Breeding performance of blue tits (Cyanistes caeruleus) and great tits (Parus major) in a heavy metal polluted area

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Breeding performance in two Parid species near a Cu smelter.

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A B S T R A C T

We compared heavy metal levels, calcium levels, breeding parameters and condition of nesting and adult Cyanistes caeruleus and Parus major along a heavy metal pollution gradient. Both species started laying earlier and showed inferior nesting growth and smaller fledging probability in the polluted areas, which are phenologically advanced in spring due to sparse forests. The major inter-specific difference in the responses was that the clutch size and hatching success were decreased in the polluted area in P. major, but not in C. caeruleus. Heavy metal profiles in nesting feces were relatively similar in the two species, though Ni and Pb levels were higher in C. caeruleus than in P. major. However, the latter species showed markedly higher fecal calcium concentrations. Lower calcium levels and higher levels of some heavy metals in C. caeruleus suggest that in Ca-deficient environments this species might be more susceptible to negative pollution effects than P. major.

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1. Introduction

The effects of heavy metal emissions on passerine bird populations have been studied intensively at a few smelter sites during the past ca. 20 years (e.g. Nyholm, 1998; Swiergosz et al., 1998; Eens et al., 1999; Dauwe et al., 2004; Belskii et al., 2005; Eeva et al., 2005b). Like many other long-term population studies in birds, pollution-related population studies have mainly focussed on hole-breeding species such as tits (Parid species) and flycatchers (Ficedula sp.). Despite many common characteristics in diet and breeding ecology of these insectivorous species, there are marked inter-specific differences in responses to human induced environmental pollution. For example, pied flycatchers (Ficedula hypoleuca) seem to easily accumulate heavy metals and to be more sensitive to their toxic effects than tits, being strongly affected in places where low Ca availability is connected to high heavy metal levels (Eeva and Lehikoinen, 2004). The combination of Ca deficiency and dietary heavy metals may lead to poor quality egg shells and increased egg and nestling mortality in this species (Eeva and Lehikoinen, 1995; Belskii et al., 2005).

Marked differences have also been found in heavy metal levels and effects on breeding of closely related Parid species. For example, adult blue tits (Cyanistes caeruleus) have shown higher Pb concentrations in their feathers than great tits (Parus major) (Eens et al., 1999; Dauwe et al., 2002). Feather concentrations, however, can partly indicate external contamination (Dauwe et al., 2003) and other indicators of internal concentrations are needed to assess the species’ tendency to accumulate heavy metals. Dauwe et al. (2000), on the other hand, found no inter-specific differences in heavy metal levels of nesting feces and feathers between P. major and C. caeruleus at a polluted area. Despite this, the breeding success of P. major has been shown to decrease in a heavy metal polluted environment while there was no corresponding change in C. caeruleus (Janssens et al., 2003b; Dauwe et al., 2005). Since Ca–metal interactions seem to have an important role in the heavy metal effects on F. hypoleuca it would be interesting to compare the Parid species for their heavy metal and Ca levels.

We compared heavy metal levels, Ca levels, breeding parameters and condition of nesting and adult C. caeruleus and P. major along a well known heavy metal pollution gradient around a Finnish copper smelter complex. These closely related species differ in their body size, P. major being 1.6 times heavier (Cramp and Perrins, 1993). Correspondingly, the metabolic rate (per mass unit) of C. caeruleus is higher than that of P. major (Svensson et al., 1998; Nilsson and Råberg, 2001), which potentially could affect the accumulation of heavy metals. These two species also differ in their clutch size, which is generally slightly higher in C. caeruleus (Cramp and Perrins, 1993). We have collected long-term (13 yr) breeding
data on these species from heavily polluted, moderately polluted and relatively unpolluted study plots. On the basis of earlier studies we expect to find negative effects of pollution on the breeding success of *P. major* (Eeva et al., 2003), but there is no prior information on the possible detrimental effects on *C. caeruleus* in this area. Our main interest is to find out (i) whether these two closely related species differ in their responses to direct or indirect effects of heavy metal pollution, (ii) at which stage of the breeding phase the detrimental effects manifest, and (iii) whether these two species show different heavy metal or Ca concentrations (measured as fecal concentrations).

### 2. Material and methods

#### 2.1. Study area

The data were collected in southwest Finland during a long-term (1996–2008) study on the effects of air pollution on wild birds. We established 21 study sites, each with 40–50 nest-boxes, in the pollution gradient of a copper smelter (61°20′N, 22°10′E) in three main directions (SW, SE and NW), in a range of 0.5–74 km from the smelter. Sulphuric oxides and heavy metals (e.g. As, Cd, Cu, Ni, and Pb) are common pollutants in this area (Kiikkilä, 2003). Elevated heavy metal concentrations occur in the soil and biota of the polluted area due to current and historical deposition, and metal contents decrease exponentially with increasing distance to the smelter, approaching background levels at sites further than 5 km from it (Eeva and Lehtonen, 1996; Derome and Nieminen, 1998). The forests in the area are dominated by Scotch 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 *Vaccinium myrtillus*) dominate. At sites closest to the factory complex, ground layer vegetation is patchy and poorly developed due to the long-term effect of pollution (Salemaa and Vanha-Majamaa, 1993; Kiikkilä, 2003). Special attention was paid in selecting study areas so that they would represent the same habitat type, i.e. relatively barren pine dominated forests typical of the study area.

#### 2.2. Breeding data

The nest-boxes were checked at least weekly to determine laying date, clutch size, hatching date, and numbers of nestlings and fledglings. The study area was divided into three zones: sites closer than 2 km from the smelter are hereafter called ‘zone I’ denoting most heavily polluted area, sites more than 5 km from the smelter are called ‘zone III’ denoting an unpolluted area. Analysing the data according to the distance to the pollution source instead of just using heavy metal levels as an explaining factor makes sense in that this way we can use larger data set and observe also any indirect effects of environmental pollution, such as due to changed food quantity and quality which are shown to occur in the area (Eeva et al., 1997a). All parameters were not measured in all nests and the numbers of observations vary in different analyses accordingly. Measures known to be affected by predation or human disturbance were also omitted. All together, the data include information on 360 nests of *C. caeruleus* and 1233 nests of *P. major*.

Body mass and wing length of females and nestlings were measured at variable stages of breeding. Females of *C. caeruleus* were captured during the incubation and nesting periods while females of *P. major* were exclusively captured during the nesting period because this species is vulnerable to disturbance at the early phases of breeding. The analyses of *C. caeruleus* females include full biometric data. Including only the nesting period, as for *P. major*, did not change the results. Because female body mass changes in both study species during the course of breeding (De Laet and Dhondt, 1989) we fitted cubic regression models ($R^2$ for *C. caeruleus* = 0.52; $R^2$ for *P. major* = 0.12) to the mass data and used the proportional (%) residuals in consequent analyses as a measure of female body mass. Respectively, the effect of age on nesting wing length and body mass was taken into account by fitting a linear regression model to the data sets on wing length ($R^2$ for *C. caeruleus* = 0.82; $R^2$ for *P. major* = 0.88) and body mass ($R^2$ for *C. caeruleus* = 0.66; $R^2$ for *P. major* = 0.51), and using proportional (%) residual wing length and proportional (%) residual body mass in consequent analyses. For the analyses we included only the measurements between the ages of 6 and 15 days, during which period nesting wing length and body mass grew relatively linearly. Adding higher order terms in any of the above mentioned models had only minor effects on the model fit.

#### 2.3. Heavy metal analyses

In summer 2008 we collected fresh feces from defeating nestlings at the age of 7 days. Fecal sacs from the same brood (2–4 nestlings) were combined, dried in a laboratory at 50°C for 72 h, and weighed (mean ± SE: *C. caeruleus*: 85 ± 9.9 mg, n = 24; *P. major*: 115 ± 8.2 mg). Two milliliters of supra-pure HNO₃ and 0.5 ml of H₂O₂ were added to the samples in Teflon bombs for digestion with a microwave system. After the digestion the samples were diluted to 50 ml with de-ionized water. The determination of metal concentrations (As, Cd, Cu, Ni, Pb) was done with ICP-MS (Elan 6100 DRC measuring instrument, PerkinElmer-Sciex). The detection limit for most of the elements was around 1 ppb (ng/l) and below. The calibration of the instrument was done with certified solution (Clariats PPT, Multi element solution 2A from Spx Certiprep). Certified reference material (mussel tissue ERM-CE278; Ca and Ni not included) was used for method validation. The mean recoveries ($±$SE) in five reference samples were as follows: As 100 ± 0.84%, Cd 100 ± 1.68%, Cu 105 ± 0.82% and Pb 103 ± 1.25%. In *P. major*, heavy metal concentrations in the alimentary canal have found to correlate positively with the concentrations in skeleton (Belskii et al., 1998).

#### 2.4. Statistics

Statistical analyses were performed with SAS statistical software 9.1 (SAS Institute, 2003). Differences in breeding and condition parameters among the three distance zones were analyzed with generalized linear models (Glimmix procedure in SAS). In the models for variation in laying date, clutch size, residual body mass and residual wing length, normal error distributions were used. For the models of variation in fledging probability (a probability of an egg to produce a fledgling; 0 vs. 1) and age distribution (young – 1 yr vs. old ≥ 2 yr) we used binomial error distributions and events/trial type dependent variable of the Glimmix procedure. Year was included as a random factor in all the models. In the model for age distribution of *C. caeruleus* the variance component for individual identity was negative. We therefore modelled this covariance as an intra-class correlation using repeated measures approach with compound symmetry covariance structure (Littel et al., 2006). This approach controls for proper type I error rate and reduces the power of the analysis. In the models for nesting body mass and wing length, brood was further used as another random factor to take account of the fact that nestlings in the same brood are not independent units.

Differences in fecal calcium and heavy metal levels between zones and between species were analyzed with generalized linear models with normal error distribution. Concentrations were log-transformed for the analyses and back-transformed for the tables. Since these data came from one year and the measurements were made from the combined sample of a brood, no random factors were included in these models. In the models comparing concentrations between distances we first included the zone and species x zone interaction as explaining factors. However, in no case was the interaction term significant and it was omitted from the final models.

The degrees of freedom were always calculated with Kenward–Roger method, if the model contained random factors. Pairwise comparisons among distance zones were performed with Tukey’s test with p-values adjusted for multiple comparisons. More detailed information on specific models and possible covariates are given in Tables 1–3.

#### 3. Results

*C. caeruleus* females started to lay 1.4 days and *P. major* females 1.6 days earlier in the heavily polluted area (zone I) than elsewhere (Tables 1 and 2). The clutch size of *C. caeruleus* was similar in all areas while in *P. major* it was 0.6 eggs smaller in the zone I (Tables 1 and 2). There were no differences in hatching probability (% hatchlings/eggs) among zones in *C. caeruleus*, while in *P. major* it was higher in the zone III than in other zones (Tables 1 and 2). Fledging probability (% fledglings/hatchlings) was 24% lower in *C. caeruleus* and 22% lower in *P. major* in the zone I than elsewhere (Tables 1 and 2). In addition, fledging probability of *P. major* was slightly higher in the moderately polluted zone II than in zone III. *C. caeruleus* nestlings were 12% lighter in the most polluted zone I than elsewhere (Table 1). *P. major* nestlings were heaviest in the moderately polluted zone II, while there was no difference between the other zones (Table 2). Nestlings of both species had shorter wings (8.9% in *C. caeruleus*; 6.2% in *P. major*) in the polluted zone I than elsewhere (Tables 1 and 2). The number of hatchlings (a covariate) was negatively related to residual body mass in both species and to residual wing length in *P. major* ($p < 0.01$ in all).

Female residual body mass or wing length did not show any significant differences among distance zones in either species, though in both species average mass residuals tended to be slightly higher in the intermediatedially polluted area (Tables 1 and 2). Young females were 1.2 mm shorter winged in both species (test results not shown). The proportion of young *P. major* females was 28%
lower in the moderately polluted zone II than elsewhere, though the difference is only marginally significant (Table 2). No significant differences among zones were found in age distributions of *C. caeruleus* (Table 1). Because of higher proportion of old *P. major* females in the moderately polluted zone we further tested post hoc whether the age distribution could explain the variation in breeding parameters among zones. Females were not trapped in all nests and sample sizes are hence considerably lower than in the whole data set. Old females had 4.3% higher clutch size ($F_{1,273} = 4.15, p = 0.043$) and their nestlings were 3.8% heavier ($F_{1,309} = 6.62, p = 0.011$), but the zone effect was still strong after including the female age in the models. Age had no significant effects on the other breeding parameters.

The offspring numbers during the nesting period are shown for the most polluted zone I and for combined zones II and III in Fig. 1. Both species show a considerable drop in offspring number in the beginning of nesting period, due to mortality of eggs and newly hatched young. As shown in Table 2 the hatching success of *P. major* was decreased in the polluted area. On the other hand, the drop in offspring number at and shortly after hatching is typically larger in *C. caeruleus*, i.e. the species with larger clutch size. However, in general pollution-related changes are very similar in the two species: after the “natal mortality”, the difference between polluted and unpolluted environment increases gradually in both species until fledging (Fig. 1).

Neither of the two species differed in their fecal Ca concentrations among the distance zones (Table 3). Instead, in both species, heavy metal levels in nesting feces were increased in the most polluted zone I (Table 3). No significant difference among zones, however, was found in Pb concentrations of *C. caeruleus*, but the lack of significance may be due to small sample numbers in zones II ($n = 3$) and III ($n = 5$) in this species. There was a clear difference in fecal Ca level between species, concentrations being 2.7 times higher in *P. major* ($\chi^2_{1,70} = 15.1, p = 0.0002$; Table 3). Fecal Ni and Pb levels were 1.5–1.8 times higher in *C. caeruleus* than in *P. major* (Ni: $\chi^2_{1,68} = 71.4, p < 0.0001$; Pb: $\chi^2_{1,68} = 8.76, p = 0.0042$; Table 3). No between-species differences in concentrations were found for As, Cd and Cu (As: $\chi^2_{1,68} = 2.51, p = 0.12$; Cd: $\chi^2_{1,68} = 0.66, p = 0.42$; Cu: $\chi^2_{1,68} = 1.69, p = 0.20$; Table 3).
Table 3
The mean (95% confidence intervals) calcium (mg/g) and heavy metal (µg/g) concentrations in feces of *C. caeruleus* and *P. major* nestlings in three distance zones* around the pollution source. Generalized linear models.b

<table>
<thead>
<tr>
<th></th>
<th>Least squares means</th>
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<tbody>
<tr>
<td></td>
<td>Zone I</td>
<td>Zone II</td>
<td>Zone III</td>
<td>df</td>
<td>F</td>
</tr>
<tr>
<td>Calcium</td>
<td>5.88 (3.19–10.8)</td>
<td>5.18 (1.26–21.3)</td>
<td>4.30 (1.44–12.8)</td>
<td>2.21</td>
<td>0.14</td>
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<tr>
<td>Arsenic</td>
<td>6.84 (5.37–8.71)</td>
<td>1.91 (1.09–3.35)</td>
<td>0.89 (0.58–1.37)</td>
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<td>40.5</td>
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<tr>
<td>Cadmium</td>
<td>2.80 (2.13–3.68)</td>
<td>2.52 (1.35–4.73)</td>
<td>1.25 (0.77–2.04)</td>
<td>2.21</td>
<td>4.55</td>
</tr>
<tr>
<td>Copper</td>
<td>2.00 (161–248)</td>
<td>131 (79.6–216)</td>
<td>64.2 (41.6–94.5)</td>
<td>2.21</td>
<td>14.4</td>
</tr>
<tr>
<td>Lead</td>
<td>9.31 (5.85–14.8)</td>
<td>3.11 (1.06–9.09)</td>
<td>4.28 (1.86–9.82)</td>
<td>2.21</td>
<td>2.81</td>
</tr>
<tr>
<td>Nickel</td>
<td>36.2 (28.4–46.0)</td>
<td>10.2 (5.87–17.9)</td>
<td>7.89 (5.13–12.1)</td>
<td>2.21</td>
<td>25.5</td>
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</table>

4. Discussion

4.1. Inter-specific differences in responses

We found clear negative effects on breeding parameters of two Parid species in the heavy metal polluted area. Both focal species showed inferior nestling growth and 22–24% smaller fledging probability in the polluted area. The major inter-specific difference in the responses was that the clutch size and hatching success of *P. major* were decreased in the most polluted area, while no corresponding changes were observed in *C. caeruleus*. Note, however, that of the two species *P. major* still showed a higher hatching success even in the most polluted area. Heavy metal profiles in nestling feces were relatively similar in the two species, as was also shown by Dauwe et al. (2000). In our study, *C. caeruleus* nestlings, however, showed higher fecal Ni and Pb concentrations than *P. major* nestlings. These differences may be related to inter-specific differences in nestling diets (see below). The accumulation of heavy metals to tissues could, of course, still differ between these species even though levels in feces were the same. However, Hogstad (2001) did not find any differences in liver heavy metal concentrations of adult *C. caeruleus* and *P. major*.

Interestingly, we found a clear difference in Ca levels between *C. caeruleus* and *P. major* nestlings, the latter species showing 2.7 times higher fecal Ca concentrations. If such a difference in Ca turnover would take place also during egg laying, we could expect that, if any, detrimental effects on egg number or quality should first manifest in *C. caeruleus*. However, clutch size and hatching success were not affected in this species, while they were decreased in *P. major*. On the basis of relatively high fecal Ca concentrations, *P. major* should not be Ca limited during the nestling period. However, deviant egg shells and laying gaps, both indicative of calcium shortage (Graveland and Berends, 1997), are frequently observed in this species at polluted sites, and the occurrence of laying gaps have been found to be negatively related to hatching success (Eeva and Lehikoinen, unpublished data). Therefore, even the *P. major* may be Ca limited in our study area at the time of egg laying. The Ca levels in *C. caeruleus* are rather close to the level of *F. hypoleuca*, a species in which severe detrimental effects of heavy metals on egg shell quality and nestling development have been found in Ca-deficient environments (Eeva and Lehikoinen, 2004). Therefore, in Ca-deficient environments nestlings of *C. caeruleus* might be more sensitive to detrimental effects of heavy metals than those of *P. major*.

Dauwe et al. (2005) found no pollution-related effects on laying date, clutch size, nestling growth, hatching success or fledging success of *C. caeruleus* in the vicinity of a non-ferrous smelter in Belgium, where the heavy metal levels (especially Pb) are generally higher than in our study area (Dauwe et al., 2000). Similarly, we did not observe any pollution-related changes in clutch size or hatching probability of this species. In our study area, however, there were marked pollution-related effects on laying dates, nestling growth and fledging success: birds started laying earlier, nestlings grew slower and their fledging probability was lower in the vicinity of the pollution source than elsewhere. Shorter winged nestlings and increased nestling mortality both suggest problems to find enough food for nestlings. Pine dominated coniferous forests of our study...
area are more barren than deciduous forests of the Belgian study area. Therefore, we consider it likely that difference between the studies is mainly due to different productivity and invertebrate abundance during the time of breeding.

Contrary to the results on *C. caeruleus*, the studies of Janssens et al. (2003a,b) reported significant effects of heavy metal pollution on hatching success, growth and fledging success of *P. major* in the same Belgian study area. In agreement, *P. major* showed decreased hatching and fledging probability in the polluted zone of our study area. In contrast to their results, we also found effects on laying date and clutch size: *P. major* females laid earlier and smaller clutches in the most polluted area, though in general, heavy metal levels were lower in our study area (except for Cu). We did not observe any pollution-related differences in wing length or body mass of breeding *P. major* females. Likewise, earlier studies on condition and size variables of *P. major* have revealed very few such effects (Eeva et al., 1997b; Janssens et al., 2003a). One common observation, however, is that *P. major* females tend to be somewhat heavier in moderately polluted areas than elsewhere (Eeva et al., 1997b; Dauwe et al., 2006). This, together with better nestling growth, might be explained by better availability of invertebrate food in moderately polluted areas (see below). Separating between correlated direct and indirect effects is a general problem when free-living animals are studied. Though environmental pollution has marked effects on invertebrate abundance (Helioväara and Väisänen, 1990; Eeva et al., 1997a) and birds’ diet (Eeva et al., 1998, 2005a; Eeva and Lehikoinen, 2004), heavy metals may also directly retard the growth of nestlings (Scheuhammer, 1991). For example, negative associations between fecal and skeletal lead concentrations and nestling body mass have been found in *P. major* nestlings along the pollution gradients of smelters (Belskii et al., 1995; Eeva et al., 2003; Janssens et al., 2003a). However, fecal lead levels in the most polluted sites of our study area are relatively low (*C. caeruleus*: 9.3 μg/g; *P. major*: 6.0 μg/g; Table 3) as e.g. compared to the Belgian study site (*C. caeruleus*: 125 μg/g; *P. major*: 80 μg/g; Dauwe et al., 2000). Despite very high lead levels in the most polluted site of the Belgian study area, *C. caeruleus* nestlings did not show reduced body mass (Dauwe et al., 2005), while this was observed in our study area. On the other hand, we did not observe any association between fecal copper concentrations and nestling body mass even though copper levels are very high in our study area (Eeva et al., 2003). The nestling growth was not either retarded in *F. hypoleuca*, which generally shows higher fecal heavy metal levels than *P. major* (Eeva and Lehikoinen, 1996; Eeva et al., 2005a,b). Therefore we believe that indirect effects of pollution are likely to have more important role in explaining reduced growth of Parids in the polluted area. A mixture of multiple heavy metals may, however, have synergistic effects on growth and we cannot rule out the possibility of direct growth effects in nestlings showing the highest heavy metal concentrations.

4.2. Inter-specific dietary differences

In general, the nestling diet is rather similar in the two bird species, *C. caeruleus* bringing nestlings about 40–60% (in numbers) and *P. major* 50–70% of caterpillars in mixed and coniferous woods (Cramp and Perrins, 1993). *P. major* has been found to provide nestlings with larger food items than *C. caeruleus* (Cowie and Hinsley, 1988). For example, in suburban environment, *P. major* brought nestlings proportionally more spiders (Araneae) and Diptera, while *C. caeruleus* brought more aphids (Hemiptera) (Cowie and Hinsley, 1988). In general, aphids tend to be very abundant in polluted environments, and their numbers have greatly increased also in our study area (Helioväara and Väisänen, 1990). They might thus be a favorable alternative food source for *C. caeruleus* in polluted areas, where caterpillar availability may be worse than in the unpolluted areas (Eeva et al., 1997a). However, aphids clearly could not compensate the smaller number of caterpillars during the nestling period, since nestlings grew worse and their mortality was higher in the polluted area in both species.

Faster advancement of phenology in spring is likely to explain the slightly earlier laying of Parid species in the polluted area. The study sites in the most polluted area are phenologically advanced because forests in this area are sparser, and ground is darker and more barren, enabling e.g. faster snow melting and earlier birch leafing in spring than in more shaded forests. Despite an earlier onset of breeding, some important food sources like birch leaf browsing autumnal moth (*Epiprita autumnata*) and winter moth (*Operophtera brumata*) larvae may actually peak later in the polluted area than in other areas (Sillanpää et al., unpublished). This may cause a mismatch between nesting period and peak food availability in the polluted environment. For example, in an earlier study we found that *P. major* fed smaller (i.e. younger) larvae to nestlings in the polluted area than in the unpolluted one (Eeva et al., 2005b). Pollution-related temporal differences in food availability could thus explain the inferior nestling growth and increased nestling mortality, which were observed near the pollution source in both species.

In both species, nestlings grew relatively well in the moderately polluted area. In *P. major*, good growth might be partly explained by a higher proportion of old females in this zone, though the difference in age distribution was only marginally significant. Additionally, caterpillar availability has been found to be relatively good in the moderately polluted zone during the nestling period of tits (Eeva et al., 1997a). Such an increase in insect numbers at the moderately polluted environments has been found to be a general phenomenon along the pollution gradients. For example, several species of herbivorous insects, which are important food items for many insectivorous birds, may increase in numbers in a moderately polluted environment, but tend to be less abundant in heavily polluted areas (Führer, 1985; Helioväara and Väisänen, 1990). Relatively good food availability might also explain the higher proportion of old *P. major* females breeding in the moderately polluted area. Such profitable breeding sites are probably favored by old and dominant birds (see Sandell and Smith, 1991).

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