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Snail consumption and breeding performance of pied flycatchers (*Ficedula hypoleuca*) along a pollution gradient in the Middle Urals, Russia

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HIGHLIGHTS

- Pied flycatchers consume less snail shells in the heavily polluted sites
- Diversity of snails collected by birds decreased in polluted sites
- The closer the smelter, the higher proportion of deserted clutches and abnormal eggs
- Brood size decreased in the polluted area, especially if snail supply was low

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ABSTRACT

During the years 1989–91, 1997–2003, and 2005–07, we studied how emissions from the Middle Urals copper smelter affect snail availability and reproduction of free-living pied flycatchers (*Ficedula hypoleuca*). We counted snail shells dropped in nests and analysed food samples of nestlings. Pied flycatchers brought to nestlings fewer shells in heavily polluted sites compared to background sites, resulting in reduced Ca intake. Species diversity of snails collected by birds decreased with decreasing distance from the pollution source. The pattern was the same both in deciduous and coniferous forests. In sites closest to the smelter, 20–50% of breeding females suffered from Ca deficiency, which resulted in an increased proportion of deserted clutches and clutches with defective eggshells. Number of fledglings per nest decreased in heavily polluted sites, especially in broods with decreased snail supply. This study demonstrated that pollution can cause both direct effect of toxicants to birds and indirect effects via reduced Ca availability.

1. Introduction

Birds need calcium (Ca) as a constructional material for eggshell and nestling skeleton. This is why Ca consumption by birds increases during breeding (Simkiss, 1967). Calcium deficiency in adult birds results in clutch desertion, eggshell defects, reduced clutch size and hatching success, retarded laying date, and irregular laying (review: Reynolds and Perrins, 2010). Snail shells are considered one of the main sources of Ca for free-living passerines (Graveland and Van Gijzen, 1994; Graveland, 1996; Bureš and Weidinger, 2000). This explains why shell availability can affect breeding success and should be taken into account when analysing bird reproduction.

The abundance and spatial distribution of land snails depend on chemistry and humidity of soil (litter) and vegetation characteristics (Wäreborn, 1992; Götmark et al., 2008). These factors determine food supply of snails and availability of Ca required for shell construction. Land snail abundance is low in ecosystems on Ca-poor soils (Drent and Woldendorp, 1989; Tilgar et al., 1999; Graveland and van der Wal, 1996; Mänd et al., 2000). Soil Ca concentrations are low in acidified areas and near industrial enterprises emitting acidifying compounds (e.g., sulphur and nitrogen oxides). The snails disappear in forests and meadows near such polluters (Vorobeichik et al., 2012; Eeva et al., 2010; Nesterkov, 2013). However, relationships between industrial pollution, snail availability, and reproduction of free-living birds have not been studied sufficiently. As regards the pied flycatcher, there were only few studies in southwest Finland (Eeva and Lehikoinen, 2004; Eeva et al., 2010).

In this study, we analysed snail consumption and some effects of Ca deficiency in local populations of pied flycatchers along a pollution gradient in the Middle Urals, Russia. We tested two hypotheses: 1) snail shell consumption is affected both by pollution and habitat; 2) breeding

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output of birds depends on availability of snails representing an important source of Ca. If snails are sensitive to acidification and vegetation change we predicted that birds in polluted sites consume less shells compared to undisturbed areas. We expected that snail abundance and diversity in the bird diet is reduced in coniferous habitat compared to deciduous forest, which is considered to be more favourable for snails. If reproduction of birds depends on calcium availability, then we predicted reduced breeding output in polluted areas.

2. Material and methods

2.1. Study area

The study was performed during the years 1989–91, 1997–2003, and 2005–07 in the vicinity of the Middle Urals copper smelter (Russia, Revda, 56°51′N, 59°53′E), which is a strong source of sulphur dioxide and polymetallic dust. Total emissions varied from 140,700 t in 1989 to 24,500 t in 2007 (Vorobeichik et al., 1994; DNRSO, 2008). Metal (Cu, Pb, and Cd) concentrations in the soil (horizon A1, extracted with 5% HNO_3 for 24 h with a soil-to-acid ratio of 1:10 by weight) decreased exponentially with increasing distance to the smelter (Fig. 1).

Zones with different levels of pollution and degradation of forest ecosystems were distinguished in the vicinity of the plant, based on investigations of soil quality and microbiological activity (Kaigorodova and Vorobeichik, 1996; Vorobeichik, 2007), vascular plants (Vorobeichik and Khantemirova, 1994), epiphytic lichens (Mikhailova and Vorobeichik, 1995), soil-dwelling (Vorobeichik et al., 2012) and epigeic invertebrates (Zolotarev and Belskaya, 2012), leaf-eating insects (Belskaya and Vorobeichik, 2013), birds (Belskii and Lyakhov, 2003) and small mammals (Mukhacheva, 2007). The zone of high pollution (impact zone) extends westward up to 2.5 km from the smelter. Copper and Pb concentrations in the soil (horizon A1) exceed regional background levels by 43.4 and 9.5 times, respectively (Belskii et al., 2005), and pH_{water} is 4.37–5.17 (Kaigorodova and Vorobeichik, 1996). The moderately polluted (buffer) zone extends 3–15 km to the west of the smelter. Soil Cu and Pb concentrations exceed regional background levels by 9.9 and 4.4 times, respectively, and soil pH_{water} is 4.48–5.77. The relatively unpolluted (background) zone is situated ≥16 km to the west of the smelter, where soil pH_{water} is 5.04–6.24.

Study sites, each with 14–81 nestboxes, were established in two habitats along the pollution gradient to the west of the smelter, within a 1–27-km range (Fig. 2). Both habitats were represented in each pollution zone. There were 1) aspen-birch (*Populus tremula* and *Betula verrucos*a + *Betula pubescens*) forests with some admixture of conifers and 2) fir-spruce (*Picea obovata* and *Abies sibirica*) forests with an admixture of pine (*Pinus sylvestris*), birch, and aspen. The forest was rarefied near the smelter, with large amounts of dead wood and depressed young growth due to the long-term (starting from 1940) effects of pollution.

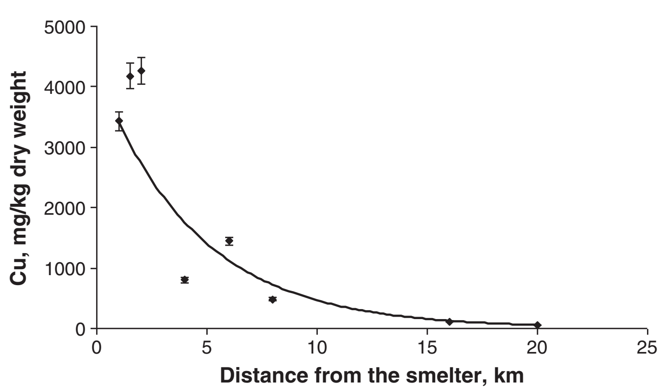

Fig. 1. Organic soil copper concentrations (±SE; extracted from humus layer with 5% HNO_3) at different distances from the Middle Urals copper smelter ($y = 4285.1 \times e^{-0.22 \times distance}$, $R^2 = 0.94$).

2.2. Model species

Nestboxes were commonly occupied by pied flycatchers (*Ficedula hypoleuca* Pall). They are small (~12 g) passerines and long-distant migrants with winter grounds in West Africa, south of the Sahara. Pied flycatchers inhabit different forest types and readily occupy nestboxes. They feed on different arthropods taken from tree crowns, on the ground, or in the air by darting out from a perch (Cramp and Perrins, 1993). Pied flycatchers breed in the study area in May–July; nestlings usually fledge at age 15 days.

2.3. Sampling

The nestboxes were checked regularly to record dates of the egg laying and hatching, number of eggs, hatchlings, and fledglings. Special attention was paid to eggs, which desiccated during incubation because of defective shells. Nests with at least one egg laid were included in the analysis.

Adult birds bring small snail shells to nestlings, which are an important source of Ca required for proper growth of nestling skeletons (review: Reynolds and Perrins, 2010). Some shells drop and build up in the bottom of nests. Numbers of spilled shells in nests reflect snail abundance in breeding territories and their consumption by birds (Graveland and van der Wal, 1996; Tilgar et al., 1999). After fledging, nests were collected in plastic bags, transported to the laboratory, and searched for dropped snail shells. Only those nests were collected where at least one nestling fledged. Only undamaged (or slightly damaged) snail shells were sampled. In total, 1113 shells in 388 nests were sampled. Snail species were identified by Maxim Grebennikov with the help of the guide by Sysoev and Schileyko (2009).

The diet of *F. hypoleuca* nestlings (6–11 days old) was studied using neck collars made of fishing line (Kuligin, 1981) at the same sites in deciduous forest in 2000, 2003, and during 2005–07. In total, 1567 food boluses were collected in 104 nests of six sites (two sites per pollution zone). Sampled snails ($n = 80$) were preserved in alcohol.

To estimate contaminant exposure, nestling faeces was sampled during 2002–03 and 2006 in 10 nests each in the background and impact zones.

2.4. Metal analyses

Faecal samples (on average 100 mg dry mass weighed to the nearest 0.1 mg) were digested in a mixture of 7 mL supra-pure HNO_3 + 1 mL de-ionised H_2O in Teflon bombs in a microwave system MWS-2 (Berghof, Germany). Copper, Zn, Cd, and Pb concentrations were measured with an AAS 6 Vario atomic absorption spectrometer (Analytik Jena, Germany) and Ca with an ICP-atomic SPECTRO Genesis emission spectrometer (SPECTRO Analytical Instruments, Germany). Certified reference material (bovine liver CRM-185R) was used for method validation. The recovery from the reference sample was as follows: Cu, 95%, Zn, 99%, Cd, 101%, and Pb, 107%.

2.5. Statistical analyses

Most statistical analyses were performed with STATISTICA v.8.0 (StatSoft, Inc., 2008). Proportion of nests with snail shells was calculated for each site as a yearly mean. The number of shells per nest was calculated only for nests with ≥1 shell. When analysing species composition of snails stored in nests, 14 sites were grouped by three pollution zones and two habitats. Species richness (number of species) was estimated per minimal sample (26 shells in nests and 11 shells in food samples) by using individual rarefaction procedure in PAST, v.1.92 (Hammer et al., 2001). Shannon diversity indices and 95% confidence limits