Arch. Environ. Contam. Toxicol. 42, 60–70 (2002)
DOI: 10.1007/s002440010292

ARCHIVES OF
Environmental
Contamination
and Toxicology

Relating Body Condition to Inorganic Contaminant Concentrations of Diving Ducks Wintering in Coastal California

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Received: 8 March 2001/Accepted: 1 July 2001

Abstract. In wild waterfowl, poor winter body condition may negatively affect migration, survival, and reproduction. Environmental contaminants have been shown to adversely affect the body condition of captive birds, but few field studies have examined body condition and contaminants in wild birds during the winter. We assessed the body condition of carcasses from a collection of canvasbacks (*Aythya valisineria*) and lesser (*A. affinis*) and greater scaup (*A. marila*) wintering in coastal California. We used Akaike information criterion (AIC) to select the model with the best balance of parsimony and goodness of fit that related indices of body condition with concentrations of Cd, Cu, Hg, Se, and Zn. Total ash-free protein in canvasbacks decreased with increasing Se concentrations, and pancreas mass decreased with increasing Hg. We combined the closely related lesser and greater scaup in analyses and found that total carcass fat, pancreas mass, and carcass mass decreased with increasing Zn concentrations, and pancreas mass decreased with increasing Hg. Our AIC analysis indicated that some indices of body condition in diving ducks were inversely related to some environmental contaminants in this collection, but additional AIC analyses should be conducted across a wider range of contaminant concentrations to corroborate our findings.

Many diving ducks in the Pacific Flyway winter in coastal California, and the San Francisco Bay estuary alone supports the largest population of canvasbacks (*Aythya valisineria*) in the flyway and up to half of the populations of greater and lesser scaup (*A. marila* and *A. affinis*) (Accurso 1992; Rienecker 1985). Canvasbacks have long been a species of concern (Hohman *et al.* 1995), and continental populations of both greater and lesser scaup have declined dramatically during the past two decades (Austin *et al.* 2000). At a recent workshop on the status of these two species (Austin *et al.* 2000), biologists concluded that contaminants were a likely factor contributing to their decline.

Contaminants such as cadmium, mercury, and selenium have been shown to adversely affect condition of captive birds by reducing their body weight, damaging organs, altering their metabolism, or causing behavioral changes (Eisler 2000a, 2000b; Furness 1996; Heinz and Hoffman 1998; Wolfe *et al.* 1998). In wild waterfowl, poor winter body condition may negatively affect migration, winter survival, annual survival, breeding propensity, and reproductive success (Sanderson and Bellrose 1986; Haramis *et al.* 1986). Although several laboratory studies have examined the relationship between environmental contaminants and body condition in waterbirds (*e.g.*, Stanley *et al.* 1996; Heinz and Fitzgerald 1993; DiGiulio and Scanlon 1984a), few field studies have been reported, and most of those studies have been limited to body weight (Hohman *et al.* 1990; Ohlendorf *et al.* 1990).

Benthic invertebrates in San Francisco Bay contain elevated concentrations of several trace elements (Brown and Luoma 1995; Luoma and Cain 1979; Luoma *et al.* 1985, 1990), and elevated contaminant concentrations have been reported in livers of diving ducks, including lesser and greater scaup, canvasbacks, and surf scoters (*Melanitta perspicillata*), wintering in the bay (Hoffman *et al.* 1998; Hothem *et al.* 1998; Miles and Ohlendorf 1993; Ohlendorf *et al.* 1986, 1989, 1991). Ohlendorf *et al.* (1989) found that liver Se concentrations increased in surf scoters collected in San Francisco Bay between January (64.2 ppm, dry weight) and March (74.8 ppm). Se and Hg in these birds approached concentrations that impaired reproduction in captive mallards (*Anas platyrhynchos*) (see Skorupa and Ohlendorf 1991; White *et al.* 1988).

We examined the relationship between body condition and inorganic contaminant concentrations in livers and kidneys (Cd only) of diving ducks wintering in coastal California. We used Akaike's information criterion (AIC) (Burnham and Anderson 1998) to select a "best approximating model" from a series of multiple regressions relating common indices of avian body condition (Brown 1996), including protein, fat, organ size, and

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body mass adjusted by structural size, with contaminants (Cd, Cu, Hg, Se, and Zn) (Hothem *et al.* 1998) recognized to produce harmful effects in birds. We also examined differences in the relationship between body condition and contaminant concentration by age and sex for all species, and differences by species and season in scaup.

Materials and Methods

Study Area and Field Methods

Canvasbacks, greater scaup, and lesser scaup were collected by the California Department of Fish and Game (CDFG) from three sites on the outer California coast (Lake Earl, Humboldt Bay, Morro Bay) and three regions (North, Central, South) within San Francisco Bay (see Hothem *et al.* 1998 for detailed descriptions of study areas), during early (December) and late (March) winter, 1986–1987 (Figure 1). In early winter, canvasbacks were collected from Lake Earl, the North and South Bay; greater scaup were collected from Humboldt Bay and the North Bay; and lesser scaup were collected from Lake Earl. In late winter, canvasbacks were collected in the South and North Bay; greater scaup were taken from the South, Central, and North Bay; and lesser scaup were collected at Morro Bay.

The CDFG collected 50 canvasbacks and 50 scaup, taken by shotgun with steel shot. From 4 to 11 ducks were collected for each species, site, and time period (see Hothem *et al.* 1998). Liver and kidneys were removed from each duck within an hour of collection, placed in chemically cleaned jars, and stored on dry ice in the field. Esophagus, proventriculus, and gizzard were also removed for prey analyses. Individually wrapped carcasses, livers, and kidneys were stored in −20°C freezers until they were analyzed.

Chemical Analyses

Inorganic elements in livers were analyzed at the Environmental Trace Substances Research Center in Columbia, MO. Hg and Se were analyzed by atomic absorption spectrophotometry (AA) using cold vapor reduction (Hg) and graphite furnace (Se) techniques (Hothem *et al.* 1998). Aluminum, arsenic, boron, barium, beryllium, cadmium (in kidney), chromium, copper, iron, lead, magnesium, manganese, molybdenum, nickel, silver, strontium, tellurium, vanadium, and zinc were measured by inductively coupled plasma emission spectroscopy (ICP). The lower limit of detection for all elements was 0.1 μg/g (ppm), dry weight. Recovery rates for spiked tissue and reference materials ranged from 96% to 106%. Precision (estimated by duplicate samples) and accuracy were acceptable for all analytes. Residue data were not corrected for recovery rates. More detailed information on analyses is presented in Hothem *et al.* (1998).

Condition Analyses

Of the 100 ducks in the CDFG collection, 41 carcasses were either consumed during organochlorine analyses (Hothem *et al.* 1998) or were missing structural components for condition analyses. We examined body condition and contaminant concentrations in the remaining 29 canvasbacks and 30 scaup (Table 1). Laboratory analyses of body condition were conducted at the Department of Zoology, University of Western Ontario in London, Ontario. Age and sex were determined from external feather characteristics and development of genitalia. Morphological features, including keel length, body length, total length, skull width and length, tarsus length, bill width, and length of the exposed culmen, were measured to the nearest 0.1 mm. The length of full and empty small intestines, large intestines, and caeca were measured to the nearest 0.1 cm. In juvenile birds, the bursa (an immune system gland present in young birds) was measured to the nearest 0.1 mm. Additionally, mass of thawed body, sheared body, skinned body, ovary, oviduct, testes, abdominal fat, heart, pancreas, full and empty small intestine, large intestine, caeca, and carcass were determined to the nearest 0.01 g. Thawed, sheared, and skinned masses excluded esophagus, proventriculus, gizzard, liver, and kidney masses because these tissues were removed for other analyses. For our analyses, we defined the carcass as the entire thawed bird without the kidney, liver, and upper gastrointestinal tract. We defined the body as the thawed bird excluding all internal organs and external appendages.

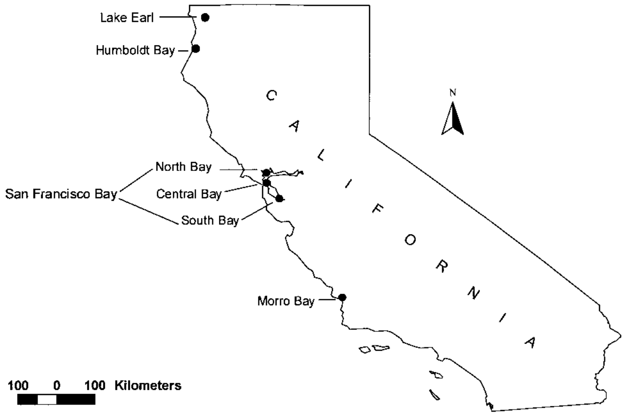

Fig. 1. Canvasback, greater scaup, and lesser scaup collection sites along the California coast that carcass

Table 1. Sample sizes by sex and age for canvasback, greater scaup, and lesser scaup

	Male		Female		
	Adult	Juvenile	Adult	Juvenile	Total
Canvasback	16	9	2	2	29
Greater scaup	8	5	2	1	16
Lesser scaup	7	6	0	1	14

Sample homogenates were prepared by grinding bodies in a 1-hp Hobart meat grinder through a 1-cm-diameter plate, followed by a 0.5-cm plate. Homogenate subsamples were dried to a constant weight at 95°C. Dried samples were weighed and, to achieve maximum homogeneity, were first ground in a Hobart grinder using a 0.5-cm plate and then in a Molinex coffee grinder (model 505). For lipid extractions, cellulose thimbles were filled with 10-g homogenate subsamples, dried to a constant weight, and extracted using petroleum ether in a modified Soxhlet apparatus. The remaining homogenate subsample was dried to a constant weight and used as a measure of total body lean mass. Lean samples were placed in Coors porcelain crucibles and ashed in a 500°C Muffle furnace overnight. Sample masses were used to calculate total carcass ash (TA). Total ash-free protein (TAFP) was calculated by subtracting TA from total body lean mass. Whole skins were sheared and dried to a constant weight. After drying, samples were ground in a hand grinder using a 0.5-cm plate, followed by a 0.3-cm plate. Lipids were extracted from skin samples using the same methods followed to extract carcass fat. We defined total carcass fat (TCF) as the sum of body, abdominal, leg, and skin fat masses.

Statistical Analyses

Body condition was adjusted for individual structural size differences with a principal components analysis (Johnson and Wichern 1988; SAS Institute 1990) that included skull width, skull length, tarsus, bill, culmen, total length, and TA. Body length was highly correlated with total length and was not included in the analysis. The first principal component, consisting of the weighted combination of variables with the highest eigenvalues, was used to adjust for structural size in each regression analysis. Also, sex and age were included as covariates in each regression analysis because we expected differences in body composition between male and female and adult and juvenile ducks.

We compared the body condition of individuals across the entire range of contaminant concentrations and sites in the collection, because we lacked adequate samples to associate body condition with contaminants within sites. Separate regression models were developed for each of five major condition indices, including TAFP, TCF, heart mass, pancreas mass, and carcass mass. Independent variable in the models were comprised of contaminants (Cd, Cu, Hg, Se, Zn, and the interaction Hg * Se) above the limit of detection in more than 50% of the samples (see Hothem *et al.* 1998) with known toxic effects (Ohlendorf *et al.* 1991). Canvasbacks were analyzed separately, but greater and lesser scaup were combined in the models to directly compare results in these closely related species. We also controlled for variation in body condition by age and sex and for species and season in scaup.

We used AIC adjusted for small sample sizes to select the best models (Burnham and Anderson 1998). For each of the five condition indices examined, there were between two and six competing models encompassing 2–11 independent variables. The competing models we considered were limited to those with an AIC value not more than twice that of the lowest AIC value (Burnham and Anderson 1998). We selected models with the smallest AIC and, consequently, the best balance of parsimony and goodness of fit (Burnham and Anderson 1998; Lebreton *et al.* 1992).

We used partial correlations (Figures 2–7) to depict inverse relationships identified in the models chosen by the AIC. Each partial correlation was adjusted for age and size, included in every model, and for other dependent variables. We obtained the residuals by regressing the condition variable on age, size, and other dependent variables identified in the model. We adjusted the mean values of the independent and dependent variables with these residual values. The adjusted values were then plotted against each other to depict the partial correlation.

Results

We determined separate means by age and sex for the seven structural size measurements of canvasbacks (Table 2) and lesser and greater scaup (Table 3). We also determined means for 13 direct condition measurements for canvasbacks (Table 4) and lesser and greater scaup (separated by season, Table 5) to document their overall body condition. We estimated means for contaminant concentrations in the subsample of 29 canvasbacks (Table 6) and 30 scaup (Table 7) used in this study, which differ from means for the entire collection of 100 ducks reported in Hothem *et al.* (1998). We report contaminant values as geometric means for comparability to other datasets, but visual inspection of these data indicate that they fit a normal distribution well. Therefore, we did not transform contaminant values for our statistical analyses.

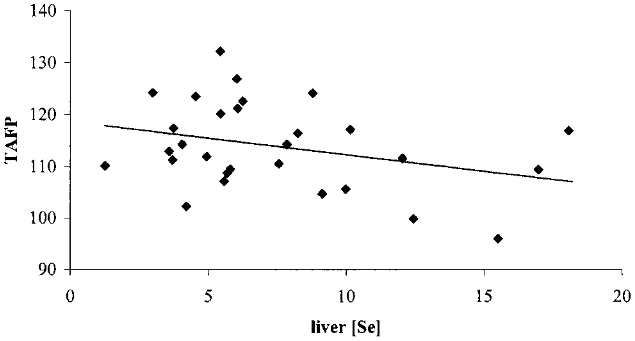

Fig. 2. Partial correlations ($r = -0.319$, slope $= -0.638$) showing that TAFP (g DW) in canvasbacks (n = 29) decreases as liver Se concentration (μg/g DW) increases. The correlation is adjusted to reflect the relationship between these two variables when the other variables indicated as contributing factors by the AIC model (age and size) are averaged

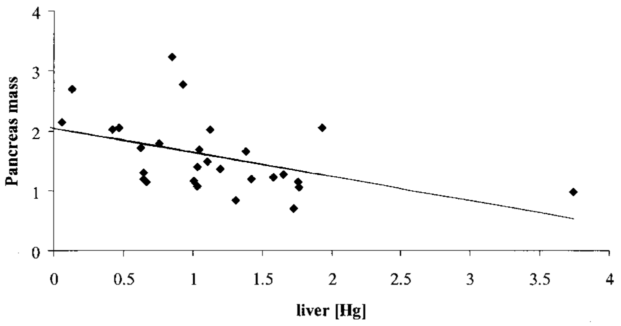

Fig. 3. Partial correlation ($r = -0.484$, slope $= -0.402$) showing that canvasback pancreas mass (g WW) decreases with increasing liver Hg concentrations (μg/g DW). The correlation is adjusted to reflect the relationship between these two variables when the other variables indicated as contributing factors by the AIC model (age, size, and liver Se concentration) are averaged

Structural Size

Several of the morphological measurements were correlated with each other. Fifty-one percent of the variability in structural size could be explained by the first axis in the principal components analysis ($\lambda_1 = 3.56$). The morphological measurements and eigenvector weights in the first principal component included skull width (0.43), skull length (0.48), total tarsus (0.38), bill length (0.25), culmen (0.43), total length (0.25), and TA (0.37).

Canvasbacks

We found relationships between three contaminants and four condition indices in canvasbacks (Table 8). TAFP decreased with increasing Se (Figure 2). Total carcass fat was positively related to Cd, and heart mass was positively related to Hg. Pancreas mass was inversely related to Hg (Figure 3), while Se was positively related to pancreas size. After adjusting for

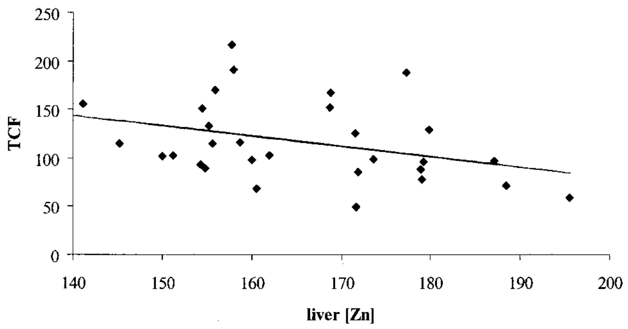

Fig. 4. Partial correlation ($r = -0.352$, slope $= -1.07$) showing that TCF (g WW) of greater and lesser scaup (n = 30) decreases with increasing liver Zn concentrations (μg/g DW). The correlation is adjusted to reflect the relationship between these two variables when the other variables indicated as contributing factors by the AIC model (age, size, season, and sex) are averaged

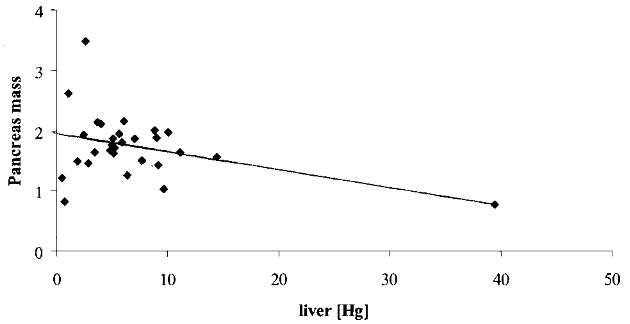

Fig. 5. Partial correlation ($r = -0.383$, slope $= -0.028$) showing that pancreas mass (g WW) of greater and lesser scaup (n = 30) decreases with increasing liver Hg concentrations (μg/g DW). The correlation is adjusted to reflect the relationship between these two variables when the other variables indicated as contributing factors by the AIC model (age, size, and zinc concentrations) are averaged

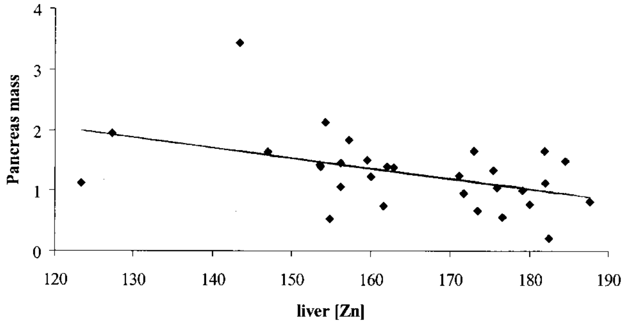

Fig. 6. Partial correlation ($r = -0.456$, slope $= -0.017$) showing that pancreas mass of greater and lesser scaup (n = 30) decreases as liver Zn concentration (μg/g DW) increases. The correlation is adjusted to reflect the relationship between these two variables, when the other variables indicated as contributing factors by the AIC model (age, size, and Hg) are averaged

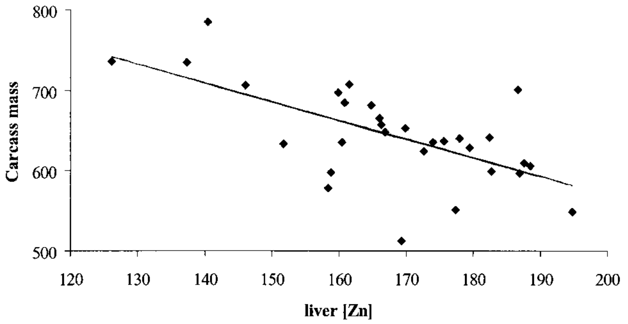

Fig. 7. Partial correlation ($r = -0.634$, slope $= -2.319$) showing that carcass mass of greater and lesser scaup (n = 30) decreases as liver Zn concentration (μg/g DW) increases. The correlation is adjusted to reflect the relationship between these two variables when the other variables indicated as contributing factors by the AIC model (age, size, season, and Se) are averaged

structural size, carcass mass was greater in juvenile canvasbacks.

Lesser and Greater Scaup

TAFP was higher in juvenile scaup, but there was no relationship found between TAFP and contaminant concentrations (Table 9). Total carcass fat was negatively related to Zn (Figure 4) and was greater in females and during early collection periods. Heart mass was greater for juveniles. Pancreas mass was inversely related to Hg (Figure 5) and Zn (Figure 6) concentrations. Finally, carcass mass varied positively with Se and negatively with Zn (Figure 7), and birds that were collected earlier were heavier than birds collected later in the winter.

Discussion

The sample of diving ducks we analyzed was limited to coastal California during a single winter, and samples were not evenly distributed across each age and sex class with fewer juveniles than adults and far fewer females than males. We were unable to control for environmental variation in sites, such as differences in available prey and prey patchiness (Lovvorn and Gillingham 1996a). In addition, the range of contaminant concentrations in our sample was reduced because specimens in the original collection from San Francisco Bay, where contamination in scaup and canvasbacks is generally higher than at coastal sites (Hothem *et al.* 1998), were consumed for organochlorine testing. Despite these limitations, our results indicated that body condition in diving ducks is related to concentrations of some environmental contaminants (Hothem *et al.* 1998).

Cadmium

Cd was positively related to TCF in canvasbacks, and adult males had a greater mean TCF than juvenile birds (Table 4). It is unlikely that Cd enhanced accumulation of TCF, but the positive relationship between Cd and TCF may be explained

Table 2. Mean and SD for seven structural size measurements (mm) of canvasbacks wintering on the California coast

	Adult		Juvenile	
Measurement	Female	Male	Female	Male
n	2	16	2	9
Body length	464.5 ± 3.5	485.7 ± 10.8	460.5 ± 6.4	482.7 ± 7.1
Skull width	28.3 ± 2.3	30.6 ± 0.6	29.5 ± 0.1	30.6 ± 0.8
Skull length	114.2 ± 2.1	120.5 ± 2.3	113.1 ± 1.3	119.1 ± 2.1
Tarsus length	43.0 ± 0.9	45.0 ± 1.3	43.2 ± 0.1	45.4 ± 1.0
Bill width	20.6 ± 0.9	20.4 ± 0.5	19.4 ± 0.3	20.1 ± 0.5
Culmen length	60.8 ± 2.3	64.2 ± 2.0	60.6 ± 1.3	63.0 ± 2.6
Bursa length	—	—	23.1 ± 10.1	25.8 ± 3.3

Table 3. Mean and SD for seven structural size measurements (mm) of greater and lesser scaup wintering on the California coast

	Greater Scaup				Lesser Scaup		
	Adult		Juvenile		Adult	Juvenile	
Measurement	Female	Male	Female	Male	Male	Female	Male
n	2	8	1	5	7	1	6
Body length	395.0 ± 4.2	409.0 ± 9.52	386.0	397.8 ± 8.79	360.2 ± 4.9	380.0	363.7 ± 4.89
Skull width	28.6 ± 1.3	29.1 ± 1.4	28.3	28.6 ± 0.82	26.2 ± 1.1	26.2	26.2 ± 0.5
Skull length	97.3 ± 1.8	99.6 ± 1.9	93.9	99.1 ± 1.2	87.86 ± 1.9	87.8	88.0 ± 2.5
Tarsus length	38.1 ± 1.0	39.7 ± 1.0	37.2	39.28 ± 1.2	35.4 ± 0.8	37.2	35.6 ± 1.7
Bill width	23.0 ± 1.3	23.9 ± 0.7	22.3	23.8 ± 1.1	21.5 ± 1.3	20.1	21.4 ± 0.6
Culmen length	45.1 ± 0.9	46.0 ± 1.7	43.6	45.8 ± 1.4	40.3 ± 2.1	42.6	41.5 ± 1.5
Bursa length	—	—	29.4	28.4 ± 5.1	—	34.2	21.4 ± 0.6

Table 4. Mean and SD of 13 body composition measurements (mass in g) for canvasbacks wintering on the California coast

		Adult		Juvenile	
Measurement		Female	Male	Female	Male
n		2	16	2	9
Leg	Fat	1.7 ± 0.9	2.4 ± 0.6	2.1 ± 0.2	1.7 ± 0.5
	Lean	9.5 ± 1.2	10.1 ± 0.8	8.8 ± 1.3	9.9 ± 0.7
Organs	Pancreas	1.2 ± 0.2	1.7 ± 0.6	1.7 ± 0.3	1.7 ± 0.8
	Heart	—[a]	8.5 ± 1.2	7.8[b]	6.6 ± 1.2
Skin	Fat	108.4 ± 79.3	124.1 ± 43.2	109.7 ± 7.9	111.6 ± 52.0
Body[c]	Abdominal fat	13.5 ± 12.7	15.0 ± 7.5	15.2 ± 1.9	11.5 ± 7.3
	Body fat	43.9 ± 19.3	53.0 ± 12.4	47.8 ± 4.0	47.5 ± 13.7
	Lean	140.0 ± 13.1	155.2 ± 10.2	135.1 ± 6.5	162.5 ± 14.0
	Body mass	445.6 ± 56.7	508.0 ± 57.6	448.5 ± 35.4	534.8 ± 49.7
Totals	Ash (TA)	37.0 ± 4.8	38.6 ± 3.8	33.0 ± 2.1	38.2 ± 3.5
	Ash-free protein (TAFP)	103.0 ± 8.2	116.6 ± 7.2	102.1 ± 4.4	124.4 ± 11.8
	Carcass fat (TCF)[d]	167.4 ± 112.2	194.4 ± 59.2	174.8 ± 13.9	172.3 ± 70.3
	Carcass mass	850.8 ± 162.9	979.5 ± 75.2	813.8 ± 95.4	991.9 ± 97.1

[a] Heart masses not available.
[b] Only one value exists for heart mass.
[c] *Body* refers to bird excluding all internal organs and external appendages.
[d] *Carcass* refers to entire bird bird excluding kidney, liver, esophagus, proventriculus, and gizzard.

because older birds are typically larger and have been accumulating Cd for a longer period of time (Warren *et al.* 1990; Henny *et al.* 1991). Cd concentrations in canvasbacks during early winter were also far lower than those known to cause problems such as altered metabolism (120 mg/kg) or kidney and gonadal toxicity (260–450 mg/kg) in mallards (DiGiulio and Scanlon 1984a; White *et al.* 1978). Mean kidney Cd concentrations in canvasbacks were also lower than those found in kidneys of long-tailed ducks (*Clangula hyemalis*) (28 mg/kg) and common eiders (*Somateria mollissima*) (12 mg/kg) considered healthy (DiGiulio and Scanlon 1984b; Karlog *et al.* 1983). Birds naturally exposed to high concentrations of Cd through a diet of mollusks may have evolved a higher tolerance to Cd than that found in other species (Furness 1996). Cd and

Table 5. Mean and SD of 13 body composition measurements (mass in g) for greater and lesser scaup wintering on the California coast

		Early		Late		
		Adult	Juvenile	Adult		Juvenile
Measurement		Male	Male	Female	Male	Female
Greater scaup						
N		2	5	2	6	1
Leg	Fat	0.9 ± 0.1	1.1 ± 0.4	1.6 ± 0.7	1.0 ± 0.6	0.9
	Lean	7.0 ± 0.7	6.8 ± 0.4	6.4 ± 0.6	6.5 ± 0.7	6.2
Organs	Pancreas	1.7 ± 0.2	2.1 ± 1.2	1.5 ± 1.0	1.3 ± 0.3	1.6
	Heart	3.0[a]	5.0[a]	4.5 ± 1.3	3.9 ± 0.4	—[b]
Skin	Fat	65.4 ± 4.6	65.9 ± 32.5	122.7 ± 43.0	36.4 ± 32.9	43.8
Body[c]	Abdominal fat	4.0 ± 1.3	3.8 ± 2.2	12.1 ± 6.3	2.8 ± 4.1	6.5
	Total body fat	29.7 ± 2.3	29.0 ± 8.8	48.2 ± 2.7	24.3 ± 10.4	28.2
	Lean	113.6 ± 9.2	107.1 ± 6.6	104.2 ± 0.8	107.4 ± 6.7	96.3
	Body mass	373.2 ± 37.4	357.9 ± 29.3	355.6 ± 18.9	339.9 ± 17.3	306.1
Totals	Ash (TA)	26.3 ± 2.6	26.0 ± 3.4	28.3 ± 2.2	27.8 ± 2.6	25.0
	Ash-free protein (TAFP)	87.4 ± 6.6	81.1 ± 4.6	75.9 ± 3.0	79.6 ± 7.1	71.3
	Carcass fat (TCF)[d]	99.9 ± 3.7	99.7 ± 42.8	184.7 ± 52.7	64.4 ± 46.8	79.4
	Carcass mass	719.7 ± 47.5	694.6 ± 67.4	750.5 ± 48.5	678.4 ± 59.9	594.3
Lesser scaup						
n		1	1	4	6	2
Leg	Fat	0.98	1.53	1.1 ± 0.4	0.7 ± 0.4	0.7 ± 0.1
	Lean	4.4	4.9	4.4 ± 0.2	4.8 ± 0.2	5.0 ± 0.5
Organs	Pancreas	1.4	1.4	1.5 ± 0.3	1.0 ± 0.5	1.1 ± 0.6
	Heart	—[b]	—[b]	4.6[a]	3.8 ± 0.5	3.7 ± 0.6
Skin	Fat	58.2	117.2	89.2 ± 38.1	39.7 ± 28.3	40.6 ± 11.1
Body	Abdominal fat	6.4	13.7	11.2 ± 7.1	3.4 ± 2.5	1.2 ± 0.2
	Total body fat	33.4	41.3	29.4 ± 7.9	20.3 ± 6.8	16.3 ± 3.6
	Lean	81.4	94.1	79.3 ± 1.7	81.1 ± 8.0	82.2 ± 7.0
	Body mass	267.5	331.5	272.9 ± 10.2	260.2 ± 28.0	255.4 ± 22.6
Totals	Ash (TA)	22.4	22.0	19.1 ± 1.4	20.8 ± 1.8	21.7 ± 3.1
	Ash-free protein (TAFP)	59.0	72.0	60.2 ± 2.1	60.3 ± 6.7	60.6 ± 3.9
	Carcass fat (TCF)	98.9	173.7	131.0 ± 53.5	64.2 ± 37.4	58.8 ± 7.1
	Carcass mass	514.9	645.3	567.0 ± 56.0	495.3 ± 70.1	499.0 ± 66.3

[a] Only one value exists for heart mass.
[b] Heart masses not available.
[c] *Body* refers to bird excluding all internal organs and external appendages.
[d] *Carcass* refers to entire bird excluding kidney, liver, esophagus, proventriculus, and gizzard.

Zn accumulation in birds are often correlated, as both induce metallothionein production and both bind to this protein (Furness 1996). In addition, elevated Zn concentrations may diminish the toxic effects of Cd (Eisler 2000a).

Copper

In comparison with waterfowl from other sites (DiGuilio and Scanlon 1984b; Custer and Hohman 1994; Hui *et al.* 1998), Cu concentrations in diving ducks are slightly elevated in San Francisco Bay (Ohlendorf *et al.* 1991; Hothem *et al.* 1998). However, we found no relationship between Cu concentrations in our samples and body condition. Cu added to the diet of waterfowl can accumulate readily (Beck 1961), and acute Cu toxicosis may erode the gizzard and proventriculus (Henderson and Winterfield 1975; Poupoulis and Jensen 1976; Jensen and Maurice 1978). Sublethal effects include anemia (Goldberg *et al.* 1956), but we did not test blood samples. Zn, which may interfere with absorption of Cu (van Campfen and Scaife

Table 6. Geometric means and ranges of trace elements (μg/g DW) in livers and kidneys (Cd only) of canvasbacks collected in early winter at all locations

	Adult		Juvenile	
	Female	Male	Female	Male
n	2	16	2	9
Cd	3.36	2.52	0.36	0.33
(kidney)	(2.4–4.7)	(0.38–5.8)	(0.19–0.67)	(0.06–1.2)
Cu	254.91	189.04	33.08	120.86
	(171–380)	(67.4–765)	(9.6–114)	(9–833)
Hg	1.33	0.58	0.21	0.22
	(0.42–4.2)	(0.18–4.2)	(ND–1.3)	(ND–0.91
Se	6.94	6.88	3.97	3.44
	(3.7–13)	(3.4–18)	(1.9–8.3)	(0.86–13)
Zn	193.08	179.83	155.97	166.08
	(160–233)	(116–259)	(153–159)	(138–199)

ND = Not detected.

Table 7. Geometric means and ranges of trace elements (μg/g DW) in livers and kidneys (Cd only) of greater and lesser scaup during early and late winter

	Greater Scaup					Lesser Scaup				
	Early		Late			Early			Late	
	Adult	Juvenile	Adult		Juvenile	Adult	Juvenile		Adult	Juvenile
	Male	Male	Female	Male	Female	Male	Female	Male	Male	Male
n	2	5	2	6	1	1	1	4	6	2
Cd	9.83	1.95	11.65	14.94	2.5	6.3	1.2	0.58	7.08	3.25
(kidney)	(4.6–21)	(0.8–3.9)	(9.7–14)	(6.6–32)				(0.29–0.93)	(3.7–18)	(2.4–4.4)
Cu	95.94	95.15	80.33	108.29	99.6	68.3	79.7	97.28	48.63	63.17
	(94.5–97.4)	(61.8–119)	(71.7–90)	(84.9–142)				(65.4–128)	(37.1–105)	(48.9–81.6)
Hg	3.43	2.89	9.55	10.78	4.4	5.32	1.1	2.3	5.6	7.58
	(2.8–4.2)	(1.8–5.18)	(1.9–48)	(8.14–19.5)				(1.4–3.6)	(3.6–9.8)	(5.79–9.92)
Se	13.42	12.83	16.61	47.94	27.0	11.0	3.5	6.30	11.13	11.93
	(7.6–23.7)	(5.8–22.3)	(8.9–31)	(34–140)				(2.8–12.2)	(7.1–19)	(8.9–16)
Zn	181.14	156.89	133.99	169.99	157.0	166.0	105	149.04	159.45	148.36
	(170–193)	(134–175)	(133–135)	(148–186)				(140–159)	(148–183)	(142–155

Table 8. AIC values and coefficients of determination (r^2) for regression models relating TAFP, TCF, heart mass, pancreas mass, and body mass to trace elements and sex (seven independent variables overall) in canvasbacks

Dependent Variable	r^2	Model	Lowest AIC	Highest AIC
TAFP	0.475	−Se	129.9	142.2
TCF	0.142	+Cd	248.0	260.9
Heart mass	0.537	+Hg	7.2	17.5
Pancreas mass	0.286	−Hg, +Se	−23.9	−8.5
Total carcass mass	0.326	—	264.7	279.9

The first principal component (representing structural size) and age are included in every model. The model reported has the lowest AIC for the corresponding dependent variable.

Table 9. AIC values and coefficients of determination (r^2) for regression models relating TAFP, TCF, heart mass, pancreas mass, and body mass to trace elements, sex, species, and collection season (10 independent variables overall) in greater and lesser scaup

Dependent Variable	r^2	Model	Lowest AIC	Highest AIC
TAFP	0.675	—	118.4	134.8
TCF	0.468	−Zn, male, early	235.3	248.6
Heart mass	0.119	—	−5.6	34.3
Pancreas mass	0.377	−Hg, −Zn	−25.0	−12.6
Total carcass mass	0.813	+Se, −Zn, early	246.0	258.8

The first principal component (representing structural size) and age are included in every model. The model reported has the lowest AIC for the corresponding dependent variable.

1967), was elevated in our samples, but we were not able to determine if an interaction existed between Zn and Cu.

Mercury

Hundreds of kg of Hg are discharged into the San Francisco Bay estuary each year from abandoned mines in the watershed, disturbed geological deposits and thermal hot springs in the coast range, water treatment plant discharges, and erodible deposits of elemental Hg left in Sierra Nevada streams during the gold rush era. Mean Hg concentrations in San Francisco Bay scaup were generally higher and increased more over winter than mean Hg concentrations in greater scaup collected in winter (0.87–2.05 μg/g DW) and spring (1.01–3.80 μg/g DW) 1996–1997 in Long Island Sound (Cohen *et al.* 2000). Mercury concentrations were elevated in canvasbacks and scaup (Hothem *et al.* 1998) above concentrations that have been shown to impair reproduction in captive mallards (Heinz 1979). We found that Hg was inversely related to pancreas mass in both canvasbacks and scaup, but positively related to heart mass in canvasbacks. We have no explanation for the positive relation to heart mass in canvasbacks. However, two recent studies on wintering surf scoters and greater scaup in San Francisco Bay (Ohlendorf *et al.* 1991; Hoffman *et al.* 1998) showed that lower body, heart, and liver mass were significantly related to increasing hepatic Hg concentrations, which seems to agree with our findings for scaup.

Selenium

Oil refinery effluents, irrigation drainwater from the San Joaquin River, and sewage treatment plant effluents are major sources of Se in the San Francisco Bay estuary (Cutter and San Diego-McGlone 1990), and Se concentrations for birds collected in the estuary were elevated over concentrations found in Louisiana canvasbacks (Custer and Hohman 1994).

In a laboratory study, Heinz and Fitzgerald (1993) found that adult male mallards fed *ad libitum* with 20 μg/g or more of selenomethionine exhibited weight loss and increased overwinter mortality. In our study, TAFP in canvasbacks decreased with increasing Se concentrations, but there was no relationship between Se and carcass mass. Mean Se concentrations in scaup were higher than in canvasbacks (Hothem *et al.* 1998) and exceeded the estimated threshold concentration (8.0–12 μg/g) for impaired reproduction in female mallards (Heinz *et al.* 1989). Despite this, we found no relationship between liver Se concentration and any of the body condition indices we tested in scaup.

We also did not find the interaction between liver Hg and liver Se concentrations to be an important variable in any of the models. Hg and Se are often regarded as being toxicologically antagonistic where exposure to one of these elements protects individuals from the toxic effects of the other (El-Begearmi *et al.* 1977). However, several significant exceptions to this rule have emerged with regard to avian species, and it seems that enhanced storage of both elements might negate the protective benefits. Beijer and Jernelov (1978) reported that elevated Se causes increased retention of Hg. According to Heinz and Hoffman (1998), elevated Hg causes increased retention of Se, and the effects of Hg and Se on avian teratogenesis and embryo mortality are additive.

Zinc

Zn may be grossly elevated in bivalve mollusks from areas near such sources as steel plating and galvanizing plants, mining, municipal and industrial water treatment plants, oil refineries, and agricultural runoff where Zn sulfate is used as a cooperative agent in fungicides (Eisler 2000a). Luoma and Cain (1979) reported elevated concentrations of Zn in clams (*Macoma balthica*) in the South Bay, and Zn concentrations may be inversely related to condition in San Francisco Bay clams (Miles, personal communication). Elevated Zn concentrations, in association with other metals, may have played a role in waterfowl mortality documented near mining and smelting operations in northern Idaho (Chupp and Dalke 1964)

Although we found no relationships between Zn and body condition parameters in canvasbacks, we found consistent inverse relationships between Zn concentrations and TCF, pancreas mass, and carcass mass in scaup. Zinc concentrations in scaup in our samples were higher than concentrations in scaup in British Columbia (134–139 μg/g), and similar to or slightly lower than concentrations found in scaup in Connecticut and New Jersey (Gochfeld and Burger 1987; Cohen *et al.* 2000). Zn concentrations were lower than those in captive mallards fed an *ad libitum* diet containing 3,000–12,000 mg Zn carbonate per kg of feed (Gasaway and Buss 1972). However, scaup from our study exhibited the same decline in pancreas mass and carcass mass with increasing Zn concentrations found in the captive mallards. The pancreas is a primary target of Zn in birds (Eisler 2000a), and Zn concentrates and remains elevated in the pancreas more than in any other organ (Lu and Combs 1988; Williams *et al.* 1989). High pancreatic Zn concentrations may suppress the release of insulin by inhibiting calmodulin (Verheyen *et al.* 1990) and would thus affect metabolic regulation and overall body condition. In Zn studies with captive birds, declines in mass are often associated with decreased food intake due to unpalatability (Gasaway and Buss 1972; Verheyen *et al.* 1990). Conversely, if Zn concentrations are high enough to affect palatability, wild ducks may simply select other prey or move to different areas. Thus, decrease in food intake due to unpalatability is unlikely to have caused the decline in mass that we found in this study. Zinc is known to interact with many chemicals to produce altered patterns of accumulation, toxicity, and metabolism (Eisler 2000a); therefore, declines in fat and overall carcass mass in scaup may represent the result of complex interactions between Zn and other substances.

Implications for Diving Duck Populations

Our results suggest that reduced body condition in diving ducks during the winter may be related to higher concentrations of some environmental contaminants. Decline in body condition, characterized by decreased body mass and nutrient reserves, may result in lower overwinter or annual survival or poor breeding performance (Haramis *et al.* 1986; Ankney and Alisauskas 1991). Reduced fat reserves may be particularly important, because fat has a major role in egg synthesis, migration, starvation avoidance, and insulation (see Johnson *et al.* 1985). Canvasbacks seem to maintain the highest fat concentrations possible within the constraints of proximate conditions during the winter (Lovvorn 1994). Lovvorn (1994) suggested that reduced body condition might have a greater effect on juvenile ducks, because juveniles have higher starvation probabilities that increase later in the winter. *Aythya* species appear to rely heavily on nutrient reserves when daily mean air temperatures remain below freezing (Lovvorn 1994), although subfreezing temperatures are not often recorded in coastal California.

Austin *et al.* (2000) suggested that contaminants might affect scaup populations in two ways: (1) contaminant concentrations in eggs may affect reproduction, or (2) secondary effects on adults may deter breeding. Thus, if contaminants acquired during the winter reduce body condition, diving ducks may have insufficient energy stores to migrate to breeding sites or alternatively, they might not breed after arriving at breeding sites (Afton 1984). Unfortunately, we have no direct data relating diving duck body condition during the winter with subsequent productivity.

Although we limited our analyses to contaminants known to have harmful effects on birds at elevated concentrations, we found a few cases where contaminant concentrations were positively related to body condition (Tables 8, 9). With the exception of Cd and TCF in canvasbacks, we were unable to explain these positive correlations, although they may be biologically meaningful. For example, Franson *et al.* (1999) found a positive relationship between blood Se concentrations and body condition of incubating female emperor geese (*Chen canagica*). They believed this relationship was the result of Se exposure in the marine environments where these geese winter and stage for migration. Birds that arrive at the breeding area from such wintering areas in good body condition may start nesting earlier and, thus, would have higher blood Se concentrations than birds in poor condition that may feed on the less contaminated breeding grounds before initiating nesting. Body condition of wintering diving ducks is also related to their diet and foraging behavior (Henny *et al.* 1991; Lovvorn and Gillingham 1996a, 1996b).

Future Research

Our analyses were limited to a subsample of sites from coastal California across a limited range of contaminant concentrations. In San Francisco Bay, nonindigenous invasive species may be altering the availability of contaminants for diving ducks in the estuary. The Asian clam (*Potamacorbula amurensis*) has replaced *Macoma balthica* as the most dominant mollusk in the northern region of the estuary (Carlton *et al.* 1990). This new clam may concentrate contaminants such as Se as much as three times more than *Macoma* (Luoma and Linville 1995), and this species now comprises a large amount of the diet of greater and lesser scaup (Takekawa, unpublished data). Diving ducks analyzed in this study were collected in 1986 during the first year the Asian clam was found in the estuary. More recent samples would be helpful in determining what effect the Asian clam invasion has had on contaminants and body condition in waterfowl wintering in the estuary. Future analyses including larger samples from sites providing a wide range of contaminant exposures and studies of metal mobilization with declining body condition may improve our ability to relate differences in body condition with contaminant concentrations.

Conclusions

We found that body condition of diving ducks was inversely related to elevated concentrations of Hg, Se, and Zn. Pancreas mass decreased with increasing Hg in canvasbacks and scaup, and TAFP decreased with increasing Se in canvasbacks. TCF, pancreas mass, and carcass mass decreased with Zn in scaup. Few researchers have investigated relationships between Zn and body condition in wild birds. Further studies relating body condition to contaminant concentrations may illuminate interactions among trace elements that may have subtle, yet significant effects on survival and reproduction of diving duck populations.

Acknowledgments: This study was funded by the U.S. Fish and Wildlife Service and the U.S. Geological Survey. We thank J. E. Takekawa, D. Lonzarich, and H. Ohlendorf for their support in accomplishing this project. J. White and P. Hofmann (California Department of Fish and Game) provided the samples for the study, and K. Gonzalez and staff at the Don Edwards San Francisco Bay National Wildlife Refuge assisted in processing samples. J. Avery and D. Ankney (University of Western Ontario) conducted the condition analyses. We thank H. Ohlendorf, J. Lovvorn, C. Marn, and D. Whitworth for their helpful comments on drafts of this manuscript.

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