Species- and age-related variation in metal exposure and accumulation of two passerine bird species

Å.M.M. Berglund*, M.J. Koivula, T. Eeva

Section of Ecology, 2004 University of Turku, Finland

ARTICLE INFO

Article history:
Received 18 April 2011
Received in revised form 1 July 2011
Accepted 3 July 2011

Keywords:
Air pollution
Insectivorous passerines
Non-ferrous smelter
Heavy metals

1. Introduction

Metal contamination of the environment is a persistent and global problem, especially close to point-sources, such as smelters and mines. In these environments soil pollution has resulted in ecosystem changes such as reduced or altered species composition of plants and insects (Kiikkilä, 2003; Koptskik et al., 2003; Zverev, 2009), but higher organisms, such as birds or small mammals, have also been affected (Kiikkilä, 2003; Mukhacheva et al., 2010). Birds have been proposed as useful biomonitoring species of pollutants (Furness, 1993) and although focus have been on waterfowl or raptors, terrestrial passerines, such as great tit (Parus major), coal tit (Periparus ater), blue tit (Cyanistes caeruleus), pied flycatcher (Ficedula hypoleuca) and collared flycatcher (Ficedula albicollis) have successfully been used to monitor the environment close to a variety of different metal industries (see for example Nyholm, 1994; Swiergosz et al., 1998; Eens et al., 1999; Bel’skii et al., 2005; Eeva et al., 2009; Berglund et al., 2010).

The metal concentration in birds can be assessed in a variety of samples, though reports of metal content in egg, blood, feathers and liver dominate the literature. The benefit of using feathers or feces over organs or eggs is the non-destructive and non-invasive sampling technique, although they might not represent the body burden of metals. For example, apart from representing metal concentrations in the bloodstream during growth of feathers, there might also be a substantial contribution of exogenous contamination of metals, due to deposition onto the surface of feathers (Furness, 1993; Dmowski, 1999; Jaspers et al., 2004). Fecal samples have been used less frequently than feathers, though it has been proposed as powerful means to assess food chain contaminants in the birds’ environment (Spanh and Sherry, 1999; Dauwe et al., 2004; Morrissey et al., 2005). While comparative studies on metal concentrations in food items and feces do occur (see for example Dauwe et al., 2004; Morrissey et al., 2005), there have not been much effort in exploring the relationship between fecal metal concentrations and the absorption in internal tissues.

It is known that even closely related bird species may differ in metal accumulation and excretion (Beyer et al., 1988; Burger and Gochfeld, 2009; Eeva et al., 2009; Hofer et al., 2010). This could be related to different diets and trophic levels, or physiological and ecological species-specific trace-element requirements etc. The age of birds is also an important factor for metal accumulation. Some elements accumulate over time, resulting in increasing accumulation with age (Furness, 1993), though growing nestlings may also accumulate higher concentrations than adults (Nyholm, 1994).

Most of the studies on metal accumulation in terrestrial passerine species have focused on nestlings, either using feathers (Burger, 1993; Dauwe et al., 2000), feces (Bel’skii et al., 1995; Dauwe et al., 2000; Eeva et al., 2009; Berglund et al., 2010) or destructive sampling of internal tissues (Nyholm, 1995; Swiergosz et al., 1998; Bel’skii et al., 2005; Berglund et al., 2010). Sampling nestlings has the benefit of

* Corresponding author.
E-mail address: asa.berglund@eng.umu.se (Å.M.M. Berglund).

We measured the concentration of several elements (arsenic [As], calcium [Ca], cadmium [Cd], copper [Cu], nickel [Ni], lead [Pb], selenium [Se] and zinc [Zn]) in adult and nestling pied flycatchers (Ficedula hypoleuca) and great tits (Parus major) at different distances to a Cu–Ni smelter in 2009. Feces of nestlings generally failed to correspond with internal element concentrations but reflected the pollution exposure, indicating an increased stress by removal of excess metals. The uptake of Cu and Ni were regulated, but As, Cd, Pb and Se accumulated in liver tissue. Pied flycatchers had generally higher element concentrations than great tits. The higher accumulation of As and Pb in pied flycatcher livers was explained by a more efficient absorption, whereas the higher Cd concentration was primarily due to different intake of food items. Age-related differences occurred between the two species, though both Cd and Se accumulated with age.
obtaining data from a limited time-period and territory while adults, as already mentioned, might accumulate metals over a longer period of time and during migration (Furness, 1993). Information on metal concentrations in adult terrestrial passerines are available, though few studies have compared metal accumulation in tissues between adults and juveniles (Hogstad, 1996) or adults and nestlings (Nyholm, 1994).

In the present study, we measured metal concentrations (arsenic (As), calcium (Ca), cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), selenium (Se) and zinc (Zn)) in two passerine species, the pied flycatcher and great tit, in a well-documented pollution gradient from a Cu–Ni smelter in Finland. This is one of the most metal polluted areas in Finland (Kubin et al., 2000), where ecological implications have been observed for the species over the last two decades (Eeva and Lehikoinen, 1995, 1996; Eeva et al., 2009). Pied flycatchers and great tits are common birds in the study area, and breed in man-made nest boxes, enabling studies on populations in the area of interest. They are also relatively high in the food chain, and may reflect the transfer of metal via the food chain.

Our aim was to i) assess the use of feces as proxy for internal metal accumulation as a basis for future studies using only non-destructive methods, ii) to evaluate species differences in metal exposure and accumulation, and iii) to study age-related trends in metal accumulation. We expect pied flycatchers to be more exposed to metals via their diet, feeding on a slightly higher trophic level than great tits (Cramp and Perrins, 1993).

2. Methods

2.1. Study area and data collection

Data was collected in 2009 in the surroundings of the Cu/Ni smelter in Harjavalta (61°20’N, 22°10’E), situated in SW of Finland (Fig. 1). Sulfuric oxides, As and heavy metals (especially Cd, Cu, Ni, Pb and Zn) are common pollutants in the area (Kiikkilä, 2003). Ten study sites, each with 40 increasing distance from the industry (Kiikkilä, 2003), reaching background levels within 2 km from the smelter complex were grouped, hereafter named pollution zone 1, and those further than 9 km from the industry were grouped into zone 2.

The study sites had similar forest habitats and the forests in the area are dominated by Scots pine (Pinus sylvestris), which forms mixed stands with spruce (Picea abies) and birches (Betula spp.). In the field layer, dwarf shrubs (Vaccinium vitis-idaea and V. myrtillus) dominate the vegetation. At sites closest to the smelter, ground vegetation is patchy and poorly developed (Kiikkilä, 2003).

Females were collected while incubating, and aged (young vs. old) based on the quality of feathers (i.e. molted or not) according to Svensson (1992). One nestling per brood was sampled at the age of 8–11 days old for pied flycatcher and 8–15 days old for great tit. The age of nestlings was determined on the basis of wing length of small nestlings, and apart from one bird of the age of 6 days old nestling great tits were generally 11–15 days old at the time of sampling. Feces were collected fresh from deserted nestlings and liver samples from females and nestlings were dissected immediately after killing them by decapitation, and preserved frozen in liquid nitrogen in sealed plastic tubes. The data were collected under the licenses of the Animal Care & Use Committee of Turku University and Regional Environmental Centre.

2.2. Metal analyses

For sample sizes, see Supporting Table S1—3. Fecal sacs and liver samples were dried at 50 °C for 72 h. Two milliliters of supra-pure HNO3 (supplied by Merck) were added to the samples in Teflon bombs for digestion with a microwave system. After digestion, samples were diluted to 50 ml with de-ionized water. The elements which are common pollutants in the area were chosen in this study (Kiikkilä, 2003), but also Ca, an element of biological importance and low availability in the area. Element concentrations (As, Ca, Cu, Cd, Ni, Pb, Se and Zn) were determined by ICP-MS (Elan 6100 DCR+ from PerkinElmer-Sciex). The calibration of the instrument was done with certified standard (Clarias PTH, Multi element solution 2A from Spx CertiPrep).

Samples were analyzed in batches with certified reference material (mussel tissue ERM-CE278, Institute for Reference Materials and Measurements). Differences between batches were within 10% (except for Se, which were 11%). Our reported absolute values have to be used with caution, as the recovery rates (dry weight) of the 10 reference samples generally were fairly poor: As 4.91 ± 0.06 (cert: 6.07 μg g⁻¹), Cd 0.29 ± 0.04 (cert: 0.35 μg g⁻¹), Cu 0.93 ± 0.52 (cert: 0.94 μg g⁻¹), Pb 1.77 ± 0.07 (cert: 2.00 μg g⁻¹), Se 2.08 ± 0.06 (cert: 1.84 μg g⁻¹) and Zn 5.92 ± 0.85 (cert: 83.1 μg g⁻¹).

2.3. Statistical analyses

Statistical analyses were performed with SAS statistical software 9.2 (SAS, 2008). Variation in liver and feces element concentrations was analyzed with general linear models (GLMMIX procedure in SAS) with normal error distribution and identity link function. To obtain normal distribution, concentrations were log10-transformed and all models included zone, species and their interaction term. The results from the GLM (F- and p-values) are presented in Supporting Table S1—3. In case of significant (p < 0.05) interactions, the two species were analyzed separately to elucidate the interaction effect. Age effect (nestlings vs. females) of metal accumulation in liver was tested as described above including age, distance and zone interaction term. Pearson correlation was used to test correlations among log10-transformed element concentrations in liver and feces for all elements apart for As, Cu and Ni. The correlation between liver and fecal concentrations of those three elements was tested with Spearman rank correlation as the data were not normally distributed (Shapiro-Wilk’s test). Data is shown as arithmetic means ± S.E.

3. Results

3.1. Metal concentrations in nestlings

Nestlings from zone 1, the sites close to the smelter, had significantly higher concentrations of As, Cd, Pb and Se in their liver than birds at zone 2 (Fig. 2). This was true for both pied flycatchers and great tits, except for the Pb concentration in great tit. Among those four elements all birds showed the proportionally highest accumulation (compared to the concentration at zone 2) for As, followed by Pb > Cd > Se for pied flycatcher and Cd > Se for great tit. Apart from Ca in pied flycatchers Ca, Cu, Ni and Zn concentrations in liver tissue did not differ between pollution zones (Fig. 2).

Pied flycatchers had higher hepatic concentrations of As, Cd, Se, Ca (zone 1) and Pb (zone 1) than great tits (Fig. 2); the opposite was found for Ni accumulation. No species differences were observed in hepatic Cu and Zn concentrations.

As for liver tissue, the fecal concentrations of As, Cd, Pb, Se, Cu and Ni, but not Ca or Zn from nestlings were significantly increased close to
the smelter (Fig. 3). Similar to liver tissue, the proportionally highest accumulation was found for As followed by Ni > Pb > Cu > Cd > Se in pied flycatcher feces and Ni > Pb > Se > Cd > Cu for great tit feces.

Pied flycatcher nestlings had significantly higher Cd, Cu, Se and Zn concentrations in feces than great tit nestlings and the opposite was found for Ca. The concentrations of As, Ni and Pb in feces did not differ between species.

In pied flycatcher nestlings (n = 23), significant positive correlations occurred between liver and feces concentrations for As (r_s = 0.70, p = 0.0002) and Pb (r = 0.62, p = 0.002), and negative correlation for Zn (r = -0.49, p = 0.02). In great tit nestlings (n = 15), significant positive correlations were observed for As (r_s = 0.82, p = 0.0002), Cd (r = 0.52, p = 0.049) and Se (r = 0.87, p < 0.0001).

3.2. Metal concentrations in females

Similar to nestlings, female pied flycatchers and great tits from zone 1 had significantly higher liver concentrations of As, Cd (only pied flycatcher), Pb and Se than birds at zone 2 (Fig. 4). Among those four elements all birds showed the proportionally highest accumulation for As, followed by Cd > Pb > Se for pied flycatcher, and Pb > Se for great tit. Neither Ca, Cu, Ni nor Zn concentrations differed in bird liver between zones (Fig. 4).

Species differences were found for all elements in female birds (Fig. 4). Pied flycatcher females had higher concentrations of As, Ca, Cd (zone 1), Ni, Pb (zone 2), Se and Zn than great tit females and the opposite was found for Cu.

3.3. Age-related differences

Nestling and female liver concentrations were compared for age-related differences in each species. Female pied flycatchers had significantly higher concentrations of Cd (18 times higher, F = 837, p < 0.001) and Se (1.4 times, F = 108, p < 0.001) than nestlings. All other elements (As, Ca, Cu, Ni, Pb and Zn) were found at similar levels in nestling and female pied flycatcher.

Fig. 2. Element concentration (mean ± S.E.; µg g⁻¹ dw) of arsenic (As), cadmium (Cd), lead (Pb), selenium (Se), calcium (Ca), copper (Cu), nickel (Ni) and zinc (Zn) in liver of pied flycatcher (F. hyp) and great tit (P. maj) nestlings. Open bars represent nestling samples in the close vicinity of the smelter (zone 1) and filled bars represent sites farther from the smelter (zone 2). Different letter within each species indicate statistical differences between zones and * denotes differences between species. For F- and p-values, see Supporting Table S1.

Fig. 3. Element concentration (mean ± S.E.; µg g⁻¹ dw) of arsenic (As), cadmium (Cd), lead (Pb), selenium (Se), calcium (Ca), copper (Cu), nickel (Ni) and zinc (Zn) in feces of pied flycatcher (F. hyp) and great tit (P. maj) nestlings. Open bars represent nestling samples in the close vicinity of the smelter (zone 1) and filled bars represent sites farther from the smelter (zone 2). Different letter within each species indicate statistical differences between zones and * denotes differences between species. For F- and p-values, see Supporting Table S2.
4. Discussion

4.1. Feces as proxy for metal contamination

Bird feces can be a sensitive indicator of environmental metal contamination and the metal availability in food items (Spahnh and Sherry, 1999; Dauwe et al., 2000, 2004; Morrissey et al., 2005). A benefit of using feces, apart from the non-destructive and non-invasive sampling technique, is that feces generally contain high concentrations of metals, often higher than the food items, enabling easy quantification (Morrissey et al., 2005). One drawback on the other hand, as this study also shows, is that feces generally cannot be used to estimate internal levels of elements.

We only found a few significant correlations between metal concentration in feces and liver, and among these As was the single element which showed strong correlations in nestlings of both species. Although there is a lack of direct relation between metal exposure (feces) and accumulation (liver) for the majority of elements, increased liver concentration of Cd, As and Pb could be expected at high feces concentrations, at least above certain exposure levels. Thus feces are, to some extent, useful as an indicator of potential accumulation of As, Cd and Pb also in internal tissues, but more importantly, it signals an increased risk for physiological stress due to spending resources on excreting excess metal from the body. The present study further indicates that using feces as proxy for liver tissue levels of essential elements might be misleading due to homeostatic regulation or active absorption of many essential elements (discussed below). However, other tissues might show different associations with fecal levels.

4.2. General species-related differences

The impact on birds (females and nestlings) from the smelter is evident with higher internal concentrations of non-essential elements (As, Cd and Pb) and Se. However, compared to passerines from similar environments, the concentrations in liver (Bel'skii et al., 2005; Dauwe et al., 2005; Berglund et al., 2007) and feces (Bel'skii et al., 1995; Dauwe et al., 2000; Berglund et al., 2009) were moderate. With a few exceptions, pied flycatchers had higher element concentration than great tits in both feces and liver tissue. Great tits seem to be less sensitive to metal pollution and accumulate less metals, also compared to the related species, blue tit (Eens et al., 1999). Higher fecal concentrations in nesting pied flycatchers are indicative of food items with higher metal content and the difference between our two species is expected in relation to the higher trophic level which pied flycatchers feed at. Although the diet of pied flycatcher and great tit nestlings resemble one another (i.e. both species are fed insects and spiders) (Cowie and Hinsley, 1988; Lundberg and Alatalo, 1992; Cramp and Perrins, 1993), the great tit is more specialized on Lepidoptera larvae while pied flycatchers are fed a larger proportion of insects of a higher trophic level (e.g. Hymenoptera, Diptera and Coleoptera) (Eeva et al., 1997, 2005).

Adult pied flycatchers feed on insects and spiders throughout the year, and thus a higher trophic level than adult great tits eating also oil-rich seeds and fruits (Cramp and Perrins, 1993; Jonsson, 2003). Of the two species included in this study pied flycatchers migrate, whereas great tits are more resident in the study area. Pied flycatcher adults may therefore also accumulate elements during migration and over-wintering and, although female birds correspond to the metal polluted environment of their breeding grounds, the accumulation during migration and overwintering cannot be discarded (Nyholm, 1994).

4.3. Essential elements under homeostatic control

The absorption of Cu and perhaps also Ni was regulated by homeostatic control in pied flycatcher and great tit nestlings, as has been suggested earlier (Outridge and Scheuhammer, 1993; Nyholm, 1995; Eisler, 1998; Dauwe et al., 2004; Berglund et al., 2010). This was evident by the maintained low internal concentration, despite a higher exposure in the vicinity of the smelter. Although the...
essential function of Ni has not been conclusively demonstrated in animals, Ni has been suggested as an essential micronutrient (reviewed by Outridge and Scheuhammer, 1993; Eisler, 1998) with increased bone strength in birds as one proposed positive effect (Wilson et al., 2001). If the accumulation of Ni was truly regulated in nestling tissue, or if the low concentrations in liver merely reflected a low intestinal absorption (estimated to approximately 1–5% in laboratory animals and humans, reviewed in Outridge and Scheuhammer, 1993) remains to be explored. Although the liver concentrations of pied flycatchers and great tits are comparable with those of birds from unpolluted environments (Outridge and Scheuhammer, 1993), few reports on fecal Ni concentrations are available for comparison of exposure level.

The concentration of Zn, an essential element which is also known to be under homeostatic control (Eisler, 1993; Nyholm, 1995), were comparable in feces within each species, irrespective of the distance to the industry, suggesting that Zn does not constitute a major hazard for nestlings in the study area. The latter has been found earlier close to similar industries (Dauwe et al., 2000, 2004).

Feces samples revealed that the food items of pied flycatcher nestlings contained higher concentrations of Cu and Zn than the food items of great tit nestlings, but even when feeding within the same trophic level inter-specific differences in metal accumulation do occur (Alleva et al., 2006). The lower levels of Cu in great tits might be explained by a diet with more Lepidoptera larvae, which have relatively low Cu concentrations in the study sites (Eeva et al., 1997, 2005). In opposite, isopods, which are commonly found in nests of pied flycatchers in the polluted area, accumulate high concentrations of Cu but also Cd in contaminated environments (Hunter et al., 1987).

4.4. Essential elements with no clear regulation

Little data is available on fecal Se concentrations in terrestrial passerines, but in our study this was the only element where birds had higher concentrations in liver than feces. Pied flycatchers were exposed to, and accumulated more Se than great tits, which could be either the result of higher exposure, or different physiological demand. Despite slightly higher accumulation of Se in liver of birds from zone 1, the levels are still well below the concentrations where toxic effects have been observed (Hoffman, 2002). Although toxic, Se is an essential element with a protective role against mercury (Hg) toxicity (Eisler, 1985; Cuvín-Aralar and Furness, 1991) and co-accumulation of Se and Hg has been shown in birds (Scheuhammer et al., 2008). However, we do not believe that Se accumulation in our study sites is an indication of Hg pollution, as Hg emissions from the smelter is fairly low (<10 kg year⁻¹, source: Harjavalta town) and unpublished data on great tit feces has revealed low Hg concentrations (generally below 0.5 μg g⁻¹, dw) in polluted sites. Instead we believe that the higher Se concentrations reflect the emissions from the smelter. Although there are no public data on Se emissions from this particular smelter, Se is known as one of the predominant elements in dust from non-ferrous smelters (Barcan, 2002).

The availability of Ca is one important factor determining the breeding success of passerines (Graveland et al., 1994; Eeva and Lehikoinen, 2004), and at the smelter site in Harjavalta, pied flycatchers have been found more susceptible to Ca deficiency than great tits (Eeva and Lehikoinen, 1995, 1996, 2004). In the present study pied flycatcher nestlings showed a higher absorption rate of Ca than great tits. This was indicated by equal liver Ca concentrations between the species (or even higher for pied flycatchers at zone 1) despite three times lower fecal concentrations in pied flycatchers. This is in agreement with earlier studies suggesting that great tits would also be more effective in finding Ca-rich food items, such as snail shells than blue tits (Eeva et al., 2009). One explanation for this could be that great tit females have a large, inter-territorial search range, to acquire Ca during egg-laying (Wilkin et al., 2009).

4.5. Non-essential elements

Calcium deficiency is known to increase the absorption of other heavy metals, such as Pb and Cd (Silver and Nudds, 1995; Scheuhammer, 1996; Dauwe et al., 2006), with the synthesis of intestinal Ca-binding proteins as the key to increased absorption of Pb, when Pb is mistaken for Ca (Fullmer et al., 1985). This would mean that pied flycatchers, with their efficient Ca absorption, would be more susceptible for accumulation of other metals such as Pb in the vicinity of the smelter. True enough, despite equal fecal concentrations of Pb, but also As in pied flycatchers and great tits close to the smelter (hence supposedly equal Pb and As levels in their food items), pied flycatchers accumulated higher concentrations in livers, indicating a more efficient absorption of Pb and As. Lead is known for its toxic effects on a variety of biological systems including hematopoietic, nervous and behavioral effects (reviewed in Eisler, 1988b), but the concentration found at the smelter is well below the range for overt toxic effects (approximately 6 ppm, wet weight) proposed for birds (Franson, 1996). Over all, As is not a well-documented element when it comes to birds, and if the more efficient absorption of As in pied flycatcher is related to their Ca-deficient diet needs to be studied more carefully. So far some protective effects of Ca have been found in rats following As-induced oxidative stress (Srivastava et al., 2010). Although As is mostly known for its toxic effects (including negative effects on respiratory, gastrointestinal, cardiovascular and hematopoietic systems), there are some studies showing beneficial properties of As at low doses (reviewed in Eisler, 1988a).

Although pied flycatcher nestlings and females had twice as high liver Cd concentration as great tits, and the absorption of Cd has been reported to increase in birds on Ca-poor diet (Silver and Nudds, 1995; Scheuhammer, 1996) we do not believe that this difference is related to a more efficient absorption of Cd, as suggested for As and Pb. The reason for this assumption is that feces of pied flycatcher nestlings also contained twice as much Cd as feces of great tit nestlings, indicating a higher exposure of Cd via the diet of pied flycatchers. As mentioned earlier, isopods, which are commonly found in nests of pied flycatchers in the polluted area, contain high concentrations of Cd in contaminated environments (Hunter et al., 1987) and are thus a potential source of Cd for flycatchers.

Pied flycatcher females, but not great tit females accumulated Cd in liver tissue in the vicinity of the smelter, indicating relatively rapid accumulation of Cd in pied flycatcher females after their arrival to the breeding grounds. This is opposite to earlier studies, which suggest that Cd mainly accumulate in pied flycatcher females during migration and over-wintering (Nyholm, 1994).

4.6. Metal accumulation due to age

Many metals accumulate with age in birds (Furness, 1993; Nyholm, 1994; Fedynich et al., 2007). In this study, the impact of age, though not necessarily accumulation with age, was more pronounced for great tits than for pied flycatchers. While only Cd and Se accumulated with age in pied flycatchers, those elements and Pb accumulated with age in great tits. Nestling great tits on the other hand showed a slightly, significantly higher demand for the essential elements and micronutrients, Ca, Ni and Zn, than females.

The greater accumulation of Cd and Se in both pied flycatcher and great tit females is probably a consequence of the longer
exposure time in the breeding area, but also and foremost for Cd due to accumulation with age (the half-time of Cd in humans are 10–30 years; Friberg et al., 1986), as has been suggested for birds (Nyholm, 1994; Fedynich et al., 2007; Orłowski et al., 2007; Malinga et al., 2010) and other vertebrates (reviewed in Burger, 2008). In fact, Cd stood out with an 18-fold increase with age. To our knowledge, there are no records on age-related Se accumulation in liver for birds, but a study on glaucous-winged gulls (Larus glaucescens) showed that fledglings generally had higher levels of Se in feathers than adults which was explained by local exposure of nestlings exceeding that of regionally obtained Se in adults (Burger et al., 2009).

The lack of age-effect on As is opposite to earlier findings, showing almost twice as high As concentrations in pied flycatcher females than nestlings (Nyholm, 1994). The findings that Pb accumulated in age with great tifs from zone 1, is also opposite to what Nyholm (1994) found in pied flycatchers. However, the concentrations of As and Pb were much lower in both females and nestlings in the present study, indicating different (lower) exposure to these elements.

5. Conclusion

In the close vicinity to the copper smelter in Harjavalta, nesting and female pied flycatchers and great tifs accumulated higher concentrations of the toxic elements As, Cd, Pb and Se in liver tissue, although the concentrations of individual elements, were not high enough to be considered toxic. The element concentrations in fecal samples revealed that apart from those elements, nestling birds were also exposed to high environmental concentrations of Cu and Ni, the elements which uptake in liver was regulated. Although both feces and liver concentrations of the non-essential elements and Se were higher in nestlings from the vicinity of the smelter, we only found a few significant correlations between sample types indicating that feces might not be suitable for estimating internal element accumulation, but rather a useful indicator of metal exposure in the environment. However, increased fecal concentrations of elements may indicate an active removal of excess elements from the body, and hence be a potential and non-destructive indicator of increased physiological stress. Metal analyses further revealed several species- and age-related differences, generally with pied flycatchers as the more susceptible species in terms of exposure and accumulation of metals, especially in combination with a Ca-poor diet. Thus, in terms of risk assessment of metal toxicity, pied flycatchers might be a better suited monitor species than great tifs. The accumulation with age was especially pronounced for Cd, and special care has to be taken for this element, not to pool young and old birds.

Acknowledgement

We thank Jussi Lampinen for his help with field work. Paul Ek and Sten Lindholm (Åbo Akademi) are acknowledged for the heavy metal analyses. Our study was financed by the Academy of Finland (project 8119367).

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.envpol.2011.07.001.

References


Burger, J., Gochfeld, M., 2009. Comparison of arsenic, cadmium, chromium, lead, manganese, mercury and selenium in feathers in bald eagle (Haliaeetus leucocephalus) and comparison with common eider (Somateria mollissima), glaucous-winged gull (Larus glaucescens), pigeon guillemot (Cepphus columba), and tufted puffin (Fratercula cirrhata) from the Aleutian Chain of Alaska. Environ. Monitor. Assess. 152, 357–367.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.


Franson, J.C., 1996. Interpretation of tissue lead residues in birds other than passerine bird species at an urban brown field site. Environ. Pollut. 90, 153–161.
