

RELATIONSHIPS OF CADMIUM, MERCURY, AND SELENIUM WITH NUTRIENT RESERVES OF FEMALE LESSER SCAUP (*AYTHYA AFFINIS*) DURING WINTER AND SPRING MIGRATION

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Abstract—Trace elements may have important effects on body condition of ducks during spring migration, because individuals are experiencing energetically costly events (e.g., migration, nutrient reserve accumulation, pair formation, feather molt, and ovarian follicle development). We examined relationships among hepatic cadmium, mercury, and selenium concentrations ($\mu\text{g/g}$ dry wt) and nutrient reserves (lipid, protein, and mineral) of female lesser scaup (*Aythya affinis*) during winter and spring migration at four locations within the Mississippi Flyway (LA, IL, and MN, USA, and MB, Canada). Selenium concentrations (range, 3.73–52.29 $\mu\text{g/g}$ dry wt) were positively correlated with lipid reserves ($F_{1,73} = 22.69$, $p < 0.001$, type III partial $r^2 = 0.24$), whereas cadmium was negatively correlated with lipid reserves ($F_{1,73} = 6.92$, $p = 0.010$, type III partial $r^2 = 0.09$). The observed relationship between cadmium and lipid reserves may be cause for concern, because lipid reserves of females declined by 55 g (47%), on average, within the range of observed cadmium concentrations (0.23–7.24 $\mu\text{g/g}$ dry wt), despite the relatively low cadmium concentrations detected. Mean cadmium concentrations were higher in Minnesota (1.23 $\mu\text{g/g}$ dry wt) and Manitoba (1.11 $\mu\text{g/g}$ dry wt) than in Louisiana (0.80 $\mu\text{g/g}$ dry wt) and Illinois (0.69 $\mu\text{g/g}$ dry wt). However, mean cadmium concentrations predict lipid reserves of females to be only 11 g lower, on average, in Minnesota than in Illinois. Previous research documented that lipid reserves were 100 g lower in Minnesota than in Illinois; consequently, cadmium is unlikely to be the sole cause for decreases in lipid reserves of females during late-spring migration.

Keywords—Cadmium Lesser scaup Lipid Mercury Selenium

INTRODUCTION

Declines in body condition have been linked to increasing levels of cadmium, mercury, and selenium in some captive and wild aquatic birds (see, e.g., [1–6]). Potential effects of trace elements on body condition of female ducks could be critical during spring migration, because individuals are experiencing energetically costly events, such as migration, accumulating nutrient reserves for breeding, courtship and pair formation, contour feather molt, and ovarian follicle development [7–10].

Trace-element contaminants may have direct and indirect effects on various aspects of a bird's physiology. Nonlinear relationships may exist between trace elements and body condition; moreover, interactions between trace elements also may occur. Selenium is an essential nutrient [11], but it is toxic at high levels [12–15]. Thus, the relationship between selenium and body condition should be positive at lower concentrations of selenium and negative at higher concentrations (quadratic relationship). Additionally, the presence of selenium may reduce the deleterious effects of mercury [2,12,16].

An evaluation of trace-element contaminant levels and their effects on nutrient reserves is a priority for lesser scaup (*Aythya affinis*) [10,17,18]. Elevated trace-element contaminants could increase adult mortality or decrease egg viability and, thus, may be a factor in the recent combined continental population decline of greater and lesser scaup [19,20]. Elevated trace-element con-

taminants have been found in lesser scaup (hereafter referred to as scaup) during spring migration in the Mississippi Flyway and the Great Lakes (USA and Canada) [17,18,21]. Anteau and Afton [10] speculated that trace-element contaminants might be indirectly affecting scaup populations by inhibiting females from accumulating nutrient reserves during spring migration and, thus, ultimately decreasing reproductive success (see the Spring Condition Hypothesis [20]). Information concerning effects of trace-element contaminants on the accumulation of nutrient reserves during spring migration, when females potentially are nutritionally stressed, would be informative for directing conservation efforts in this species [10,22] (<http://etd.lsu.edu/docs/available/etd-01242006-093828>; M Anteau, Master's thesis, Louisiana State University, Baton Rouge, Louisiana, USA, <http://etd.lsu.edu/docs/available/etd-0707102-155816>). Accordingly, we investigated the relationships of hepatic cadmium, mercury, and selenium ($\mu\text{g/g}$ dry wt) with nutrient reserves (lipid, protein, and mineral) of female scaup during winter and spring migration in the Mississippi Flyway.

MATERIALS AND METHODS

Study area, collection of specimens, and body composition analyses

We used steel shot to collect scaup at four locations in the year 2000: Southern Louisiana (USA; hereafter LA), pool 19 of the Mississippi River between Hamilton and Niota (IL, USA; hereafter IL), northwestern Minnesota (USA; including collection sites at Thief Lake Wildlife Management Area, Agassiz National Wildlife Refuge, and Roseau River Wildlife

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Management Area; hereafter MN), and on a Prairie-Parkland breeding area west of Erickson (MB, Canada; between Sandy Lake and Elphinstone and the area 35 km south of these towns; hereafter MB). Detailed descriptions of these locations have been provided previously [23–26] (M. Anteau, Master's thesis). Collections and body composition analyses have been described by M. Anteau (Master's thesis) and by Anteau and Afton [10]. For body composition analysis, the entire carcass, less a 5-g liver sample and the gastrointestinal tract contents, was dried and homogenized. At the Avian Energetics Laboratory (University of Western Ontario, London, ON, Canada), samples were dried and weighed, lipids extracted with petroleum ether, and protein and minerals analyzed by combusting lean samples in a muffle furnace.

Trace-elements analysis

Initially, we conducted trace-element analysis on the livers of 10 female scaup randomly selected from birds collected at each of four locations (LA, IL, MN, and MB) [10,18] (M Anteau, Master's thesis). Subsequently, to improve estimates and to test for potential trace-element relationships with lipid reserves, we randomly selected 10 additional livers from female scaup collected at each location ($n = 80$ total samples). All samples were selected from scaup collected during the spring of 2000. The first set of 40 samples was analyzed by Research Triangle Institute (Research Triangle Park, NC, USA) [18]; the second set of 40 samples was analyzed by Trace Element Research Laboratory (Texas A&M University, College Station, TX, USA) using protocols identical to those for the first set (Patuxent Analytical Control Facility contract and protocols). The Patuxent Analytical Control Facility (U.S. Fish and Wildlife Service, Shepherdstown, WV) has a rigorous, five-step process to assure accuracy, precision, and compatibility among their contract laboratories. In brief, tissues were homogenized and then digested in the presence of nitric acid. Inductively coupled plasma-atomic emission spectrophotometry was used for cadmium. Mercury was determined with cold-vapor atomic absorption, and selenium was analyzed using graphite-furnace atomic absorption. Blanks, duplicates, and spikes were run at a frequency of at least 5% of the total number of samples. Standard reference material (TORT-2, lobster hepatopancreas; National Research Council, Ottawa, ON, Canada) also was analyzed; recoveries from the first and second set, respectively, were as follows: Cadmium, 100 and 97%; mercury, 100 and 91%; and selenium, 92 and 100%. Similarly, recoveries of spiked materials were 102 and 91% for cadmium, 94 and 81% for mercury, and 94 and 98% or selenium, respectively. Concentrations were not corrected for percentage recovery, and they are expressed on a dry-weight basis. Moisture content of livers averaged $69.17\% \pm 0.27\%$ (mean \pm standard error) for use in converting to wet weight if needed.

We classified trace-element concentrations as background, elevated, or potentially harmful based on available literature. We considered cadmium concentrations to be background at less than 3 $\mu\text{g/g}$ dry weight, elevated at 3 $\mu\text{g/g}$ dry weight or greater, and potentially harmful at 7 $\mu\text{g/g}$ dry weight or greater [18,27–29]. We considered mercury concentrations to be background at less than 3 $\mu\text{g/g}$ dry weight and elevated at 3 $\mu\text{g/g}$ dry weight or greater [18,30–32]. Finally, we considered selenium concentrations to be background at less than 10 $\mu\text{g/g}$ dry weight, elevated at 10 $\mu\text{g/g}$ dry weight or greater, and potentially harmful at 33 $\mu\text{g/g}$ dry weight or greater [12,33].

Statistical analyses

We first conducted a principal components analysis of the correlation matrix on four morphometrics (body length [i.e., total length–rectrix length], keel length, wing cord, and tarsus bone) using PROC PRINCOMP in SAS software [34]. We then used the first principal component (PC1) to index body size [7]. We natural log-transformed all cadmium, mercury, and selenium concentrations ($\mu\text{g/g}$ dry wt) to meet model assumptions of normality and homogeneity of variance [18]. We tested for a collection-location effect on trace-element concentrations in separate analyses of covariance (ANCOVAs) for each trace element; we included body size and the concentrations of the other trace elements as covariates (PROC MIXED) [34]. We used backward elimination procedures ($\alpha = 0.05$) to select final models [35]. If the location effect was retained in the final model, we used the least-square-means statement to estimate mean concentrations for each location (PROC MIXED) [34]; we also used the PDMIX800 macro [36] to group similar means for each location. However, overall means were estimated with the solution statement if the location effect was not retained in the final model (intercept model) [34]. Trace-element concentrations are presented as geometric means with the 95% confidence interval [18].

The potential for nonlinear relationships or interactions between trace elements requires testing a priori models based on physiological theory and using a single overall statistical model to test for effects of trace elements on each component of body condition (lipid, protein, and mineral reserves). Accordingly, we used a separate ANCOVA for lipid, protein, and mineral reserves to examine effects of trace-element concentrations (cadmium, mercury, and selenium) on each nutrient reserve of female scaup while controlling for effects of location, liver mass, and body size (PROC GLM) [34]. We included a selenium \times mercury interaction and a quadratic term for selenium in our initial models; while testing the quadratic term, we used non-log transformed selenium concentrations. We used backward elimination procedures ($\alpha = 0.05$) to select final models [35]. For each significant effect of interest (cadmium, mercury, or selenium), we plotted and examined the type III partial relationship and calculated the type III partial r^2 of that effect on the response of interest (lipid, protein, or mineral) solely by, first, rerunning the final model without that effect (exporting the response residuals; ANCOVA and PROC GLM) [34]; second, by conducting an analysis with that effect as a response and remaining variables from the final model as predictor variables (exporting the effect residuals; ANCOVA and PROC GLM) [34]; third, by regressing the residuals of the effect on the residuals of the response to calculate the type III partial r^2 (PROC REG) [34]; and finally, by plotting the results with SigmaPlot (Ver 8.02; SPSS, Chicago, IL, USA).

RESULTS

In the principal components analysis, all correlations between morphometrics were positive; eigenvectors of PC1 ranged from 0.303 to 0.568. The PC1 accounted for 51% of the observed variation in the morphometrics of female scaup.

Trace-element concentrations

Cadmium concentrations varied among locations ($F_{3,74} = 3.92$, $p = 0.012$) after controlling for body size ($F_{1,74} = 6.38$, $p = 0.014$) and selenium concentration ($F_{1,74} = 50.72$, $p < 0.001$) (Table 1). Cadmium concentrations were higher in Min-

Table 1. Least-square geometric mean (mean), 95% confidence interval (CI), and range (R) of hepatic cadmium and selenium concentrations for female lesser scaup (*Aythya affinis*) collected at four locations ($n = 20$ females/location) in the Mississippi Flyway (LA, IL, and MN, USA, and MB, Canada) during the year 2000^a

Location	Cadmium					Selenium				
	Mean ($\mu\text{g/g}$ dry wt)	CI ($\mu\text{g/g}$ dry wt)	R ($\mu\text{g/g}$ dry wt)	E (n [%])	H (n [%])	Mean ($\mu\text{g/g}$ dry wt)	CI ($\mu\text{g/g}$ dry wt)	R ($\mu\text{g/g}$ dry wt)	E (n [%])	H (n [%])
Louisiana	0.80 B	0.61–1.05	0.26–6.57	2 (10)	0 (0)	11.81 A	9.94–14.03	6.04–52.29	12 (60)	1 (5)
Illinois	0.69 B	0.52–0.90	0.40–2.38	0 (0)	0 (0)	12.21 A	10.26–14.53	6.14–20.03	12 (60)	0 (0)
Minnesota	1.23 A	0.94–1.61	0.23–7.24	3 (15)	1 (5)	9.20 B	7.72–10.97	3.98–35.85	9 (45)	1 (5)
Manitoba	1.11 A	0.84–1.47	0.26–6.68	2 (10)	0 (0)	8.17 B	6.88–9.71	3.73–30.47	6 (30)	0 (0)

^a Numbers and percentages of females with elevated (E) and potential harmful (H) levels of cadmium and selenium are noted (see text for criteria). Means with different uppercase letters (within a trace element) differed significantly ($p < 0.05$).

nesota and Manitoba than in Louisiana and Illinois (Table 1). Overall, 7 of 80 females (9%) had elevated cadmium levels ($\geq 3 \mu\text{g/g}$ dry wt), and one female (1%) had potentially harmful levels ($\geq 7 \mu\text{g/g}$ dry wt).

Selenium concentrations also varied among locations ($F_{3,74} = 5.01$, $p = 0.003$) after controlling for body size ($F_{1,74} = 4.32$, $p = 0.041$) and cadmium concentration ($F_{1,74} = 50.72$, $p < 0.001$) (Table 1). Selenium concentrations were higher in Louisiana and Illinois than in Minnesota and Manitoba (Table 1). Overall, 39 of 80 females (49%) had elevated selenium levels ($\geq 10 \mu\text{g/g}$ dry wt), and two females (3%) had potentially harmful levels of selenium ($\geq 33 \mu\text{g/g}$ dry wt).

Mercury concentrations did not differ among collection locations ($p > 0.05$). Mercury concentrations averaged $1.02 \mu\text{g/g}$ dry weight (95% confidence interval, 0.90 – $1.16 \mu\text{g/g}$ dry wt), with a range of 0.25 to $4.31 \mu\text{g/g}$ dry weight. Four of 80 females (5%) had elevated mercury levels ($\geq 3 \mu\text{g/g}$ dry wt).

Influence of trace elements on nutrient reserves

Lipid reserves. Our final lipid reserve model included effects of collection location, body size, cadmium, and selenium concentrations ($F_{6,73} = 20.03$, $p < 0.001$, $r^2 = 0.62$). The mercury main effect and selenium \times mercury interaction effect were not retained in the final model (all $p > 0.343$). No evidence indicated that liver mass was correlated with lipid reserves ($p = 0.764$); thus, it was not included in the final model. Weak evidence indicated a quadratic selenium effect (estimate = $6.70x - 0.07x^2$; $F_{1,72} = 3.06$, $p = 0.085$); however, this effect also was not retained in the final model. Collection location ($F_{3,73} = 16.43$, $p < 0.001$) and body size (estimate = 8.88 ; $F_{1,73} = 7.63$, $p = 0.007$) fit well in the model. Selenium concentrations were positively correlated with lipid reserves (estimate = 55.83 ; $F_{1,73} = 22.69$, $p < 0.001$) (Fig. 1), whereas cadmium was negatively correlated with lipid reserves (estimate = -19.64 ; $F_{1,73} = 6.92$, $p = 0.010$) (Fig. 1). Selenium concentration explained 24% of the residual variation after collection location, body size, and cadmium concentrations were included in the model. Cadmium concentration explained 9% of the residual variation after collection location, body size, and selenium concentration were included in the model.

Protein and mineral reserves. Cadmium, mercury, and selenium were not correlated with protein or mineral reserves of female scaup (all $p > 0.249$) after controlling for body size, liver mass, and location.

DISCUSSION

Trace-element concentrations

Size-adjusted body mass and lipid reserves of female scaup during spring migration were lower in 2000 and 2001 than in

1986 to 1988 in Minnesota and 1977 to 1980 in Manitoba [10] (M Anteau, Master's thesis); correspondingly, cadmium concentrations were highest in these two locations. Our second data set contained more females with elevated or potentially harmful levels of cadmium and selenium than in the original set, and our mean cadmium concentrations in Minnesota and Manitoba were qualitatively higher than the overall level reported in the original sample [18]. Differences in percentages of females with elevated/harmful cadmium concentrations and

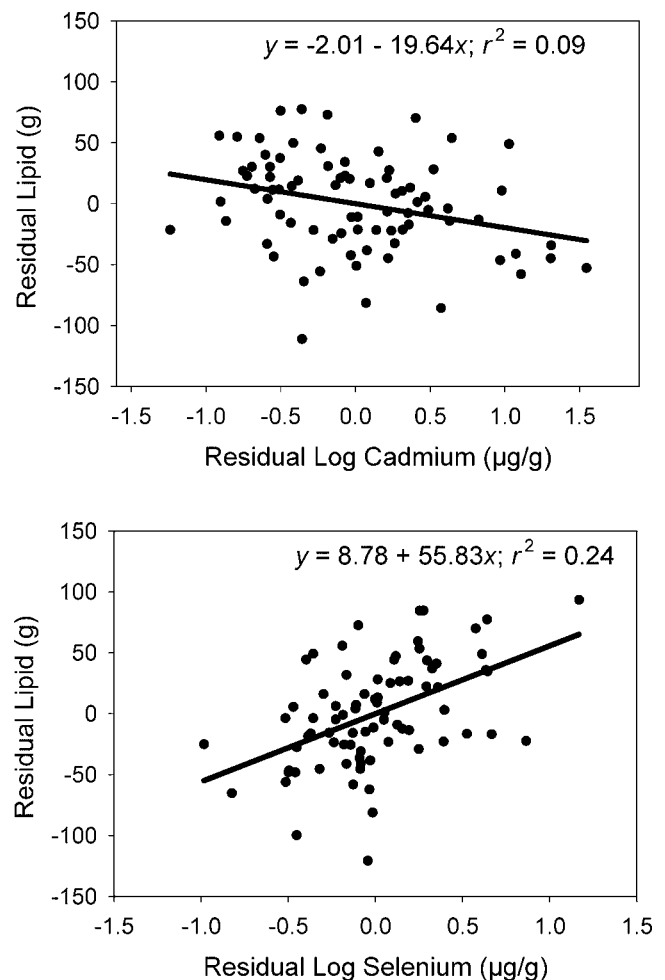


Fig. 1. Type III partial relationships between lipid reserve residuals (see *Materials and Methods*) and log hepatic cadmium and selenium concentration residuals (see *Materials and Methods*) for 80 female lesser scaup (*Aythya affinis*) collected from four locations (LA, IL, and MN, USA, and MB, Canada) within the Mississippi Flyway during the year 2000.

mean cadmium concentrations between our original data and second data sets probably represent random sampling error and underscore the need for large sample sizes when evaluating trace-element concentrations in wild populations of migrating birds. However, our analyses of concentrations reported here are controlled for body size, which might have contributed to small differences in mean concentrations and, thus, increased precision of the location test.

Influence of trace elements on nutrient reserves

Changes in liver mass (associated with changes in body condition) might influence hepatic concentrations of trace elements without a change in total hepatic trace-element levels. Thus, it was important to consider liver mass in models examining correlations between trace-element concentrations and nutrient reserves. However, the observed correlations between cadmium or selenium and lipid reserves of female scaup cannot be explained by variations in liver mass influencing hepatic concentrations of metals, because liver mass was not correlated with lipid reserves.

Lipid reserves declined by 55 g (47%), on average, within the range of observed cadmium concentrations, even though 91% of females had cadmium concentrations that were considered to be background. Cadmium concentrations were negatively correlated with body mass in wild common eiders (*Somateria mollissima*) [4,6,37]. We found that cadmium concentration in scaup were 5- to 35-fold lower than those in common eiders [4,6,37]. Despite the large amount of variation not explained by cadmium, the relatively large observed effect size on lipid reserves of female scaup (55 g) from low levels of cadmium may be of concern, especially if cadmium concentrations in scaup were to increase.

Effects of trace-element concentrations on body condition of captive and wild waterfowl often differ [5,6]. Studies have indicated that cadmium has negligible effects on body condition of captive mallards (*Anas platyrhynchos*) [38–40]. However, higher levels of dietary cadmium increased the energy stresses observed in captive mallards on a restricted diet [38], suggesting that cadmium influences lipid reserves indirectly [5,6]. Accordingly, cadmium and other trace elements may indirectly influence lipid reserves (e.g., decreasing foraging or energy metabolism efficiency). Furthermore, trace-element contaminants may affect nutrient reserves of active birds (e.g., during spring migration) more than those of less active birds (e.g., during winter or incubation or in captivity) if influences of trace-element effects are indirect and mediated by a metabolic response. For example, selenium concentration was negatively correlated with blood hemoglobin concentration in captive mallards [14]. Blood hemoglobin concentrations in scaup may be important determinants of body condition during spring migration, because scaup forage intensively in the spring by diving [9].

Lovvorn and Barzen [41] defined stress as “a situation when demands of one event (physiological, behavioral, or otherwise) are great enough to interfere with desirable allocation of resources to other processes.” Northern spring-stopover areas are important for accumulation and maintenance of lipid reserves subsequently used by breeding scaup, and females should be gaining lipid reserves in the Upper Midwest [7,10]. Females currently are catabolizing lipids [22] and have low lipid reserve levels throughout the Upper Midwest [22]. Forage quality (nutritional value of forage consumed) of scaup in the Upper Midwest currently is low, and it probably has declined

from historical values [22,42]. Scaup may be spending more time searching for food (within and between wetlands) than they did historically [22]. Thus, nutritional demands of female scaup during the spring in the Upper Midwest (e.g., migration, courtship and pair formation, contour feather molt, and ovarian follicle development) [8,10] probably are interfering with the accumulation of nutrient reserves for breeding. Taken together, all these results indicate that females are nutritionally stressed during spring migration, which could explain why the relatively low levels of cadmium that we found had the observed influence on lipid reserves.

Elevated selenium levels are a concern for scaup in the Great Lakes region and within the Mississippi Flyway [17,18,21]. Selenium is an essential nutrient, but in high levels, it increases mortality, decreases body mass, impairs reproduction, reduces growth, and causes histopathological lesions, oxidative stress, and alterations in hepatic glutathione metabolism [12–15]. Selenium caused more physiological stress to captive mallard ducklings on high-protein diets compared with those on low-protein diets (44% vs 22%) [1]. Accordingly, scaup could be at particular risk of selenium toxicity, because they consume foods that are rich in protein, especially during the spring [22,42–44].

The observed positive correlation between selenium and lipid reserves (Fig. 1) is consistent with the idea of selenium (at the levels observed) acting as a nutrient. However, this correlation also could occur if lipid reserves and selenium concentrations increase simply because females eat more food. In contrast to predictions, high levels of selenium were not associated with low levels of lipid reserves, at least at the levels observed during the present study.

Hepatic selenium concentrations were not correlated with body mass or lipids in a combined sample of greater and lesser scaup during winter in California [45]. Takekawa et al. [45] attempted to fit a linear regression between selenium concentrations and body mass and lipids; however, a quadratic relationship might have been more appropriate (see above). We expected selenium and lipid reserves might be negatively correlated at higher concentrations of selenium, particularly because females in Minnesota and Manitoba may be nutritionally stressed. We found weak evidence of a quadratic term for selenium ($p = 0.085$), suggesting that the effects of selenium in lipid reserves level off at 47 $\mu\text{g/g}$ dry weight and become negative thereafter; however, our data are sparse at selenium concentrations of greater than 33 $\mu\text{g/g}$ dry weight ($n = 2$). Regardless, the quadratic term for selenium was excluded from our final model based on our a priori selection of $\alpha = 0.05$. If selenium negatively influences lipid reserves, this must occur at levels higher than those we observed within the Mississippi Flyway.

Implications for conservation of lesser scaup

In the spring of 2000 and 2001, lipid reserves of female scaup migrating through Minnesota were 100 g lower than those in Illinois; historically, females likely gained lipid reserves as they migrated north through the Upper Midwest [10] (M. Anteau, Master's thesis). We found that increases in cadmium within the low range of concentrations observed were correlated with as much as 55 g (47%) less lipid reserves, on average, in females. However, the log of mean cadmium concentrations in Illinois and Minnesota (Table 1) only predicts lipid reserves of females to be 11 g lower, on average, in Minnesota than in Illinois (Fig. 1). Thus, cadmium concen-

trations could be a contributing factor to the recently documented decrease in lipid reserves for scaup migrating through the Upper Midwest [10,18]; however, cadmium concentrations are unlikely to be the sole cause of the current low levels of lipid reserves in the Upper Midwest.

In conclusion, the negative correlation between cadmium and lipid reserves suggests that cadmium might be of some conservation concern by inhibiting accumulation of lipid reserves by female scaup. Small declines in lipid reserves of females during the spring migration could have large impacts on reproductive performance and, ultimately, on population size through declines in breeding propensity and delays in nest initiation, which in turn causes declines in nest, duckling, and fledgling success [10,22]. However, observed cadmium concentrations seemingly do not explain the marked declines in lipid reserves of females observed throughout the Upper Midwest. Other mechanisms in addition to the apparent cadmium-related effects probably are driving the decline in female scaup body condition during spring migration in the Upper Midwest. Scaup presently are faced with decreases in habitat [9] and in availability of quality foods [22,42] during spring migration in the Upper Midwest, which may have relatively larger effects on lipid reserves in females. Nutritional stress of females may cause them to be more sensitive to hepatic cadmium concentrations; thus, cadmium may be a negative-synergistic interacting factor with nutritional stress on lipid reserves. Although perhaps unlikely, if levels of cadmium were to increase in scaup, cadmium potentially could cause larger decreases in lipid reserves of female scaup during spring migration, especially when females may be otherwise nutritionally stressed.

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