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Seasonal Variation in Heavy Metal Levels in Tissues of Common Guillemots, *Uria aalge* from Northwest Scotland

F. M. Stewart[1], D. R. Thompson[1], R. W. Furness[1], N. Harrison[2]

[1] Applied Ornithology Unit, Department of Zoology, University of Glasgow, Glasgow G12 8QQ, Scotland, United Kingdom
[2] R.S.P.B. The Lodge, Sandy, Bedfordshire SG19 2DL, United Kingdom

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Abstract. Mercury, cadmium, zinc, and copper concentrations were analyzed in three samples of common guillemot (in April, June, and November). Levels measured were uniformly low, and not enough to have any toxic effects. Adult guillemots had significantly more cadmium in their livers and kidneys than juveniles, with juvenile levels ranging from 25% to 89% of adult levels. Mercury concentrations in liver and kidney were also higher in adults. Juvenile levels represented from 80% to 94% of adults, but there were no age differences in feather and muscle mercury. Mercury levels declined throughout the year in internal tissues from April through June to November. There was a strong seasonal fluctuation in cadmium levels in liver and kidney, rising significantly between April and June and declining again from June to November. These changes were apparent in both adult and juvenile birds. The influences of seasonal processes (namely breeding and moult) and seasonal dietary differences as causative factors in the changes in metal burdens are discussed. These findings have implications for the use of seabirds as monitors of heavy metals in the marine environment.

Seabirds have been advocated as useful monitors of heavy metal pollutants in the marine environment (Walsh 1990; Thompson *et al.* 1992). Although there is an extensive literature describing heavy metal levels in seabirds, few papers have examined seasonal variation in metal burdens or concentrations within a population. One of the most important features of a biomonitor is that measurements adequately reflect the bioavailability of the contaminant (Phillips 1990). Therefore, it is important to have knowledge of the kinetics of the contaminant in the species used, considering such factors as metabolic, physiological, and dietary specialisation. Only then can seabirds be used as effective indicators of environmental quality (Walsh 1990; Furness 1993). In particular, variation in metal concentrations in soft tissues has to be considered as mercury excretion occurs in eggs (Becker *et al.* 1989) and growing feathers (Honda *et al.* 1986a), and cadmium burdens may also be affected by physiological processes.

Problems common to studies of seasonal variations in cadmium concentrations in birds have been low sample sizes and high individual variation in metal levels, and often seasonal changes in fat or protein and content of organs have not been monitored.

It has been suggested that the common guillemot *Uria aalge* is particularly suitable as an indicator of pollution in European coastal areas, as it is a common bird in most areas, is a year-round resident, and thus could reflect local bioavailability of heavy metals (Tasker and Becker 1992). In making comparisons between seasons, it is essential that birds from only one, discrete population are being sampled at each time of year. Analysis of ring recovery data and of biometrics has shown that this was the case for these guillemots, and results are published in Furness *et al.* (1994).

In this paper we present mercury, cadmium, zinc, and copper concentrations in common guillemots from the population in northwest Scotland sampled in spring, summer, and winter, and examine season, sex, and age effects. The northwest of Scotland is a clean environment, especially in comparison to some European coastal areas.

Materials and Methods

Sample Collection and Preparation

Guillemots were sampled on three occasions, on 27 April, 25 June, and 1–2 November 1988, from the waters surrounding the Summer Isles at the mouth of Loch Broom, northwest Scotland. These samples were taken for dietary studies by the Joint Nature Conservation Committee Seabirds-at-Sea Team, and were subsequently made available to us. All birds were shot at sea, under licence, from an inflatable boat using a 12-bore shotgun. Guillemots were returned to shore within 5 min and were weighed, measured, and plumage and moult status recorded.

The body cavity was opened, the liver carefully removed, and the crop and gizzard were removed for dietary analysis. Birds were sexed by internal examination, and aged by presence or absence of bursa noted. The composition of the three samples was as follows: 26

Correspondence to: F. M. Stewart

Table 1. Tissue dry masses (g) and mercury and cadmium contant (μg) of liver, kidney, and one pectoral muscle of adults and juveniles (J) from the three collections. All values are means (μg) with standard deviations in parentheses

		Liver			Kidney (mass 3.56 g)		Muscle	
Group		Mass	Hg cont.	Cd cont.	Hg cont.	Cd cont.	Mass	Hg cont.
Adults	April	10.82	39.16	17.36	13.98	32.04	28.56	49.80
		(1.99)	(12.05)	(7.38)	(3.77)	(18.67)	(2.33)	(16.31)
Juveniles		12.97	31.36	17.64	9.44	14.43	26.97	33.72
		(0.84)	(5.95)	(4.24)	(1.05)	(4.33)	(3.72)	(6.82)
Adults	June	10.47	26.30	26.35	9.04	41.74	28.34	23.67
		(1.99)	(11.38)	(15.06)	(3.16)	(18.57)	(2.77)	(10.71)
Juveniles		11.02	17.01	21.29	6.81	37.38	28.50	18.63
		(2.32)	(5.38)	(5.63)	(2.13)	(17.63)	(1.48)	(8.13)
Adults	Nov.	11.34	9.73	18.27	2.97	21.87	29.41	13.63
		(1.44)	(3.12)	(5.83)	(0.86)	(7.28)	(2.36)	(6.64)
Juveniles		12.80	13.28	14.06	3.63	5.87	29.37	14.94
		(1.63)	(5.26)	(3.69)	(0.88)	(2.53)	(2.55)	(4.19)

April = 24 adults, 6 immatures (23 males and 7 females), 25 June = 21 adults, 6 immatures (16 males, 11 females), and 1–2 November = 20 adults, 5 immatures (17 males, 7 females, and 1 which could not be sexed due to gun-shot damage).

After transport to the laboratory, kidney and muscle tissues were dissected out and fresh masses of tissues were determined (to 0.001 g). All tissues were stored deep frozen at −20°C prior to further treatments. Liver, kidney, and muscle tissues were defrosted, homogenized, and dried to constant mass in an oven at 50°C prior to metal analysis. In addition, four to ten body feathers were sampled from the back (dorsal) region of each bird, surface contamination removed using an acetone/chloroform washing regime (Muirhead 1986), and feathers dried at ambient laboratory temperature (ca. 22°C) prior to analysis. In order to determine whether changes in concentration of metals in tissues reflected changes in tissue burdens of metal, the entire liver and the pectoral muscle from the left side of the keel were dissected and dried to constant mass so that metal burdens could be determined. Because of the difficulty in dissecting complete kidney tissues, these were taken from a subsample of six birds.

Mercury Analysis

Liver, kidney, and pectoral muscle samples from birds from the first (April) collection initially underwent a fractionation in order to extract methyl mercury. The method used was based on that of Uthe *et al.* (1972) and is described in Thompson and Furness (1989). Extracted methyl mercury concentrations were compared to corresponding total mercury concentrations for each bird and for all three tissues. The two measurements did not differ significantly from each other (paired t-tests for liver, kidney, and pectoral muscle; $P = 0.13$, 0.47, and 0.21, respectively), indicating that virtually all the mercury present in the three tissues was methyl mercury. Consequently, all feather samples and internal tissues from June and November samples were analyzed for total mercury only.

Total mercury in acid-digested samples was determined by a cold vapor technique, using a Data Acquisition Ltd. DA 1500-DP6 Mercury Vapor Detector (Furness *et al.* 1986). Accuracy and reproducibility of mercury determination were tested by analyzing International Atomic Energy Agency horse kidney Reference Material H-8.

Cadmium, Zinc, and Copper Analyses

Samples of 0.5–1.0 g dried tissue (kidney, liver and muscle) were acid digested in 10 ml conc. nitric acid on a hot plate, by first soaking at 100°C for 2 h, then boiling at 120°C for 20 min. Samples were diluted to 15 ml, using distilled water. Metal concentrations were analyzed by Atomic Absorption Spectrophotometry, using a Phillips PU 2000 AAS. Accuracy and reproducibility of metal determinations were tested by analyzing horse kidney Reference Material H-8, Detection limits were 0.014 μg/g for Cd, 0.01 μg/g for Zn, and 0.035 μg/g for Cu, in the digested sample. All metal concentrations are expressed on a dry weight basis.

Statistical Analyses

Preliminary tests were performed of the goodness of fit of data to normal distributions (Kolmogorov-Smirnov one-sample tests). Where fit was good, subsequent analyses were made using parametric statistics. Where data deviated significantly from normality, defined throughout this paper as $P < 0.05$, we used nonparametric statistics. Statistical tests were performed with the SPSS-PC+ package (Norusis 1986, 1988).

Results

Organ Weights and Metal Content

A two-way ANOVA revealed that neither sex nor sampling date were significant factors with respect to liver dry mass (sex: $F_{1,63} = 1.50$, N.S.: collection date: $F_{2,63} = 1.2$, N.S.). Similarly, sample date did not affect pectoral muscle mass significantly ($F_{2,63} = 1.8$, N.S.), although a significant difference was found between the sexes ($F_{1,63} = 4.9$, $p < 0.05$). Thus significant changes in metal burden (μg), in liver and muscle tissues over the sampling period, were likely to have been a function of metal concentration, rather than tissue mass. Kidney masses averaged 15.01 g (fresh) and 3.56 g (dry) for a sample of six birds.

Tissue masses and total metal contents of the birds are shown in Table 1. As organ weights did not change seasonally, all data analyses were performed using metal concentrations (μg/g) in tissues.

Metal concentrations in tissues and feathers of adult and juvenile birds are shown in Table 2. Results of two-way

Table 2. Mercury, cadmium, copper, and zinc in tissues collected in April (coll. 1), June (coll. 2), and November (coll. 3)

		Cadmium		Zinc			Copper			Mercury			
Group	Coll.	Liver conc. (s.d.) c.v.	Kidney conc. (s.d.) c.v.	Liver conc. (s.d.) c.v.	Kidney conc. (s.d.) c.v.	Muscle conc. (s.d.) c.v.	Liver conc. (s.d.) c.v.	Kidney conc. (s.d.) c.v.	Muscle conc. (s.d.) c.v.	Liver conc. (s.d.) c.v.	Kidney conc. (s.d.) c.v.	Muscle conc. (s.d.) c.v.	Feather conc. (s.d.) c.v.
Adults		1.56	9.00	58.42	72.22	25.17	15.02	13.82	11.52	3.66	3.93	1.76	2.15
n = 24	April	(0.49)	(5.25)	(7.72)	(9.90)	(3.23)	(1.76)	(2.01)	(1.41)	(1.05)	(1.06)	(0.62)	(0.52)
		31.41	58.22	12.36	13.71	12.83	11.72	14.54	12.24	28.69	26.97	35.23	24.19
Adults		2.49	11.72	68.89	74.13	25.98	16.09	13.69	13.96	2.52	2.54	0.84	2.09
n = 21	June	(1.33)	(5.21)	(7.41)	(11.90)	(7.28)	(3.10)	(2.09)	(1.32)	(0.99)	(0.89)	(0.38)	(0.78)
		53.41	44.45	10.75	16.05	28.02	19.27	15.27	9.46	39.28	35.03	45.24	35.88
Adults		1.66	6.14	69.70	72.31	20.89	15.48	13.00	10.68	0.87	0.84	0.47	1.71
n = 20	Nov.	(0.52)	(2.04)	(11.58)	(6.98)	(1.80)	(2.29)	(1.70)	(1.20)	(0.28)	(0.24)	(0.26)	(0.57)
		31.32	33.22	16.61	9.65	8.62	14.79	13.08	11.23	32.18	9.45	55.32	33.33
Juv.		1.35	4.05	58.56	67.62	23.29	12.92	13.96	12.03	2.40	3.43	1.27	1.26
n = 6		(0.30)	(1.21)	(7.62)	(8.28)	(2.71)	(0.86)	(1.72)	(1.77)	(0.34)	(0.58)	(0.30)	(0.33)
	April	22.22	29.87	13.01	12.24	11.63	6.66	12.32	14.71	14.17	16.91	23.62	26.19
Juv.		1.98	10.50	67.77	74.03	24.11	15.62	15.24	13.50	1.57	1.91	0.65	2.68
n = 6	June	(0.56)	(4.95)	(8.15)	(13.11)	(2.34)	(1.65)	(2.13)	(1.48)	(0.53)	(0.60)	(0.27)	(1.64)
		28.28	47.14	12.02	17.71	9.70	10.56	13.98	10.96	33.76	31.41	41.38	61.91
Juv.		1.09	1.56	60.78	59.30	22.54	13.34	12.26	10.21	1.06	1.02	0.52	0.87
n = 6	Nov.	(0.22)	(0.71)	(7.65)	(14.79)	(3.61)	(2.64)	(2.66)	(1.11)	(0.44)	(0.25)	(0.18)	(0.42)
		20.18	45.51	12.59	24.94	16.01	19.79	21.70	10.87	41.51	24.51	34.61	48.27

n = sample size. s.d. = standard deviation. c.v. = coefficient of variation. Conc. = mean concentration μg/g dry weight internal tissue.

ANOVA tests of metal level by age (juvenile/adult) and collection date are shown in Table 3. Cadmium was not detected in any of the muscle samples (<0.015 μg/g dry tissue mass).

Table 3. Two-way ANOVA analyses of metal concentrations in Guillemots, *uria aalge*, to show age, sex and seasonal differences

		Age and season		Sex and season	
Metal	Organ	Age ($F_{1,81}$)	Season ($F_{2,81}$)	Sex ($F_{1,63}$)	Season ($F_{2,63}$)
Cadmium	Liver	5.26	13.62	0.44	8.54
		*	***	N.S.	**
	Kidney	9.73	15.14	3.63	8.11
		**	***	N.S.	**
Mercury	Liver	10.86	66.04	2.2	57.2
		**	***	N.S.	***
	Kidney	8.60	89.73	1.5	73.2
		*	***	N.S.	***
	Muscle	3.89	57.34	0.0	43.8
		N.S.	***	N.S.	***
	Feather	3.7	6.26	4.9	3.0
		N.S.	*	*	N.S.
Zinc	Liver	1.64	12.60	0.59	14.15
		N.S.	***	N.S.	***
	Kidney	3.87	1.29	0.23	0.22
		N.S.	N.S.	N.S.	N.S.
	Muscle	0.48	7.17	1.52	7.18
		N.S.	*	N.S.	*
Copper	Liver	6.34	2.92	0.03	1.12
		*	N.S.	N.S.	N.S.
	Kidney	0.54	2.58	6.27	0.99
		N.S.	N.S.	*	N.S.
	Muscle	0.10	40.00	0.67	32.77
		N.S.	***	N.S.	***

N.S. = not significant at $p < 0.05$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Sex Effects, Age Effects, and Seasonal Effects

Due to the small sample size for juveniles, differences in metal concentrations between the sexes were examined only for adults (Table 3). Mercury in feathers showed a significant difference, males tending to have higher levels than females (males n = 56, mean = 2.00, s.d. = 0.85, females n = 25, mean = 1.77, s.d. = 0.66). Copper concentrations were significantly higher in the kidney of females (females n = 25, mean = 14.44, s.d. = 2.29, males n = 56, mean = 13.27, s.d. = 1.82).

Mercury concentrations were significantly higher in adult liver and kidney, but not in feathers or muscle (Table 3). Juvenile mercury levels represented from 80% to 94% of adult mercury concentrations. Cadmium concentrations were also significantly higher in liver and kidney of adults. Juvenile cadmium levels ranged from 25% to 89% of adult levels. Zinc concentration showed no age differences. Copper concentration in adult liver was significantly higher than in juveniles.

Both mercury and cadmium concentrations in the liver and kidney showed strong seasonal trends. This is seen in both adult and juvenile birds. These are illustrated in Figure 1. Mercury concentrations in internal tissues showed a general decline from April through to November. Cadmium concentrations, however, increased significantly between April and June, then de-

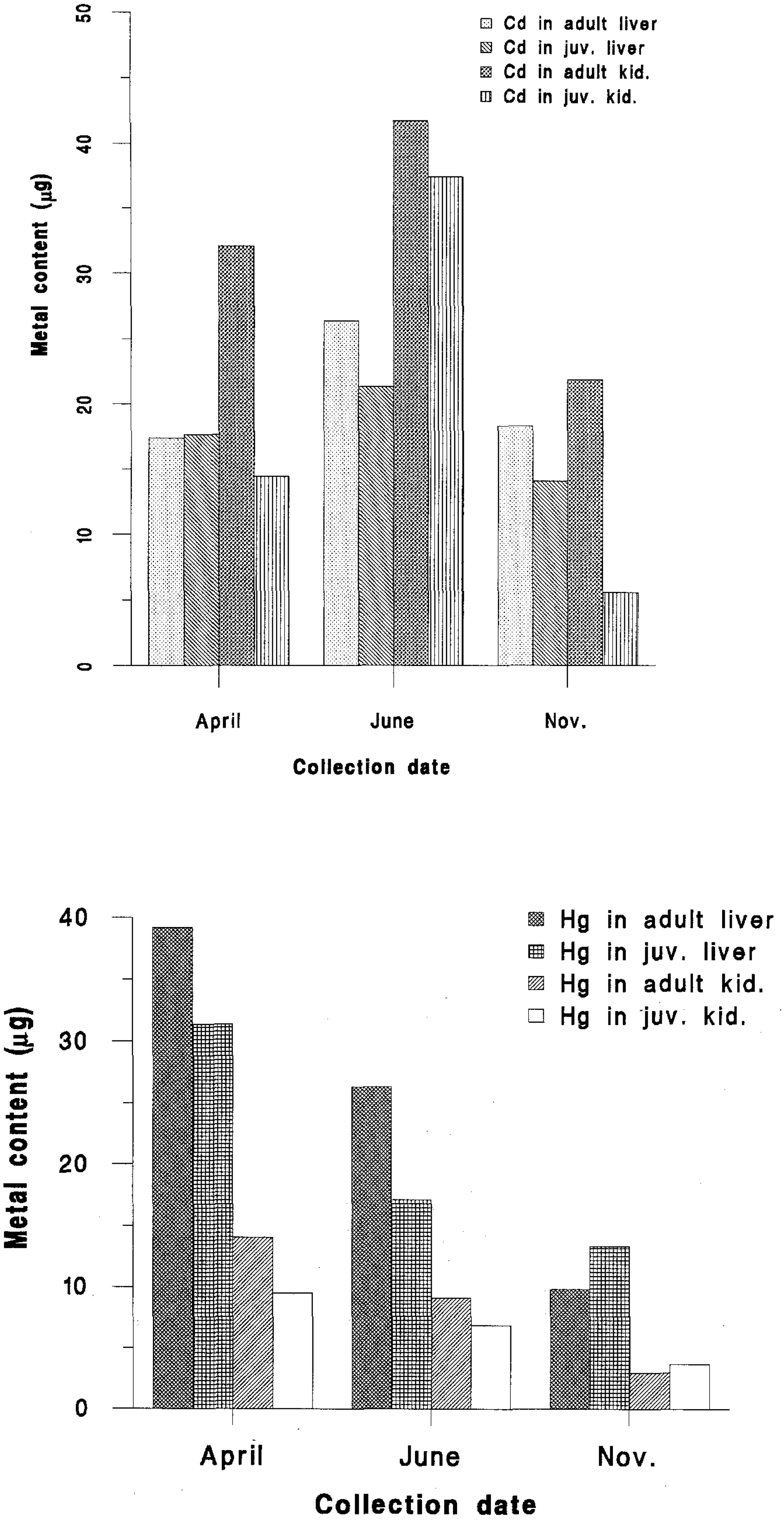

Fig. 1. Seasonal variation in guillemot (*uria aalge*) metal loads

creased to almost half the June level by November. Mercury levels in the muscle of the juvenile birds drops by almost half between April and June and is even lower by November. The feather levels also vary in juveniles but the small sample sizes (n = 6, in each collection) make further analysis difficult. Zinc levels in both adult and juvenile liver show a peak in the June collection, and muscle zinc levels also show some seasonal variation (Table 3).

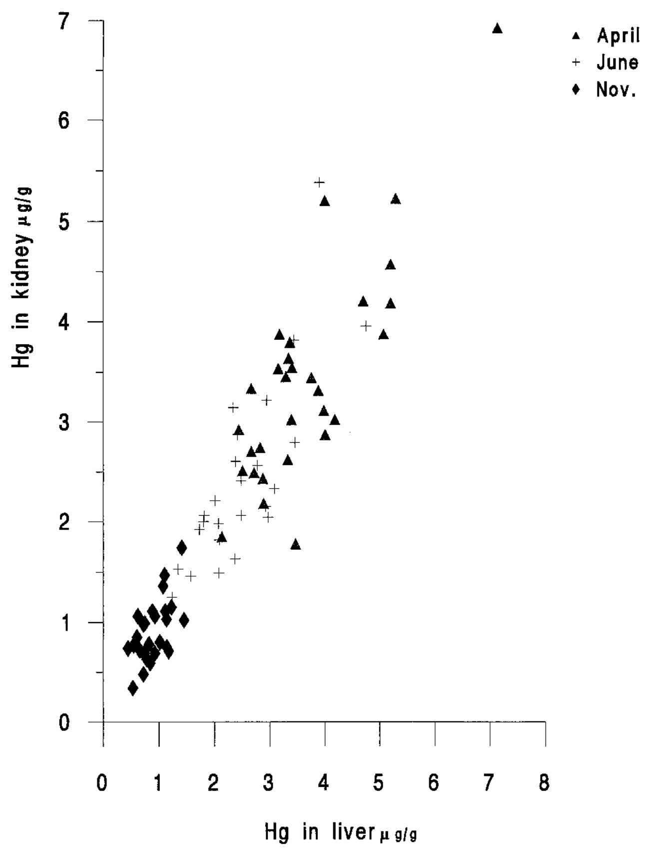

Fig. 2. Intertissue and intermetal relationships in the sample

Inter-Tissue and Inter-Metal Correlations

There were several intertissue and intermetal relationships in the sample. Mercury levels in liver and kidney tissues were found to be significantly positively correlated in birds from all three collections (Figure 2), (April, $r = 0.77$, $P < 0.05$; June, $r = 0.81$, $P < 0.001$; November, $r = 0.48$, $P < 0.05$). Mercury levels in liver and muscle tissues were significantly positively correlated in birds from the first and second collections (April, $r = 0.59$, $P < 0.01$; June, $r = 0.51$, $P < 0.05$). Feather mercury concentrations were found to be positively and significantly correlated with liver mercury levels in birds from the third collection ($r = 0.47$, $P < 0.05$).

Cadmium in the kidney was significantly positively correlated with zinc in the kidney in April and June, but not in the November collection (April, $r = 0.43$, $P < 0.05$; June, $r = 0.52$, $P < 0.05$; November, $r = 0.12$, N.S.). Cadmium in the liver was significantly negatively correlated with zinc in the liver in the first collection (April, $r = -0.46$, $P < 0.05$), but significantly positively correlated in the second and third collections (June, $r = 0.82$, $P < 0.001$; November, $r = 0.53$, $P < 0.05$).

Copper and zinc concentrations in the kidney were significantly positively correlated in all three collections grouped ($r = 0.63$, $P < 0.001$). Copper and zinc concentrations in the liver were significantly positively correlated in all collections grouped ($r = 0.55$, $P < 0.001$).

Mercury concentration in the kidney was significantly positively correlated with copper and zinc concentrations in the kidney in the first collection (April, $r = 0.66$, $P < 0.05$ and $r = 0.63$, $P < 0.05$, respectively), but not in the other two collections. There was no relationship between cadmium and mercury levels in any of the collections.

Coefficients of Variation

Coefficients of variation (CV) are shown in Table 2. The CV can be a useful tool in looking at the regulation of metals in birds (Walsh 1990). The CV of the essential metals, copper, and zinc are generally low and quite uniform between age classes and seasons, usually under 20, whereas the CV of the non-essential metals are much higher and fluctuate more through the two age classes and three collection dates.

Discussion

Few studies have analyzed metal levels in common guillemots. Most studies sampled birds during the summer months and so are comparable with the June collection in this study (Honda *et al.* 1987; Norheim *et al.* 1987; Furness *et al.* in press). Where necessary, we have converted concentrations expressed in relation to wet weights to a dry weight equivalent, using mean water content of common guillemot tissues determined in this study.

Mean liver cadmium levels were 2.49 µg/g and kidney levels of 11.72 µg/g (dry weight) in birds from Loch Broom. These are slightly higher than in common guillemots sampled in the North Pacific which had mean liver levels 1.4 µg/g and kidney levels 9.0 µg/g (Honda *et al.* 1990), but lower than in common and Brunnich's guillemots *Uria lomvia* from Iceland, which had mean liver levels of 5.58 and 9.84 µg/g, respectively (Furness *et al.* in press,b). Brunnich's guillemots from Spitsbergen (Norheim *et al.* 1987) also had considerably higher levels, with mean liver levels of 15.6 µg/g and kidney 64 µg/g.

Mean liver and kidney mercury levels in this study (2.52 µg/g and 2.54 µg/g, dry weight) are slightly higher than in North Pacific common guillemots (0.88 µg/g in liver and 0.72 µg/g in kidney), and also higher than mercury in common and Brunnich's guillemot from Iceland (1.32 and 1.20 µg/g dry weight in livers, respectively) but similar to the Brunnich's guillemot from Spitsbergen (2.4 µg/g in liver).

These differences both within a species and between two closely related species probably reflect geographical variations in the cadmium and mercury in the oceans, and thus in the foodweb, though dietary differences may also be important. Levels were uniformly low in all studies, and would not cause any toxic effects.

Inter-Organ and Inter-Metal Correlations

There was a correlation of mercury concentrations between internal tissues (particularly liver and kidney tissues), birds with relatively high mercury levels in one tissue tending to have high levels in other tissues. Such intertissue correlations have been found in a variety of species (Fimreite 1974; Furness and Hutton 1979; Hutton 1981; Ohlendorf *et al.* 1985; Thompson *et al.* 1991), and indicate that mercury is able to accumulate in a range of tissues, although the highest levels have invariably been found in the liver and kidney (Table 1). The single weak correlation between liver and body feather mercury concentrations in birds from the third collection may be a result of body feathers being relatively unimportant in terns of mercury loss. It may be that internal tissue mercury concentrations would correlate more strongly with the mercury levels in first moulted feathers (flight feathers).

The relationship between cadmium and zinc concentrations in kidney and liver tissues is well established (Scheuhammer 1987). They both tend to bind onto the same low molecular weight protein (metallothionein). The correlation between cadmium and zinc concentrations in the kidney in June ($r = 0.52$) was stronger than in April ($r = 0.43$). It is possible that, because of the rise in cadmium, more zinc has become bound onto the metalloprotein compared to the other zinc proteins. The November collection shows no significant relationship between cadmium in the kidney and zinc in the kidney tissue. Cadmium levels were almost half that of the June value in November. This may mean that cadmium levels are below the threshold limit for inducing increased metallothionein synthesis and therefore do not cause a corresponding increase in zinc levels. The relationship in the liver was somewhat different, probably due to the liver function as a zinc store and therefore likely to have high levels of endogenous metallothionein.

Mercury and cadmium in the birds' tissues showed rather different patterns throughout the year, and there were no relationships between cadmium and mercury concentrations in any of the collections. This is probably because all the mercury was in the methyl form and so would be lipid-soluble and also not be bound to metallothionein for storage.

Age Differences

Significantly higher cadmium levels in adults than in juveniles have been found in several other species (Reid and Hacker 1982; Maegden *et al.* 1982; Blomquist *et al.* 1987; Honda *et al.* 1986c). Comparisons of adult and juvenile mercury levels in internal tissues are less well documented. Pectoral muscle levels of mercury in adult baltic great cormorants, *Phalacrocorax carbo,* common guillemots and black guillemots, *Cepphus grylle,* were higher than in juveniles (Jensen *et al.* 1972). In this study, muscle levels were not significantly higher in adults, though levels in liver and kidney levels were. Several studies have found an increase in cadmium with increasing age (Furness and Hutton 1979; Hutton 1981; Reid and Hacker 1982; Maegden *et al.* 1982; Blomquist *et al.* 1987), suggesting that the metal remains bound in the kidney, with a long biological half-life.

The evidence for bioaccumulation of both mercury and cadmium between hatching and reaching maturity is strong (see Walsh 1990 for more examples), but the continuing accumulation with increasing adult age is less clear.

Seasonal Variations in Metal Levels

There were clear differences in mercury, cadmium, and zinc levels throughout the year in both adult and juvenile birds.

There are two hypotheses to consider: (1) The seasonal changes observed are due to physiological processes especially related to breeding and moult. (2) The fluctuations are a result of seasonal dietary changes.

Physiological Processes

The dates of the three collections spanned two major processes which could affect metal levels in internal tissues and feathers, namely, reproduction and moult. Precise data for the timing of egg laying were not obtained for the birds sampled, but most eggs would almost certainly have been laid in May (Birkhead 1980; Harris and Wanless 1985), between the first (26 April) and second (25 June) collections.

The seasonal fluctuations shown by metal concentrations and burdens between the first and second collections could be associated with lipid and protein mobilization during reproduction. The peak concentrations of both cadmium and zinc in the internal tissues appear in the June collection, just after egg laying. During reproduction both male and female birds undergo large physiological changes which involve the uptake of nutrients including zinc and copper (Lofts and Murton 1973). Cadmium is known to associate with these metals, binding onto the same metalloprotein, and it is possible that more protein binding sites are available at this time and so more cadmium could be bound in the liver and kidney. Between the first and second collections, the mercury contents of tissues were reduced significantly. As the mercury in guillemot tissues was in the methyl form and not bound to metalloprotein, it would not be affected by changes in zinc and copper concentrations. The reduction in mercury in the birds at this time could be due to transport into the eggs (Lewis *et al.* 1993). Using data provided by Ratcliffe (1970) and Birkhead and Harris (1985), the fresh mass of egg contents in a guillemot egg from northwest Scotland would be approximately 100 g. Parslow and Jefferies (1975) reported mean mercury concentrations in guillemot eggs from north and northwest Scotland of 1.2 μg/g dry weight (0.24 μg/g fresh weight). These values would lead to a theoretical figure of $100 \times 0.24 = 24$ μg mercury in a guillemot egg from northwest Scotland. The reduction in mercury contents in liver and muscle tissues in female guillemots in this study over the egg-laying period (17 and 42 μg, respectively) exceed this value. The egg can act as an excretory route for mercury, but mercury concentrations in eggs are generally low when compared to mercury burdens of females (Honda *et al.* 1986b). In addition, the reduction in mercury content of the male birds and the lack of sex differences in metal loads suggest that the egg is not being used as a major mercury sink.

Guillemots undergo a complete post-nuptial moult which generally commences in July in British birds (Harris and Wanless 1990). The primaries, secondaries, and tail feathers are dropped simultaneously, though at slightly different times, depending on the feather type, once the adults leave the nesting ledges. Moult of body and head feathers may commence before the birds depart for the sea (Birkhead and Taylor 1977; Ginn and Melville 1983; Harris and Wanless 1990). Therefore, birds will have undergone, and largely completed, post-nuptial moult between the second (25 June) and third (1–2 November) collections. Two juveniles (that is, 1-year-old) birds, collected in June, had already dropped, and were regrowing their primary feathers.

Between the second and third collections, internal tissue mercury levels dropped still further as moult and feather growth was underway. These results clearly point towards the feathers being a major eliminatory pathway for mercury. Such a finding agrees with the well-documented examples for other species. A decline in tissue mercury concentrations associated with feather growth has been demonstrated in black-eared kites *Milvus migrans lineatus* (Honda *et al.* 1986a) and Bonaparte's gull *Larus philadelphia* (Braune and Gaskin 1987), while mercury concentrations in primary feathers have been shown to correspond to the relative position of a feather in the moult sequence (Furness *et al.* 1986; Honda *et al.* 1986a; Braune 1987; Braune and Gaskin 1987). The mercury levels in guillemot body feather samples exhibited no significant seasonal trend over the three collection dates, as would be expected since these are renewed once per year. The significant drop in cadmium concentrations in liver and kidney between the second and third collections could also be due to loss into growing feathers. Although concentrations of cadmium in feathers are usually extremely low and often below detection limits, the amount of cadmium lost from kidney and liver is small and would be difficult to detect in feathers.

Dietary Changes

The changes in metal levels during the breeding season could be explained if birds switch to a prey item which is naturally higher in cadmium and zinc but lower in mercury. The birds sampled showed seasonal differences in diet. In April, 97% of the diet consisted of sandeel, *Ammodytes marinus,* but by June this was reduced to around 50%, with whiting, *Merlangius merlangus,* making up the largest part of the diet. By November no sandeel and few whiting were found, and the diet was mainly made up of poor cod, *Trisopterus minutus* (34.4%), sprats, *Sprattus sprattus* (25.8%), cod, *Gadus morhua* (23.4%) and herring, *Clupea harengus* (16.4%), (Halley *et al.* in press). Although no data are available on metal levels in these prey specimens, they are likely to have differing metal burdens, between age/size and species, and birds will concentrate the heavy metals (Thompson 1990; Burger and Gochfeld 1993). Therefore, the diet alone could create the changes in metal levels if turnover of cadmium and mercury is faster than previously estimated. Blomquist *et al.* (1987) calculated a half-life of 1.5–2.0 years for cadmium in the kidney of the dunlin, and some authors suggest cadmium concentrations in kidney increase throughout life (Hutton 1981). However, Muirhead and Furness (1988), Stock *et al.* (1987), and Nicholson (1981) suggest that some seabirds could regulate levels of cadmium.

The active excretion of cadmium has been suggested by Stock *et al.* (1987), from their study of oystercatchers, *Haematopus ostralegus;* birds showed an increase in renal and hepatic cadmium levels with increasing age up to maturity, but adult birds did not have increasing cadmium burdens. Many other studies have noted significant age differences between adult and juvenile birds, but there is little evidence for an increase with increasing age continuing throughout adulthood. Stock *et al.* (1987) proposed birds such as the oystercatcher which would have been exposed to natural sources of cadmium could balance cadmium intake with excretion, agreeing with the findings of Nicholson (1981). If guillemots could partially regulate cadmium concentrations in the kidney and liver, this may explain the seasonal variations in metal levels, caused by seasonal changes in their diet. This would explain the parallel changes in metal levels in juvenile birds through the season. Guillemots do not start breeding until 4–5 years old (Cramp and Simmons 1985). The young birds in this study therefore would not be breeding and would not undergo the physiological changes which may influence the uptake and excretion of metals. However, they were foraging with the adult birds. In addition, the birds in the study were shot at sea and not at the colony, so not all the birds classed as adults would be breeding.

The ability to regulate concentrations of some non-essential metals could also explain the lack of seasonal variation in cadmium and mercury in dunlin *Calidris alpina* (Goede *et al.* 1987). However, levels of metals in that study were very low (often below detection levels), and the samples sizes were very small. Osborn (1979a,b) found fat and protein content of the liver varied throughout the year as much as metal concentrations and concluded that organ loads of metals should be used in preference to concentrations. In this study we used dry weight, and organs did not vary in mean dry weight through the year. Therefore, changes in concentrations of metals were equivalent to changes in organ loads.

For birds which undergo a complete annual moult and which are exposed to relatively low levels of mercury, feather growth following moult constitutes the major eliminatory pathway for mercury. The single egg, although likely to contain mercury at levels comparable to those found in other studies of this species (Parslow and Jefferies 1975; Barret *et al.* 1985), is unlikely to represent an important excretory route for mercury in this species.

This study has suggested that cadmium has a shorter biological half-life than previously thought, in contrast with cadmium in humans and other mammals (Scheuhammer 1987). Further studies would be needed to establish if this is due to an active regulatory mechanism, or merely a product of normal protein and cell turnover. Seabirds have been exposed to cadmium in the marine environment throughout their evolution, and it is possible that they have evolved stronger regulatory mechanisms than found in terrestrial mammals or birds.

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