

Temporal dynamics and repeated samples. In previous laboratory and field studies, selenium typically declined nonlinearly after exposure was terminated [10,17,21], and in at least one study, blood lead concentrations were positively correlated with stage of incubation [18]. Thus, we considered models in which lead and selenium varied from early to late incubation. We examined within-female temporal variation in blood concentrations using females sampled twice within the same site-year. Herein, we used a method similar to repeated-measures analysis, in which we controlled for variation among individuals and then examined variation between early and late incubation. We did so using separate analyses of variance for lead and selenium. To maintain results comparable with those of previously published studies [17,21], we also calculated daily change in trace elements using nonlinear regression on repeated samples. Herein, we fit our data to the formula [21]

$$\text{rate of change} = \left(\frac{x_{t_2}}{x_{t_1}}\right)^{1/(t_2-t_1)}$$

where x_t is the concentration at a given time t, t_1 is the first sample, and t_2 is the second sample. Finally, we used a general linear model to examine the relationship between ranked blood lead and selenium concentrations and body mass after controlling for incubation stage.

Selection of life-history traits for analysis

In examining demographic effects of contaminants, we chose life-history traits based on their direct relation to productivity or survival, their association with lead and/or selenium effects in laboratory or field studies of waterbirds, and whether we had sufficient data to conduct robust demographic analyses. Based on patterns of elevated blood lead and associated negative impacts on the survival of spectacled eiders [21,25], as well as documented lead poisoning in local common eiders [9], we hypothesized that high blood lead would have a negative effect on life-history traits. Similarly, we reasoned that elevated selenium also would result in negative effects on survival and reproduction [10,14,26]. We did not, however, rule out the possibility that as an essential element, selenium also might have positive effects [27].

Clutch size and nonviable eggs. Given the documented negative effects of elevated selenium on embryo viability [14,26] and the detrimental properties of lead in relation to adult physiology [13], we hypothesized that clutch size would be negatively related to contaminant burdens. According to the same logic, we reasoned that the probability of a clutch containing at least one nonviable egg (i.e., an egg that was never fertilized or that showed no development) would be positively related to blood concentrations of lead and selenium in the hen. We used general linear models to examine the effect of rank lead and selenium on clutch size after controlling for study site, year, initiation date, and incubation stage. Similarly, we used logistic regression [24,28] to model the probability of at least one nonviable egg in a nest, as a function of blood selenium and lead concentrations in the hen, after controlling for incubation stage at sampling. Using relationships described by our best approximating models, we then estimated the probability of a clutch containing at least one nonviable egg across the range of trace element concentrations observed in the present study.

Nest survival. We hypothesized that nest survival would be negatively related to lead concentrations. We did not make similar predictions for relationships with selenium, however, because nest survival has been both negatively [26] and positively [27] related to selenium in previous studies. We used logistic regression to model the probability of at least one egg in a nest hatching (i.e., nest survival) in relation to trace element concentrations in the hen. Because nests of females sampled later during incubation had higher probabilities of hatching than those sampled earlier (because of shorter time until hatch), we controlled for incubation stage at sampling [29]. We calculated expected nest survival using the formula

$$\text{nest survival} = \prod_{i=j}^{26} \text{DSR}$$

Table 2. Top models used to assess spatial (site) and temporal variation (year, incubation stage [INC]) and contaminant interactions in blood lead and selenium concentrations of female Pacific common eiders (*Somateria mollisima v-nigrum*) nesting on the Yukon–Kuskokwim Delta (AK, USA) from 2002 to 2004

Model	Variables	k[a]	AIC_c[b]	Deviance	ΔAIC_c	w_i[b]
Lead						
1	Site, year, INC	5	6,167.09	6,156.91	0.00	0.58
2	Site, year, INC, selenium	6	6,168.33	6,156.08	1.24	0.31
3	Site, year, INC, selenium, site × year	7	6,170.33	6,156.00	3.24	0.11
Selenium						
1	Site, year, INC, lead, site × year	7	6,239.37	6,225.04	0.00	0.61
2	Year, site, INC	5	6,241.19	6,231.01	1.81	0.24
3	Year, site, INC, lead	6	6,242.42	6,230.17	3.05	0.13

[a] k = number of parameters in model.
[b] The best approximating model has the lowest Akaike's Information Criterion adjusted for small sample size (AIC_c) value and the highest model likelihood (w_i) relative to others in the model set.

where nest survival was the product of site-year, incubation stage–specific (i), daily nest survival rates (DSR) from previous nest survival analysis (unpublished data) for the interval between incubation stage at time of sampling (j) and hatch (26 d). After controlling for expected nest survival given stage at sampling, we considered only models that allowed probability of hatching to vary according to lead and selenium concentrations, nest survival alone, or not at all (i.e., intercept-only model).

Apparent survival of adult females. Based on reduced apparent survival rates in adult female spectacled eiders exposed to lead (blood lead, >0.02 μg/g) on the YKD [25], we hypothesized that apparent survival of adult female common eiders would be negatively related to their blood lead concentrations. We did not, however, make similar directional predictions for selenium. We examined apparent annual survival in relation to blood lead and selenium concentrations using data from individuals sampled in 2002 and/or 2003 and recaptured in 2003 and/or 2004. Individual lead and selenium concentrations were adjusted for incubation stage by subtraction from predicted values for a given stage of incubation (i.e., residuals from linear regression). As such, concentrations were functionally standardized to a mean of zero. Females that were unobserved in a particular year but sampled previously were assigned the mean standardized contaminant concentration in years they were not encountered. We modeled annual apparent survival (φ) and encounter (p) probabilities using a Cormack-Jolly-Seber model in program MARK [30]. We treated adjusted blood concentrations of lead and selenium as annual time-varying individual covariates (e.g., t_1 = 2002, t_2 = 2003) of survival [30], and we used a logit link to bound parameter estimates between zero and one. We developed a limited suite of biologically plausible models in which apparent survival varied with individual trace element concentrations, with lead or selenium differently between study sites, or not at all. Similarly, encounter probabilities could vary across study sites or years, or they could remain constant. Our most parameterized model included an effect of individual trace element concentrations that varied between study sites and encounter probabilities that varied across study sites and years. We examined possible overdispersion ($\hat{c}$) of the data and adjusted AIC_c values if $\hat{c} > 1.0$.

RESULTS

We collected a total of 403 blood samples from 360 individual females and 23 males. We detected lead (> 0.01 μg/g) in 84% of birds sampled (Table 1). Although lead was detected in 86% of females and in 26% of males, almost all detections (96%, n = 323) were at concentrations below the subclinical toxicity threshold of 0.2 μg/g [13]. No males had lead concentrations above subclinical toxicity; however, we found elevated lead concentrations ranging from 0.2 to 7.0 μg/g in 14 (3.6%) incubating females (Table 1). In contrast, all birds had detectable selenium (Table 1), and most (81%) were at blood concentrations associated with death in experimental mallards (5–14 μg/g [10]).

Variation in blood concentrations of trace elements

Rank lead and selenium concentrations in females were highly variable between study sites both within and among years (Table 2). The best approximating model of variation in rank blood lead included study site, year, and incubation stage (Table 2, model 1, lead), whereas the top selenium model included each of these variables in addition to a correlation term between selenium and lead and an interaction between study sites and years (Table 2, model 1, selenium). Rank lead concentrations were highest in 2002; selenium concentrations were highest in 2003 (Table 1). Females at KI generally were higher in lead but lower in selenium compared with those at TR except in 2002 (Table 1). Additionally, the correlation between rank lead and rank selenium was included among the top models for each element (Table 2). This correlation was negative and had reasonably high support ($\Sigma\ w_{lead}$ = 0.42, $\Sigma\ w_{selenium}$ = 0.75).

Dynamics of trace elements in blood

After controlling for study site and year, our data supported trends of increasing lead and decreasing selenium concentrations throughout the incubation period ($\Sigma\ w_{incubation\ stage}$ = 0.99) (Table 2). The linear increase in blood lead was 0.002 ± 0.001 μg/g/d; selenium concentrations decreased at 0.07 ± 0.02 μg/g/d. We had an insufficient sample size of repeatedly sampled females with detectable blood lead (n = 10) to perform repeated-measures analyses. Thus, a nonlinear rate of decline in blood lead could not be calculated. After controlling for individual effects, paired measurements of selenium indicated a decreasing trend with incubation stage ($F_{1,19}$ = 4.07, p = 0.04) of 0.05 ± 0.02 μg/g/d. Furthermore, we estimated the nonlinear daily rate of decline in blood selenium to be 0.963% ± 0.003% per day. Mass of female common eiders did not vary with blood lead or selenium concentrations after controlling for incubation stage at sampling ($\Delta AIC_c > 5.23$). On

Table 3. Top models of the probability of at least one nonviable egg in the nest as a function of blood lead and selenium concentrations (μg/g wet wt) after controlling for incubation stage at the time of sampling in female Pacific common eiders (*Somateria mollisima v-nigrum*) nesting on the Yukon–Kuskokwim Delta (AK, USA) from 2002 to 2004

Model	Variables	k^a	AIC_c^b	$-2\log(L)$	ΔAIC_c	w_i^b
1	Selenium	2	185.18	181.18	0	0.34
2	Intercept only	1	186.28	184.28	1.10	0.20
3	Selenium, lead	3	186.95	180.95	1.77	0.14
4	Lead	2	187.98	183.98	2.80	0.08

[a] k = number of parameters in model.
[b] The best approximating model has the lowest Akaike's Information Criterion adjusted for small sample size (AIC_c) and the highest model likelihood (w_i) relative to others in the model set.

average, females lost 17.09 ± 2.90 g of body mass per day of incubation.

Clutch size and nonviable eggs

We found no support for relationships between clutch size and female blood concentrations of lead or selenium ($\Delta AIC_c > 5.19$). Our best approximating model of the probability of at least one nonviable egg in the nest (Table 3, model 1) indicated a positive relationship with blood selenium (odds ratio, 1.15; 90% confidence interval [CI], 1.01–1.31). These results indicated that the odds of at least one nonviable egg occurring in a clutch increased 1.15-fold per each 1 μg/g increase in blood selenium (Fig. 2). Some support was found for an effect of lead in combination with selenium (ΔAIC_c = 1.77), but overall, $\Sigma\ w_{lead}$ (0.33) was much smaller than $\Sigma\ w_{selenium}$ (0.66). Moreover, lead relationships were poorly estimated (odds ratio, 0.61; 90% CI, 0.05–6.99) and opposite the direction of hypothesized adverse effects. Overall, we detected nonviable eggs in 7.7% of the nests of females that were sampled for lead or selenium and for which data regarding clutch size were complete (n = 284). Blood selenium concentrations in females with at least one nonviable egg ranged from 4.10 to 14.80 μg/g. Furthermore, using model results, we predicted females at the average blood selenium concentration (6.96 μg/g) would have a 7.2% probability of at least one nonviable egg in their clutch (Fig. 2) and would approach the 50% effect level at 24.8 ± 0.14 μg/g of selenium.

Nest survival

We examined 290 nests of hens that were sampled for contaminants over the three years of our study. We found little support for a relationship between trace element concentrations and probability of hatching at least one egg in the nest after controlling for predicted nest survival given incubation stage. All models including lead and selenium had ΔAIC_c values at least equal to those of the intercept-only model, and $\Sigma\ w_i$ values for all models containing lead and selenium (0.20 and 0.32, respectively) were less than half of those for models containing nest survival (0.73). Overall, probability of hatching did not appear to be related to blood lead concentrations (ΔAIC_c = 1.95, $\Sigma\ w_{lead}$ = 0.20; odds ratio, 1.13; 90% CI, 0.48–2.69), but there was some support for a model that included selenium (ΔAIC_c = 0.45). However, selenium effects were weak and poorly estimated (odds ratio, 1.09; 90% CI, 0.97–1.22).

Of females with elevated blood lead levels (>0.02 μg/g) for which we had complete nest data (n = 12), 25% were unsuccessful in hatching young, two females because of abandonment (0.5 and 0.6 μg/g, respectively) and one female (0.38 μg/g) because of predation. Of females with nonelevated lead (n = 92), 18% were unsuccessful in hatching young. Moreover, the female with highest lead blood concentration (7.0 μg/g) successfully hatched all eggs in her clutch during the year of her exposure but was not encountered again during subsequent years. In contrast, a female with similarly high lead concentrations (6.6 μg/g) in 2002 was encountered again two years later and nested successfully during both years she was observed.

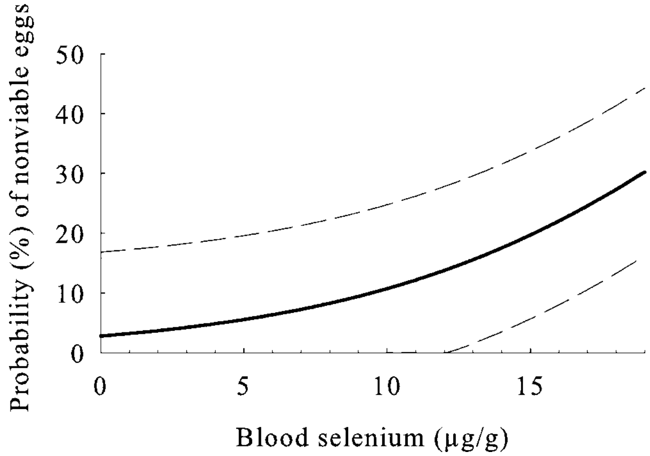

Fig. 2. Predicted probabilities (%) of at least one nonviable egg occurring in a nest as a function of blood selenium concentrations for female Pacific common eiders (*Somateria mollisima v-nigrum*) on the Yukon–Kuskokwim Delta (AK, USA) from 2002 to 2004. Range of selenium values represent concentrations observed in the field. Dashed lines represent 90% confidence intervals.

Adult female apparent survival

Our survival dataset included 164 breeding adult females captured and sampled for contaminants in 2002 and/or 2003, resulting in 78 future recaptures and resightings (2003–2004). We had no band recoveries (i.e., bands reported from dead birds) during the course of the present study. We examined 25 candidate models of adult female survival and encounter probabilities that incorporated the effects of adjusted selenium and lead concentrations as well as variation between site-years (Table 4), and we found no evidence of overdispersion in our most parameterized model ($\hat{c}$ = 1.0).

In our best approximating model, apparent survival varied with blood selenium concentrations, and encounter probabilities varied across sites and years (Table 4, model 1). We found no support for reduced parameter structure in encounter probabilities ($\Delta AIC_c > 4.83$) (Table 4, model 5) and little support for a relationship between apparent survival and blood lead ($\Sigma\ w_{lead}$ = 0.18). Although moderate model selection uncertainty existed (Table 4), overall support for a selenium effect was high ($\Sigma\ w_{selenium}$ = 0.74). Our second best model (Table 4, model 2) described a selenium effect that varied between study sites; however, this model did not substantially improve fit (ΔAIC_c = 1.87). Thus, it provided little support for additional variation across study sites [23]. Our best model indicated that adjusted blood selenium concentrations were positively related to apparent survival, although precision in this positive effect was low ($\beta_{selenium}$= 0.73 ± 0.37). Using the odds ratio from this model (odds ratio, 2.09; 90% CI, 1.12–3.88), we estimated that each 1 μg/g increase in blood selenium would be related to a twofold increase in the odds of surviving.

Table 4. Models of annual apparent survival for adult female Pacific common eiders (*Somateria mollisima v-nigrum*) at the Kigigak Island and Tutakoke River study areas, Yukon–Kuskokwim Delta (AK, USA), from 2002 to 2004 in relation to blood selenium and lead concentrations adjusted by incubation stage. Encounter probabilities (p) were similar for all top models (site × year) unless otherwise noted.

Model	Apparent survival hypothesis	k[a]	AIC_c[b]	Deviance	ΔAIC_c	w_i
1	Varies with selenium exposure	6	267.88	255.39	0.00	0.49
2	Varies with selenium differently between study sites	7	269.76	255.09	1.87	0.19
3	Varies with lead exposure	6	270.49	258.00	2.61	0.13
4	Intercept only	5	271.60	261.25	3.72	0.07
5	Varies with selenium; encounter probability varies with sites + year	5	272.71	262.36	4.83	0.04

[a] k = number of parameters in model.
[b] The best approximating model has the lowest Akaike's Information Criterion adjusted for small sample size (AIC_c) and the highest model weight (w_i) relative to others in the model set.

Interpretation of these effects requires caution, however, because when rates (herein survival rates) are near the boundaries of zero and one, large changes in odds result from small changes in estimated probabilities [28]. For example, a change in blood selenium from 6 to 7 μg/g (i.e., around population means) would result in only a 0.0004 increase in the apparent survival probability.

DISCUSSION

Lead

Elevated lead concentrations within the range that we observed were indicative of subclinincal exposure (≥ 0.2 μg/g) to severe clinical poisoning (> 1.0 μg/g) based on laboratory studies of freshwater birds [13]. The proportion of common eiders above subclinical toxicity thresholds was low (3.6%), which is consistent with the results of earlier local studies (3% [5]). Moreover, average blood lead concentrations (Table 1) were less than or equal to those reported previously for the YKD (0.14 ± 0.01, n = 9 [21]). Overall, common eiders appeared to have markedly reduced exposure to lead in comparison to sympatrically nesting spectacled eiders (36% [5]) and rarely were at levels associated with toxic effects in waterfowl. We suggest that interspecific differences in lead exposure likely result from differences in foraging behavior and brood-rearing strategies [5]. Common eiders fast, whereas spectacled eiders feed during incubation. Furthermore, common eiders raise broods at sea, but spectacled eiders raise broods on upland ponds, where spent lead shot may remain available more than three years after deposition [7,20,31]. In total, nesting common eiders spend approximately half as much time in areas with available shot as do spectacled eiders, significantly reducing their opportunity for exposure. Furthermore, we suspect that previously reported poisoning of common eiders [9] was likely a result of prenesting foraging in waters adjacent to the breeding grounds.

Selenium

In contrast to lead, all birds sampled in the present study had detectable blood selenium. Average selenium concentrations were consistently above background levels (< 0.4 μg/g [18,32,33]) and often at levels associated with mortality in captive mallards (5–14 μg/g [10]). We observed no obvious selenium-related health effects, however, and average detection rates and concentrations were similar to those reported previously for local common eiders [5,21]. Selenium concentrations in male common eiders were much lower than those observed in male spectacled eiders [21], and we suggest this interspecific variation may result from differences in selenium elimination times during migration and exposure on wintering and staging areas [21,22].

Trace element dynamics

Blood lead levels tended to slowly increase through incubation, similar to levels in nesting common eiders in Finland [18]. The low concentrations and slow increase of lead that we found supports chronic, low-level metabolic release rather than point-source exposure (e.g., via ingestion of lead pellets). We agree with others [18] who have suggested that small increases in blood lead are related to reproductive physiology—specifically, the mobilization of stored lead through metabolism of medullary bone. Medullary bone in birds acts as a labile reservoir for calcium used in eggshell formation [34], and because lead is chemically similar to calcium, it may be easily assimilated into medullary bone [35]. After egg production, common eiders may continue to utilize medullary stores to meet the nutritional demands of the incubation fast. If so, metabolic release of stored lead could be responsible for the temporal increases in blood lead that we observed.

Laboratory studies demonstrate that selenium is metabolically pliable, rapidly accumulates during exposure, and declines once exposure is terminated [17]. Declining blood selenium concentrations during nesting suggest that exposure to selenium on breeding grounds probably was negligible in the present study. Furthermore, the majority of selenium that we measured likely was derived from selenium-rich wintering and staging areas in the Bering Sea [11,12,21,22]. Selenium elimination rates in common eiders were reduced compared to those in spectacled eiders (1.9% YKD [21], 2.3% in northern Alaska [22]) and YKD emperor geese (±1%, *Chen canagica* [11]) and much slower than in captive freshwater mallards (7.1% [10,17]). This suggests that the slowed metabolism of common eiders during the incubation fast may decrease their rates of selenium elimination in comparison to nonfasting species.

Life-history traits and trace element concentrations

The positive relationship between blood selenium concentrations and egg nonviability is consistent with patterns in wild birds at selenium-contaminated areas (e.g., black-necked stilts [*Heimantopus mexicans*] [36] and eared grebes [*Podiceps nigricollis*] [26]) as well as selenium-dosed mallards in laboratory studies [37]. The average rate of nonviability that we observed (7.7%) was more than triple the average egg infertility rate for other diving ducks (~2.2% [38]). This suggests that YKD common eiders may be experiencing much higher frequencies of nonviability than other diving species. Spectacled eiders nesting on the YKD, however, appear to have even higher nonviability rates (24% of spectacled eider nests had at least one nonviable egg [29]), corresponding with their higher blood selenium levels [21]. We suspect that both species are exposed to elevated selenium on their Bering Sea wintering grounds, but we hypothesize that spectacled eiders likely winter in areas with higher natural concentrations of selenium [12,20,21].

Diminished productivity resulting from reduced egg survival could have major implications for population dynamics [38]; however, reductions in clutch size because of selenium-related nonviability represent only a small portion of overall fecundity [38]. For long-lived species such as the common eider [31], fecundity is expected to have a much lower proportional influence (i.e., elasticity) on prospective population growth than would adult survival [38]. Therefore, although elevated selenium may have acute reproductive costs, we suggest that population-level consequences at the concentrations we observed are expected to be relatively minor.

We found limited evidence for a positive relationship between blood concentrations of selenium and apparent survival of adult females, but effects were estimated with poor precision. Overall, our results suggest that selenium is not detrimental to the survival of adult females within the range of concentrations we observed. This supports the hypothesis that seabirds living in high-selenium environments may have evolved higher selenium tolerances based on their chronic exposure [1,11,14,21,22]. However, we stress that further interpretation of our apparent survival results requires caution, and we emphasize that our correlative approach cannot infer causal mechanisms. For example, given the brief period of the present study, periodic nonbreeding could have been confounded with emigration or mortality. Moreover, positive correlations between selenium and body condition [9,39] could have further confounded results. We found no evidence, however, of a relationship between blood selenium concentrations and body mass (after controlling for incubation stage) [18]. Thus, selenium–body condition relationships could not fully explain the present results. Finally, the thresholds between selenium essentiality and toxicity generally are unknown for marine species. Measures of oxidative stress have been positively related to selenium in at least one study of emperor geese [40], whereas a study of common eiders nesting in Canada showed an inverse relationship between corticosterone (stress response) and selenium in nesting hens, suggesting that selenium actually may help to modulate adverse effects of chronic stress in adult birds [39]. We believe that selenium may have both positive and negative effects on the life-history variables of marine birds at the concentrations we measured. Furthermore, we suggest that tolerance and effect levels appropriate for these birds deserve further investigation.

CONCLUSION

The present study links contaminant levels in wild birds to life-history traits through integration of demography and nonlethal blood sampling. The results suggest that elevated selenium may be related to reduced egg fertility and hatchability, resulting in a potential reproductive cost to nesting eiders. Selenium was not detrimental to the probability of apparent survival, however, suggesting that adult marine birds may have higher selenium tolerances than freshwater species. Reproduction appeared to be more sensitive than adult survival to selenium toxicity, but based on average selenium concentrations, we suggest that high rates of nonviability are not likely to occur. Furthermore, selenium-related reductions to clutch size are expected to be inconsequential at the scale of overall population dynamics.

Overall, we saw no obvious signs of compromised health in adults, ducklings, or limited samples of embryos during the course of the present study, and we conclude that for Pacific common eiders, the adverse effects of lead and selenium are minimal. We also suggest eiders that do not forage in areas with accessible lead shot are unlikely to show significant effects of lead contamination. Although management actions focused on education and enforcement of nontoxic shot regulations are encouraged for species such as the spectacled eider, the present results suggest these actions may not have large effects on common eider populations. We encourage continued field and laboratory research to expand on relationships between selenium and life-history traits established in the present study. Specifically, future studies should examine selenium tolerances appropriate for marine birds, redistribution and toxicity of blood lead and selenium in species that undergo periodic fasting, and sources of selenium in the marine and terrestrial environment. Finally, we advocate increased integration of nonlethal sampling in long-term demographic studies to better examine contaminant-related fitness consequences and impacts of contaminants on overall population dynamics.

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