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Effects of pollution on land snail abundance, size and diversity as resources for pied flycatcher, *Ficedula hypoleuca*

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ABSTRACT

Passerine birds need extra calcium during their breeding for developing egg shells and proper growth of nestling skeleton. Land snails are an important calcium source for many passerines and human-induced changes in snail populations may pose a severe problem for breeding birds. We studied from the bird's viewpoint how air pollution affects the shell mass, abundance and diversity of land snail communities along a pollution gradient of a copper smelter. We sampled remnant snail shells from the nests of an insectivorous passerine, the pied flycatcher, *Ficedula hypoleuca*, to find out how the availability of land snails varies along the pollution gradient. The total snail shell mass increased towards the pollution source but declined abruptly in the vicinity of the smelter. This spatial variation in shell mass was evident also within a single snail species and could not be wholly explained by spatially varying snail numbers or species composition. Instead, the total shell mass was related to their shell size, individuals being largest at the moderately polluted areas. Smaller shell size suggests inferior growth of snails in the most heavily polluted area. Our study shows that pollution affects the diversity, abundance (available shell mass) and individual quality of land snails, posing reproductive problems for birds that rely on snails as calcium sources during breeding. There are probably both direct pollution-related (heavy metal and calcium levels) and indirect (habitat change) effects behind the observed changes in snail populations.

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1. Introduction

Human activities may have detrimental effects on land snail populations. For example, snails are known to be sensitive to acidification or pollution of environment (van Tol et al., 1998; Johannessen and Solhoy, 2001), and they are shown to easily accumulate pollutants, such as heavy metals (Berger and Dallinger, 1993; Jordaens et al., 2006). Land snails have therefore been suggested as sentinel organisms for biomonitoring (Regoli et al., 2006). Snails have also been recognized as one of the most important sources of calcium for many passerine bird species (Graveland and Drent, 1997; Tilgar et al., 1999a; Mänd et al., 2000; Bureš and Weidinger, 2000). Therefore, changes in snail populations are reflected higher up in the food chain. Decreased snail abundance may pose a problem to birds, especially during the breeding period, when birds need to acquire extra calcium for developing egg shells and for a proper growth of the nestling skeleton (Graveland and van Gijzen, 1994). We are, however, not aware of any studies trying to quantify population level changes in terrestrial snail numbers in environments exposed to pollution.

We studied how air pollution affects the abundance, species richness and structure of land snail communities along a pollution gradient of a copper smelter. To get relevant information on pollution-related changes in snail populations from the viewpoint of birds we sampled remnant snail shells from the nests of an insectivorous passerine, the pied flycatcher, *Ficedula hypoleuca*. This species frequently feeds the nestlings with small land snails and a part of them drop to the nest cup, and can be later counted. Earlier studies have shown that egg shells of *F. hypoleuca* were thinner and egg volume and clutch size were smaller in the vicinity of the smelter compared to the background area (Eeva and Lehikoinen, 1995). *Ficedula hypoleuca* nestlings also had problems with their bones: their leg or wing bones did not develop normally (Eeva and Lehikoinen, 1996). Thin egg shells and poorly developing bones are likely due to low calcium availability and increased heavy metal concentrations in the birds' diet in heavily polluted sites (Eeva and Lehikoinen, 2004).

In the current study we want to find out what kind of changes in land snail populations may be behind the calcium-related reproductive problems in *F. hypoleuca*. We expect that availability of snail shells is inferior in the heavily polluted area, where most severe egg shell thinning in *F. hypoleuca* has taken place. Snail shell availability may vary in three ways: 1. the number of snails differs, 2. the size of individuals differs, or 3. the snail species composition differs. First, we explored how the shell numbers and the amount of shell mass in *F. hypoleuca* nests

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vary along the pollution gradient. Second, we tested for the most abundant species whether the individual size (shell mass) of snails varies along the pollution gradient. Third, we wanted to find out whether the variation in total shell mass was related to changes in species composition, i.e. whether smaller sized species dominate in different parts of the pollution gradient than larger sized species.

2. Methods

2.1. Study area

The data were collected during two breeding seasons (2003 and 2006) in the surroundings of a copper smelter in Harjavalta (61°20′ N, 22°10′ E), SW Finland. Sulphuric oxides and heavy metals (especially Cu, Zn, Ni, Pb and As) are common pollutants in the area (Kubin, 1990; Jussila and Jormalainen, 1991). Elevated heavy metal concentrations occur in the polluted area due to current and long-term deposition, and metal contents decrease exponentially with increasing distance to the smelter approaching background levels at sites farther than 5 km from the smelter (Jussila et al., 1991; Koricheva and Haukioja, 1995; Eeva and Lehikoinen, 1996). Organic soil copper concentrations along the pollution gradient are shown in Fig. 1. The amount of exchangeable Ca in the organic layer of soil has decreased near the smelter due to leaching but soil pH is the same or even slightly higher than in the background area (Fritze et al., 1989; Jussila, 1997; Derome and Nieminen, 1998).

Twelve study sites, each with 40–50 nest-boxes, were established along the air pollution gradient in the three main directions (SW, SE and NW) away from the copper smelter complex. The forests in the area are dominated by Scotch pine (*Pinus sylvestris*), which forms mixed stands with spruce (*Picea abies*) and birches (*Betula* spp.) with the occasional occurrence of other deciduous trees like aspen (*Populus tremula*), rowan (*Sorbus aucuparia*) and willows (*Salix* spp.). Special attention was paid to selecting study areas so that they would represent the same habitat type, i.e. relatively barren and dry pine dominated forests typical of the study area. Earlier studies have shown that land snail numbers are generally much lower in coniferous and Ca poor than deciduous and Ca rich habitats (Andersen and Halvorsen, 1984; Mänd et al., 2000), and ambient Ca levels may affect their shell morphology (Goodfriend, 1986). Therefore we expect that barren habitat is likely to make the land snail populations of our study area vulnerable to pollution stress.

2.2. Counts of snails in nests

Ficedula hypoleuca parents feed small land snails to nestlings and drop some of the snails into the bottom of the nest. This species does not clean dropped items from the nest and the number of snail shells can be counted after fledging. We collected 120 nests from 12 study sites along the pollution gradient (2003: $n = 55$; 2006: $n = 65$) of *F. hypoleuca* after fledging (30th June–24th July) and searched them for remnant snail shells. Only those nests were collected where at least one nestling fledged. Therefore, territories with worst breeding success (e.g. none of the eggs hatch) are underrepresented in our data but this should only make our analyses more conservative and does not bias comparisons among sites.

Nests were frozen, air dried and sieved to remove most of the nest material. Snail shells were then picked up from the remaining sample. Snail species were identified by OS with the help of the guides by Kerney et al. (1979) and Hutri and Mattila (1991), and shells were individually weighted. Shells containing soil or a dead snail were emptied with a thin needle before weighing. The shell mass and number of individuals were used as an index of snail abundance in birds' territories. Experimental supplementation of snail shells in *F. hypoleuca* territories has confirmed that the availability of snails is really reflected in the numbers of remnant snail shells in nest material (Tilgar et al., 1999b).

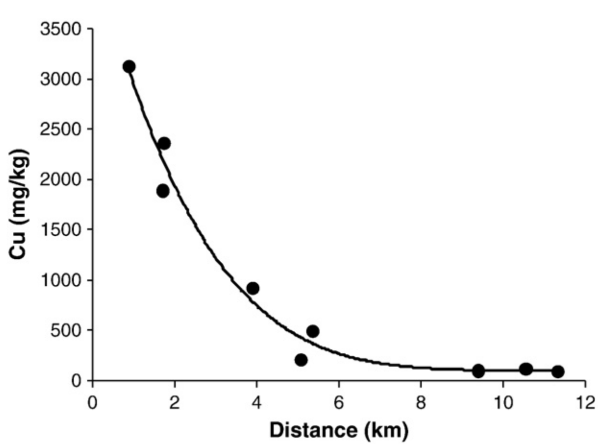

Fig. 1. Organic soil copper concentrations (mg/kg) along the pollution gradient of a copper smelter. Cu concentrations were determined with ICP-MS spectrometer and certified reference material (mussel tissue ERM-CE278) was used for method validation. The recovery from the reference sample was 106%.

2.3. Statistics

The variations in total snail shell mass per nest and total shell numbers per nest were analyzed by using generalized linear models (with negative binomial error distribution and log-link function) in a glimmix procedure of SAS statistical software 9.1 (SAS Institute, 2003). Zero observations (nests with no shells) were included in these analyses. Year and first, second and third order terms of the log-distance to the pollution source were used as independent variables. Accounting for possible non-linear responses, the second order term (distance × distance) corresponds a quadratic and third order term (distance × distance × distance) a cubic response to distance. Non-significant terms were dropped from the models one-by-one, starting from higher order terms. Year was, however, retained in the final models to avoid temporal pseudoreplication. Brood size (a number of hatchlings) was first included as a covariate in the models, but it was omitted from final models as a non-significant variable. For evaluating the goodness of fit of the models we always checked the scaled Pearson statistic (χ^2/df), which should optimally be 1. Note, however, that with negative binomial distribution the glimmix procedure always includes this scaling parameter in the model to correct for possible under- or overdispersion in data. The scaled Pearson statistics and other details on specific models are given in Table 2. Since five of the sampled nests contained a few snails from moist/wet habitat (Table 1) we also ran the previous models without those nests to confirm that our analyses are not biased by more moist habitats next to some territories. Omitting those nests, however, did not change the models and the full data was used in all analyses.

Variation in snail size (individual shell mass) was analyzed by using a generalized linear model (with negative binomial distribution and log-link function; SAS Institute, 2003) containing year and first, second and third order terms of the log-distance to the pollution source as independent variables. Individual shell mass variation could only be tested for the most common species, *Discus ruderatus*, because the spatial distribution of this species was representative over the whole pollution gradient and the sample size was adequate to get a satisfactory model fit. Since some of the nests contained multiple *D. ruderatus* shells, nest was used as a random factor in this analysis. We also ran the same model by including the data on all the species, by adding species as a further random factor to account for species specific size variation. We further analyzed the relationship between the average shell mass of a species and the average sampling distance of the species with a linear regression model (REG procedure in SAS). Average shell mass values were $\log_{10}$-transformed to make the distribution normal (after transformation, Kolmogorov–Smirnov test: $p > 0.15$).

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