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Trace Element Accumulation in Three Seabird Species from Hornøya, Norway

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Abstract. Soft tissues and body feathers of Common Guillemots *(Uria aalge)*, Brunnich's Guillemots *(Uria lomvia)*, and Kittiwakes *(Rissa tridactyla)* collected at Hornøya (northern Norway) were analyzed for total mercury, selenium, cadmium, zinc, and copper. Kittiwakes revealed highest cadmium and mercury concentrations in most tissues compared to both guillemot species, whereas interspecific differences in concentrations of essential elements were less obvious. The results are discussed in relation to feeding habits and migration patterns of the different seabird species. Age-dependent accumulation of selenium, mercury, and cadmium was clearly recognizable when comparing trace element contents in fully-fledged Kittiwakes to adult specimens. There was no evidence that the analyzed birds suffered from acute toxicities of heavy metals.

Polar regions have been considered to be unpolluted remote areas far from industrial activities or other sources of anthropogenic pollutants. In recent years, however, several investigations were carried out that suggested the long-range transport of various pollutants, such as organochlorines and trace metals, from industrialized countries to Antarctic and Arctic areas (Muir *et al.* 1992; Djupström *et al.* 1993). This transport may lead to accumulation of pollutants in marine ecosystems of polar regions (Waldichuk 1989; Daelemans *et al.* 1992). Top predators of these food chains, such as mammals and several seabird species, are particular target organisms of this accumulation. Seabirds were often used to measure organochlorine and trace element levels in remote ecosystems (Norheim and Kjos-Hanssen 1984; Schneider *et al.* 1985; Nettleship and Peakall 1987; Norheim 1987). In several investigations, interspecific differences between the accumulation patterns of pollutants were observed as a result of different trophic levels of the analyzed birds (Honda *et al.* 1986; Braune 1987; Ohlendorf and Fleming 1988; Guitart *et al.* 1994).

The aim of the present study was to determine whether the relationship between trace element accumulation and trophic level could also be found in seabird species living in the remote area of Hornøya, northern Norway. Further objectives of this paper were to compare the trace element concentrations in different age classes of Kittiwakes, and to discuss whether essential and non-essential trace elements were likely to favor adverse effects in the birds to be studied.

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Materials and Methods

Sample Material and Collection of Samples

Soft tissues and feathers of adult ($n \leq 27$) and juvenile ($n = 10$) Kittiwakes, *Rissa tridactyla,* adult Brunnich's Guillemots, *Uria lomvia* ($n \leq 15$), and Common Guillemots, *Uria aalge* ($n = 10$), were analyzed for total mercury, cadmium, zinc, copper, and selenium. Soft tissues available for analyses were breast-muscle and liver for all species, and kidney, gonad, and lung samples for guillemots. Body feathers originated from just above the right leg. Birds were collected at Hornøya in the summers of 1992 and 1993. Collection took place at breeding grounds with nets or fishing hooks.

Sample Preparation and Trace Element Analysis

After dissection, soft tissues were stored in acid-cleaned glass containers and feathers were stored in metal-free polyethylene bags at −20°C. Prior to analysis, the soft tissues were freeze-dried for approximately 5 days and homogenized using acid-cleaned pestle and mortar. Body feathers were thoroughly washed in acetone and double distilled water as described by Das (1981) and Chatt (1985) for hair samples. The feathers were oven-dried at 60°C for approximately 12 h and kept at room temperature for another 24 hours.

Samples were digested under pressure in PTFE-containers. For cadmium, copper, and selenium analyses, samples were digested in TÖLG-digestion-systems for 4 h at 170°C using 65% super pure nitric acid (HNO_3). Digested samples were dried at 90°C for 20 h after mixing with diluted hydrochloric acid (1 normal). Sample residues were dissolved in diluted nitric acid (0.25 normal). For mercury and zinc, microwave digestion was applied using a 5:1 mixture of HNO_3 (65%) and hydrogen peroxide (H_2O_2) as oxidizing agent. Cadmium, copper, and selenium concentrations were determined by graphite furnace atomic absorption spectrometry using a Perkin Elmer Zeeman 3030 Spectrometer for cadmium and copper and a Zeeman 5100 for selenium. Both units were equipped with HGA 600 and AS 60. To avoid vaporization of selenium at high temperatures, matrix modifiers ($Pd(NO_3)_2$and $Mg(NO_3)_2$ were added to each aliquot during the analytical procedure. Zinc was analyzed by means of flame atomic absorption spectrometry (Perkin Elmer 4000 with HGA 500). Mercury concentrations were measured by the cold-vapor-technique (Perkin Elmer Fias 200). A $K_2Cr_2O_7$ solution was used to stabilize the digested and diluted aliquots for mercury analyses (Korunova and Dedina 1980). A potassium permanganate solution ($KMnO_4$) was added during the analyses in order to minimize adsorption effects of mercury to the walls of the containers (Melcher 1978).

Prior to analysis, the reproducibility and accuracy of the analytical procedure was tested by repeatedly analyzing the standard material "Pig Kidney" (BCR 186) of the Bureau of Reference. The standard deviations of 3 measurements with 15 samples each were less than 10%. Analyses were carried out in batches of 24 to 30 samples. At least two blanks and two samples of the standard material were simultaneously analyzed with these batches. Recoveries ranged from 90–97% for copper, 99–105% for zinc, 97–104% for cadmium, 90–102% for selenium, and 80–93% for mercury. All concentrations, except for feather samples, are expressed on a dry weight basis.

Statistical Analysis

All statistical tests were run by means of the SYSTAT-computer program (Wilkinson 1992). Data were tested for normal distribution using the Kolmogorov-Smirnov test. Nonparametric tests (Wilcoxon-, Friedman- and Man-Whitney-U-Test) were applied to test for significant differences in metal concentrations between different tissues, species, or age classes. Correlations were carried out in order to compare different metal contents in each tissue. Pearson's linear correlation coefficients were determined for normally-distributed samples and Spearman rank correlations were used for distributions that differed from Gaussian.

Results

Interspecific Differences

The concentrations of cadmium, zinc, copper, mercury, and selenium in tissues of the different seabird species are summarized in Table 1.

Selenium: Only few significant differences between Kittiwakes and Guillemots were found for selenium. Kittiwakes showed higher selenium concentrations than Brunnich's Guillemots in liver samples ($p < 0.05$), while its feather selenium levels were lower than those in both Guillemot species ($p < 0.001$). In most organs, significant differences were found between the two Guillemot species. In liver, kidney, and gonads, Common Guillemots showed higher concentrations than Brunnich's Guillemots ($p < 0.05$).

Mercury: The analyzed birds showed a high interspecific variability in mercury concentrations (Figure 1(a)). Kittiwakes contained highest concentrations in liver, feather, and muscle samples compared to the same tissues from Brunnich's and Common Guillemots ($p < 0.05$). Interspecific differences between Common and Brunnich's Guillemots were also found in all tissues except feathers. Common Guillemots accumulated more mercury in liver, kidney, gonad, and lung samples than Brunnich's Guillemots ($p < 0.02$).

Cadmium: The accumulation pattern of cadmium in the different seabird species was similar to that of mercury (Figure 1(b)). Again, Kittiwakes contained higher concentrations in liver and muscle samples than both Guillemot species ($p < 0.01$). Cadmium levels in feathers of Kittiwakes also exceeded those of Common Guillemots ($p < 0.001$). Differences between Common and Brunnich's Guillemots were also observed for this element. However, in contrast to mercury accumulation, Brunnich's Guillemots contained higher cadmium loads in feathers, gonads, lungs, and muscles than Common Guillemots ($p < 0.05$).

Copper and Zinc: Interspecific differences for these essential metals were not as pronounced as they were for the non-essential ones (Table 1). Nevertheless, Common Guillemots had higher copper concentrations and Kittiwakes had higher zinc concentrations than the other species. Copper levels in feathers of the former species exceeded those in the same tissue of Kittiwakes and Brunnich's Guillemots ($p < 0.01$). Additionally, concentrations of both metals were higher in muscles of Common Guillemots than in muscles of Brunnich's Guillemots ($p < 0.05$).

Kittiwakes had higher concentrations of zinc in feathers than did both Common and Brunnich's Guillemots, whereas significant differences in muscle levels were only found between Kittiwakes and Brunnich's Guillemots (Kittiwakes > Brunnich's Guillemots; $p < 0.005$). Both Guillemot species showed similar zinc concentrations in all tissues except in lung samples (Brunnich's Guillemots > Common Guillemots; $p < 0.01$).

Age-Dependent Accumulation

Table 1 shows trace element concentrations in feather, liver, and muscle samples of adult and juvenile Kittiwakes. Significant differences were found in the accumulation of non-essential metals with adult birds having higher amounts than juveniles ($p < 0.001$). Livers of adult Kittiwakes contained nearly 13 and 68 times as much mercury and cadmium, respectively, as juveniles. The corresponding factors for feathers were nearly 4 and 6.

A different accumulation pattern was observed for the essential elements. Zinc levels were significantly higher in feathers of juvenile Kittiwakes compared to adults, while selenium concentrations were higher in both feather and liver samples of adults ($p < 0.005$). Copper concentrations showed no significant differences between age classes.

Correlations Between Metals

The results for Brunnich's and Common Guillemots are summarized in Table 2. Significant correlations between metals were found in all species, especially between copper and zinc in liver samples ($p < 0.02$). Apart from this correlation (Spearman correlation: $r = 0.64$ in adult Kittiwakes; $r = 0.83$ in fully-fledged Kittiwakes) completely different relationships be-

Table 1. Trace element concentrations in soft tissues (μg/g dry wt) and body feathers (μg/g wet wt) of Kittiwakes, Common Guillemots, and Brunnich's Guillemots expressed as means ± standard deviation and medians (in parentheses)

Species	Tissue	n	Hg	Se	Cu	Cd	Zn
Common Guillemot	feathers	10	0.88 ± 0.19 (0.91)	2.59 ± 0.33 (2.75)	18.35 ± 2.18 (17.69)	0.026 ± 0.01 (0.027)	66.13 ± 11.3 (68.0)
	liver	10	1.88 ± 0.41 (1.77)	17.6 ± 5.04 (15.51)	20 ± 2.9 (19.54)	3.08 ± 1.12 (2.83)	86.7 ± 14.88 (85.5)
	kidney	10	1.46 ± 0.18 (1.49)	43.74 ± 9.6 (44.62)	14.44 ± 1.9 (14.61)	24.06 ± 7.46 (23.75)	114 ± 13.28 (116.79)
	muscle	10	0.42 ± 0.05 (0.42)	—	19.22 ± 0.9 (19.03)	0.18 ± 0.05 (0.19)	49.28 ± 3.34 (48.11)
	gonads	10	1.17 ± 0.32 (1.22)	21.93 ± 5.7 (22.37)	6.01 ± 0.8 (6.10)	1.125 ± 0.52 (0.91)	122.6 ± 17.5 (117.0)
	lung	10	1.25 ± 0.52 (1.13)	—	2.57 ± 0.39 (2.48)	0.29 ± 0.10 (0.26)	44.57 ± 4.24 (44.17)
Brunnich's Guillemot	feathers	14	0.78 ± 0.18 (0.78)	2.75 ± 1.27 (2.73)	13.34 ± 4.1 (12.28)	0.12 ± 0.08 (0.105)	66.65 ± 6.46 (66.67)
	liver	14	1.11 ± 0.51 (1.27)	7.05 ± 3.48 (5.57)	18.13 ± 2.8 (18.44)	5.51 ± 4.24 (4.28)	93.93 ± 13.1 (91.56)
	kidney	7	1.16 ± 0.21 (1.12)	15.77 ± 5.7 (19.14)	15.34 ± 1.6 (15.58)	46.73 ± 31 (38.41)	127 ± 42.74 (134.91)
	muscle	15	0.33 ± 0.14 (0.34)	—	17.84 ± 2.4 (17.82)	0.53 ± 0.25 (0.53)	46.14 ± 8.22 (44.01)
	gonads	5	0.66 ± 0.19 (0.58)	12.24 ± 5.3 (13.06)	6.01 ± 0.33 (6.08)	3.01 ± 1.88 (2.7)	120.5 ± 22.5 (110.17)
	lung	9	0.53 ± 0.18 (0.60)	—	3.06 ± 0.64 (2.76)	1.14 ± 0.66 (1.13)	53.08 ± 5.11 (52.63)
Kittiwake adult	feathers	27	2.03 ± 0.4 (2.03)	1.75 ± 0.25 (1.75)	11.2 ± 1.64 (11.41)	0.13 ± 0.09 (0.12)	90.92 ± 12.1 (88.32)
	liver	22	2.85 ± 1.02 (2.72)	16.91 ± 9.5 (13.58)	19.62 ± 5.7 (18.98)	14.37 ± 11.3 (12.3)	111.8 ± 52.3 (94.51)
	muscle	27	0.58 ± 0.22 (0.55)	—	18.1 ± 1.25 (18.37)	1.24 ± 0.64 (1.17)	53.5 ± 7.05 (53.18)
Kittiwake fledgling	feathers	10	0.55 ± 0.1 (0.54)	1.26 ± 0.15 (1.29)	12.37 ± 2.3 (12.12)	0.02 ± 0.008 (0.02)	117 ± 15.57 (113.02)
	liver	10	0.24 ± 0.12 (0.21)	8.87 ± 2.99 (8.01)	23.43 ± 9.4 (21.74)	0.18 ± 0.03 (0.18)	89.09 ± 18.6 (85.32)
	muscle	10	0.03 ± 0.06	—	18.41 ± 6.3 (16.6)	N.D.[a]	57.2 ± 5.88 (58.51)

[a]Not detected.

tween metals were found in adult and juvenile Kittiwakes (Figure 2). Adult Kittiwakes showed positive correlations between copper and cadmium (Pearson's correlation: $r = 0.61$, $p < 0.005$) and between cadmium and zinc (Spearman correlation: $r = 0.45$) in liver samples, whereas in juvenile Kittiwakes, copper levels were related to mercury concentrations (Spearman correlation: $r = 0.72$) and selenium was negatively correlated with cadmium (Pearson's correlation: $r = -0.74$, $p < 0.05$) in the same tissue.

In body feathers, mercury was positively correlated with selenium in adult Kittiwakes (Pearson's correlation: $r = 0.51$, $p < 0.01$), and zinc concentrations were related negatively to copper concentrations in juvenile birds of the same species (Pearson's correlation: $r = -0.67$, $p = 0.05$).

In breast muscles of adult Kittiwakes, copper was positively correlated with zinc (Pearson correlation: $r = 0.53$, $p < 0.01$) and negatively with cadmium (Pearson correlation: $r = -0.44$, $p < 0.05$). In juvenile specimens, no significant correlations between metals were found in this tissue.

Discussion

Sources of Trace Element Accumulation in the Analyzed Seabirds

Interspecific differences of trace element accumulation in seabirds are often considered a result of trace element availability and/or different feeding habits (Leonzio *et al.* 1986; Ohlendorf and Harrison 1986; Ternes and Rüssel 1986; Braune 1987; Ohlendorf and Fleming 1988; Guitart *et al.* 1994). The same conclusion can be drawn for the birds studied in this paper. Kittiwakes had higher concentrations of selenium, mercury, and cadmium than Common and Brunnich's Guillemots. One reason for the elevated levels in Kittiwakes may be the relatively variable feeding habits of this species. Although Kittiwakes are often considered fish feeders (Lønne and Gabrielsen 1992), they also feed on a variety of food items of other taxonomic groups as well as offal from ships, carcasses, and even

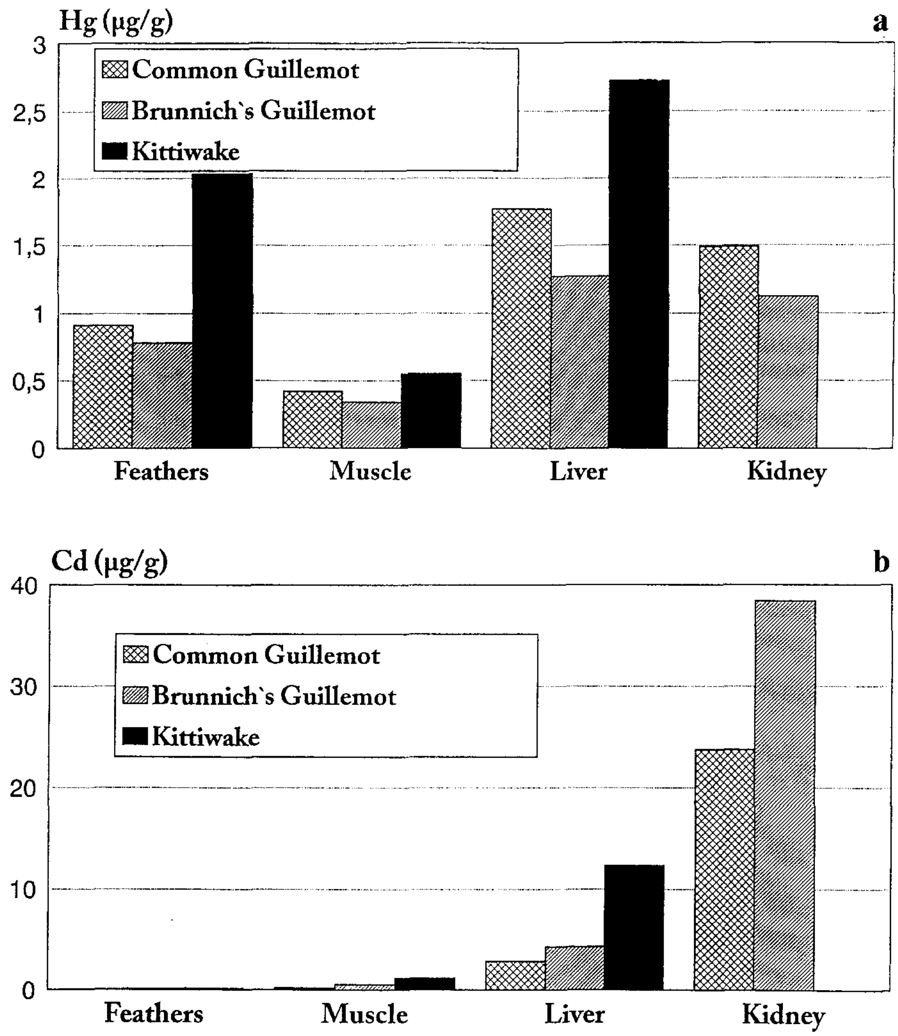

Fig. 1. Mercury (a) and cadmium (b) concentrations (µg/g dry weight for soft tissues and µg/g wet weight for feathers) in Common Guillemots, Brunnich's Guillemots, and Kittiwakes. Values are given as medians

Table 2. Correlations between each pair of trace elements in different tissues of Common and Brunnich's Guillemots. Given are Spearman rank (*) and Pearson's linear correlation coefficents

Common Guillemots (*Uria aalge*), n = 10					Brunnich's Guillemots (*Uria lomvia*), n = 10 (lungs), n = 15 (others)				
Tissues	Elements	Corr. coefficent	Probability	Equation	Tissues	Elements	Corr. coefficent	Probability	Equation
	(y)-(x)	(r)	(p)			(y)-(x)	(r)	(p)	
Liver:					Liver:				
	Zn-Cu	0.71	0.02	y = 13.56 + 3.66x		Zn-Cu	0.77	0.001	y = −12.09 + 5.77x
	Zn-Cd	0.78	0.008	y = 54.67 + 10.38x					
	Zn-Hg	0.88	0.001	y = 26.81 + 31.38x					
	Hg-Cd	0.63	0.05	y = 1.16 + 0.23x					
Kidney:					Lung:				
	Cu-Zn	0.82	0.004	y = 1.36 + 0.12x		Cu-Zn	0.70	0.04	y = − 1.59 + 0.09x
	Cu-Se	−0.80	0.006	y = 21.31 − 0.16x		Cu-Cd	0.95	0.0005	y = 2.01 + 0.92x
	Zn-Se	−0.91	0.0005	y = 169.71 − 1.28x		Cu-Hg	−0.73	0.03	y = 4.42 − 2.58x
Gonads:					Feathers:				
	Zn-Hg	0.80	0.006	y = 71.26 + 43.86x		Cu-Se	−0.77*		

vegetable material (Cramp and Simmons 1983; Gjertz *et al.* 1985; Barrett and Furness 1990; Furness *et al.* 1992). Mehlum and Gabrielsen (1993) found that in coastal areas of polar regions, 30.3% of the Kittiwakes feed on amphipods and 48% feed on fish. During chick rearing, which was the sampling period for the birds analyzed in the present paper, euphausiids

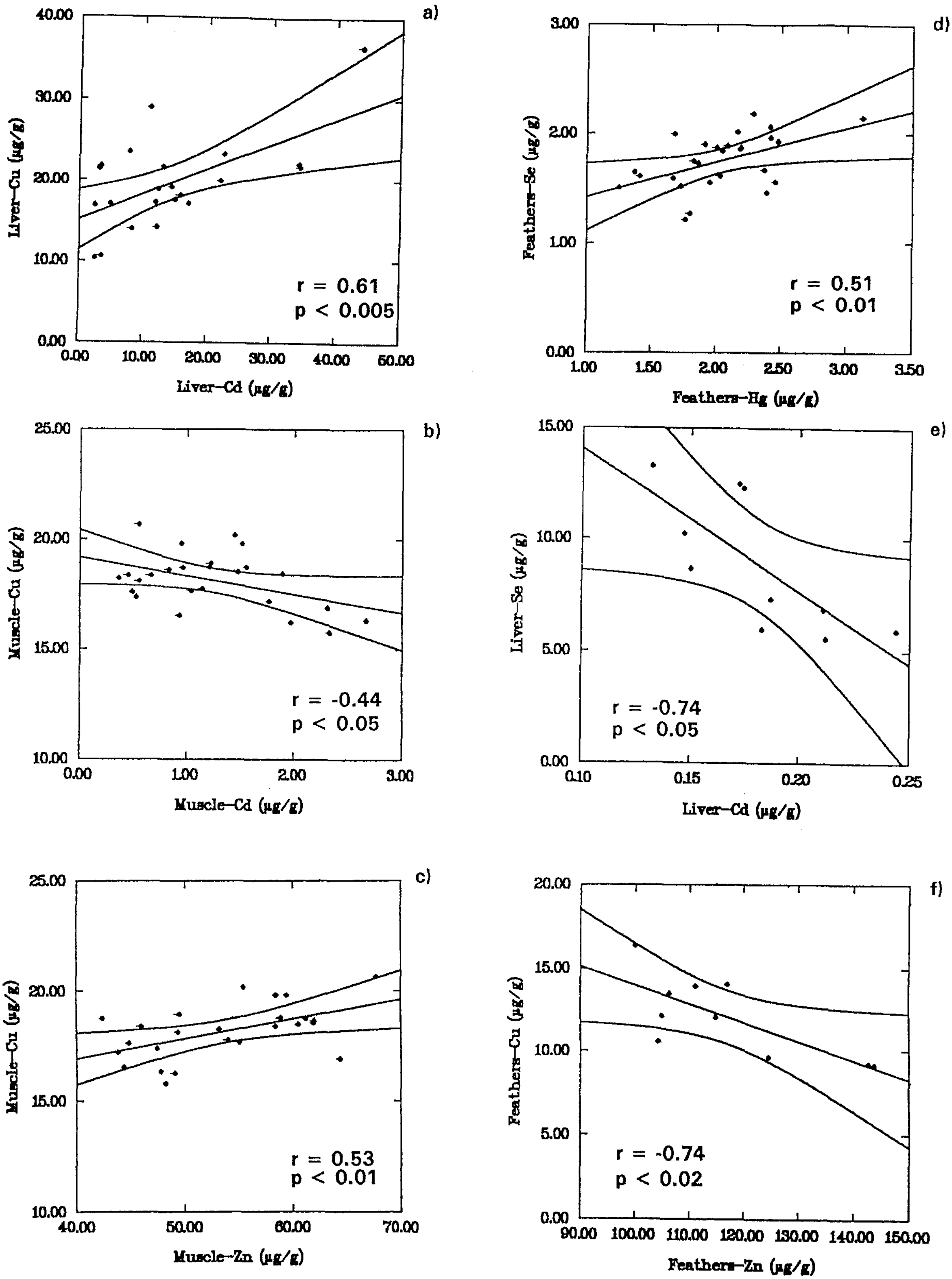

Fig. 2. Pearson's product moment correlations between different metals in adult (a–d) and juvenile (e–f) Kittiwakes

and amphipods were even more frequent in Kittiwakes with amphipods accounting for 46.3% of the bird stomach contents, and euphausiids, polar cod, and polychaetes accounting for 24.4% (Mehlum and Gabrielsen 1993). Therefore, Kittiwakes are flexible feeders compared to Common and Brunnich's Guillemots (Blotzheim and Bauer 1982; Cramp 1985).

Fish accumulate mercury, since excretion of mercury from fish can be extremely slow (Gardner 1978; Airey 1984; Kruse and Krüger 1984; Greenwood and Burg 1984), whereas invertebrates such as squid and crustaceans may accumulate considerable quantities of cadmium (Hamanaka and Ogi 1984; Muirhead and Furness 1988; Macdonald and Sprague 1988;

Rainbow 1989). Additionally, Zunk (1984) noted that the intake of fisheries offal may result in increased cadmium concentrations in seabirds. Fish entrails especially, such as liver and kidney, may contain high levels of cadmium (Macdonald and Sprague 1988). The utilization of these variable food items may account for the higher levels of cadmium and mercury in Kittiwakes compared to Guillemots. The preference of particular food items may vary geographically and seasonally according to availability.

Common Guillemots feed principally on fish throughout the year (Bradstreet and Brown 1985; Cramp 1985). In Arctic regions, Common Guillemot prey may be restricted to one or two fish species (Erikstad and Vader 1989; Barrett and Furness 1990). In comparison, Brunnich's Guillemots feed on more invertebrates than Kittiwakes and Common Guillemots and also exploit benthic resources (Erikstad and Vader 1989; Lønne and Gabrielsen 1992; Mehlum and Gabrielsen 1993). This may be the reason for high cadmium levels in Brunnich's Guillemots compared to Common Guillemots.

However, locally variable feeding habits are not the only reasons for interspecific differences in metal accumulation among seabirds. Migration patterns may also influence metal distribution (Lindberg and Odsjö 1983; Norheim and Kjos-Hanssen 1984). Although Kittiwakes are rather sedentary as adults, they migrate long distances as immatures. Ringing analyses of Kittiwakes from European colonies showed that immature birds can disperse from the western Barent Sea to Greenland and Newfoundland or the Mediterranean (Cramp and Simmons 1983). Kittiwakes may spend more time in polluted industrial areas than the entirely Arctic or Subarctic Brunnich's Guillemots. This may entail higher contaminant levels in Kittiwakes than in Guillemots. Common Guillemots are entirely pelagic birds. They spend most of the year at sea, and only approach coastal areas when breeding. They do not follow boats or feed on refuse or offal from ships. Therefore, lower trace element levels in this species compared to Kittiwakes are to be expected.

Age-Related Accumulation in Kittiwakes

The increase of trace element concentrations in adult Kittiwakes compared to fully-fledged nestlings is consistent with the findings of other investigations. Thompson *et al.* (1991) analyzed the age-dependent accumulation of mercury in the Great Skua *(Catharacta skua)* and found higher levels in feathers of adult birds than in those of chicks. Furness and Tasker (1992) reported that cadmium concentrations in kidney samples of Great Skuas, Laughing Gulls, Royal Terns, and Sandwich Terns increased with age. Similar results were obtained for several other bird species (Dale *et al.* 1974; Lindberg and Odsjö 1983; Goede 1985; Honda *et al.* 1986; Nielsen and Dietz 1989; Scharenberg 1989; Stock *et al.* 1989; Kühnast 1991; Lock *et al.* 1992; Burger and Gochfeld 1993; Burger *et al.* 1994; Stewart *et al.* 1994). Consequently, the age-dependent accumulation of (the non-essential metals) cadmium and mercury in Kittiwakes found in this study supports the hypothesis that bioaccumulation from chick development to adult stage is a widespread phenomenon in birds in general.

A different accumulation pattern with age was observed for the essential elements. Differences between adult and juvenile birds are less pronounced for these elements than for the non-essential metals except in the case of selenium (Nielsen and Dietz 1989; Burger 1993; Burger *et al.* 1994; Stewart *et al.* 1994). The age-dependent increase of selenium levels in liver and feather samples of Kittiwakes is consistent with the findings of Furness and Hutton (1979), who found positive correlations between age and mercury, selenium, and cadmium concentrations in Great Skuas. Nevertheless, differences in short-term exposure to selenium rather than accumulation with age may account for differences between selenium levels in juvenile and adult birds (Goede *et al.* 1989; Burger *et al.* 1992). Goede *et al.* (1989) found rapidly decreasing selenium concentrations in the Dunlin *(Calidris alpina)* after departure from more polluted winter quarters in the Wadden Sea compared to less polluted breeding grounds in northern Norway and attributed this decline to the short biological half-life of selenium.

In some bird species, either copper or zinc levels were higher in juvenile birds than in adults (Honda *et al.* 1986; Wiemeyer *et al.* 1987; Lock *et al.* 1992). In the present study, no such relationships between Kittiwakes of both age classes were found, indicating that metabolic regulation of both copper and zinc appears to prevent the bioaccumulation of these metals from chick to adult status in soft tissues of Kittiwakes.

Zinc is one of the elements believed to be required for feather development (Sunde 1972). Thus it is incorporated in this tissue during feather growth. Honda *et al.* (1986) found comparatively high zinc levels in feathers of eastern Great White Egret fledglings and suspected that this metal participated in the keratinization process.

Zinc concentrations of feathers were higher in fully-fledged Kittiwakes compared to adult birds. According to Burger (1993), there are three explanations for age differences in pollutant residues in birds: 1) adults accumulate pollutants over a longer time period; 2) adult and young birds differ in their feeding habits or foraging habitats; and 3) there may also be age differences in intestinal absorption or in toxicokinetics. Since zinc is regulated metabolically and no accumulation of this metal with age was observed in soft tissues of Kittiwakes, the differences in metal levels of feathers between adult and fully-fledged birds may be due to differences in recent diet or exposure (Burger *et al.* 1994). Consequently, elevated zinc levels in juvenile Kittiwakes compared to adults indicate higher zinc intake in the breeding grounds compared to the winter quarters.

Toxic Relevance of Trace Element Concentrations

Several studies have been carried out to investigate the toxic relevance of trace element accumulation in birds by focusing on correlations between essential and non-essential elements. These correlations appear to indicate the existence of detoxifying mechanisms. Muirhead and Furness (1988) found significant positive correlations between cadmium and zinc in seabirds. They concluded that seabirds use storage of bound metals for detoxification and therefore they are not able to adequately regulate the concentrations of these metals. Similar interactions were observed between copper and cadmium, but the biochemical mechanism of this relationship is not yet fully understood (Prasada Rao *et al.* 1989). Presumably, this mechanism involves binding of the metals to metallothionein. According to Scheuhammer and Templeton (1990), cadmium, zinc, and copper induce metallothionein production in both liver and kidney. The present study also revealed positive correlations between cadmium and zinc in adult Kittiwakes and Common Guillemots and between cadmium and copper in adult Kittiwakes, indicating that detoxification mechanisms also play an important role in these birds.

It is known that selenium can counteract the toxicity of mercury and cadmium and vice versa (Hill 1974; Diplock *et al.* 1986). Correlations between these elements are often considered as evidence for such detoxification mechanisms in seabirds (Furness and Hutton 1979). No positive correlations between selenium and cadmium or selenium and mercury were found in internal tissues of the birds analyzed. Leonzio *et al.* (1986) suggested that non-correlations between mercury and selenium may be a result of too-low mercury levels. These authors investigated mercury and selenium levels in Black-necked Grebes and observed that no correlation was found when mercury concentrations were lower than 10 μg/g, whereas significant correlations were observed when mercury levels exceeded 50 μg/g. Mercury concentrations found in the present study were far lower than 10 μg/g. So the explanation offered by Leonzio *et al.* (1986) may be valid here too.

There is no evidence that the trace element concentrations measured in the present study were at toxic levels, since all values were lower than those regarded as toxic in the literature. According to Scheuhammer (1988), neurological dysfunction occurs at mercury levels of about 40 μg/g wet weight in livers of Zebrafinches, although reproduction is impaired at lower levels. Hatchability of eggs is reduced in pheasants when liver levels of methyl-mercury are about 2 μg/g wet weight. Consequently, it is unlikely that the analyzed seabirds suffered from any toxic effects. Additionally, it has been assumed that at least some seabirds must be far less sensitive to mercury toxicities than terrestrial or freshwater birds because methyl-mercury levels of 4.8–16 μg/g and inorganic mercury levels up to 280 μg/g wet weight caused no effect on reproduction in albatrosses (Lock *et al.* 1992).

Presser and Ohlendorf (1988) found unusual rates of deformity and death in embryos and hatchlings of wild aquatic birds due to elevated concentrations of selenium in Kesterston National Wildlife Refuge. The highest frequency of embryotoxicity was observed when values averaged 69.7 ppm dry weight in eared grebe eggs and 30.9 ppm dry weight in coot eggs. In the less polluted Volta Wildlife Management Area, egg values were generally below 2 ppm, and no abnormalities were found in the embryos. Selenium levels in bird livers from Kesterston Reservoir ranged from 19.9 to 127 ppm dry weight, whereas concentrations in birds from Volta ranged from 4.4 to 8.8 ppm. It has been suggested that selenium toxicity results from incorporation into amino acids in place of sulfur, thereby altering the functions of proteins and enzymes (Stadtman 1974). In general, selenium concentrations in liver samples of the seabirds analyzed in this study were lower than the critical values measured by Presser and Ohlendorf (1988). However, taxonomic differences in critical values of trace elements may exist and have to be taken into account when comparing metal toxicity or detoxification of trace metals in different species.

Zinc and copper concentrations in Guillemots and Kittiwakes were far below levels considered as toxic in previously published results. Poultry can tolerate up to 2,000 ppm zinc (Johnson *et al.* 1962; Ewan 1978) and up to 300 ppm copper (National Academy of Sciences 1980) without showing any toxic effects. Doneley (1992), however, observed moderate to severe nephrosis in caged and aviary birds containing zinc levels of 320 ppm and 534 ppm dry weight. Kidney damage was found at kidney levels of 100–200 μg cadmium/g dry weight and 5–13 μg mercury/g dry weight in birds from Scotland (Nicholson *et al.* 1983). Birds showed patchy necrosis of the proximal tubules and glomerular damage resulting in changes in membrane permeability and loss of ion regulation in the cells.

However, nothing is known to date on long-term low-level effects of trace elements in the seabirds analyzed in this study. The conclusion that there is no evidence of toxic levels in these birds, therefore, only applies for acute toxicities.

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