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Interspecific variation in the spatially-explicit risks of trace metals to songbirds

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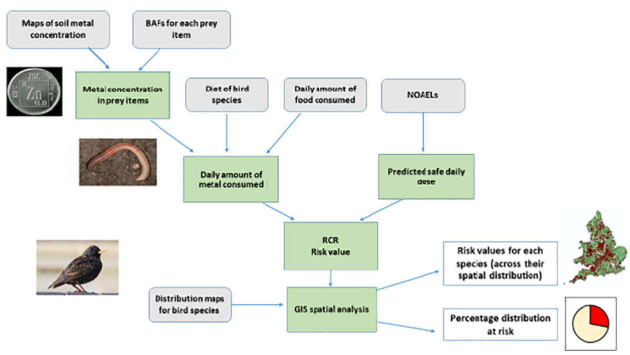
HIGHLIGHTS

- A spatially explicit modelling framework is presented to estimate risks of metal to birds.
- The model has been applied to soil metal contamination and thirty songbird species.
- Our spatial model showed interspecies variation in metal toxicity risks to UK songbirds.
- Pb and Zn exposure posed high toxicity risks to adults and nestlings via diet as indicated by the model.
- Despite the model limitations, this study can be a useful for environmental risk assessment.

GRAPHICAL ABSTRACT



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ABSTRACT

Many wild animals can be adversely affected by trace metals around point sources but little is known about the risks to birds across their ranges. Trace metals in the soil are ubiquitously, if heterogeneously distributed, across the world due to natural and anthropogenic sources. Here, we built, parameterized and applied a spatially explicit modelling framework to determine the risks of soil-associated metals to 30 invertebrate-consuming passerine species across their spatial distribution in England and Wales. The model uses a risk characterization approach to assess the risks of soil-associated metals. Various monitoring datasets were used as input parameters: soil metal concentrations in England and Wales, bird spatial distribution; bird diet, bioaccumulation and toxicity data were extracted from the literature. Our model highlights significant differences in toxicity risks from Cd, Cu, Pb and Zn across the UK distributions of different species; Pb and Zn posed risks to all species across most of species' distributions, with more localised risks to some species of conservation concern from Cd and Cu. No single taxa of invertebrate prey drove avian exposure to metal toxicity. Adults were found to be at higher risk from Pb and Zn toxicity across their distributions than nestlings. This risk was partially driven by diet, with age differences in diets identified. Our spatially explicit model allowed us to identify areas of each species' national distribution in which the population was at risk. Overall, we determined that for all species studied an average of $32.7 \pm 0.2\%$, $8.0 \pm 0.1\%$, $86.1 \pm 0.1\%$ and $93.2 \pm 0.1\%$ of the songbird spatial distributions in the UK were characterized at risk of Cd, Cu, Pb and Zn, respectively. Despite some limitations, our spatially explicit model helps in understanding the risks of metals to wildlife and provides an efficient method of prioritising areas, contaminants and species for environmental risk assessments. The model could be further evaluated using a targeted

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monitoring dataset of metal concentration in bird tissues. Our model can assess and communicate to stakeholders the potential risks of environmental contaminants to wildlife species at a national and potentially international scale.

1. Introduction

Wildlife species, such as birds, are considered to be good indicators of ecosystem health because they live in a wide range of habitats and generally occupy a high trophic level (DEFRA, 2010). Direct monitoring of local bird populations around point sources of metal pollution can be successful in identifying the adverse effects of metal exposure (Eeva et al., 2009a; Llacuna et al., 1995; Swaileh and Sansur, 2006). For example, several studies have demonstrated adverse effects of trace metal contamination on breeding success of passerine birds in the vicinity of metal smelting sites (Belskii et al., 1995; Belskii et al., 2005; Eeva and Lehikoinen, 1996; Janssens et al., 2003a). Such localised studies, however, yield no indication of the potential risks to birds of differing concentrations of trace metals found across species' ranges. Notably, most studies lack a spatial dimension and thus variations of exposure risks over an entire range remain poorly understood (but see Hernout et al., 2015; Hernout et al., 2013; Hunsaker et al., 1990). Moreover, monitoring studies are time and cost consuming and only provide an assessment of a limited number of species and regions. In contrast, modelling exercises can utilise existing monitoring data, and can relatively quickly and cheaply provide predictions about risk (Hernout et al., 2011; Hernout et al., 2013; Schmolke et al., 2010; Smart et al., 2006). Indeed, they are strongly encouraged in environmental risk assessment (ERA) (Schmolke et al., 2010; Smart et al., 2006; Suter, 2006). Spatially explicit models can also extend the predictive scope and the geographic scale of experiment investigations, as well as integrate relevant ecological parameters of food chain models in ERA.

Trace metals are present naturally in the environment and their concentrations in soils vary spatially according to local geology (Fairbrother et al., 2007). In addition, human activity can increase the deposition rate of trace metals to the soil. The main anthropogenic sources of trace metals in the environment are point sources, such as mines, chemical factories, smelters and landfill sites (EA, 2009). Trace metal contamination in soil can last long after emissions from initial point sources cease, and therefore, they remain bioavailable to living organisms and can accumulate through the food chain (EA, 2009). The main exposure route of trace metal elements in higher trophic level organisms, including birds, is ingestion (Dauwe et al., 2005).

Birds have high energetic requirements (Klasing, 2000), so they need to consume large quantities of food compared to their body mass. Insectivorous birds are thought to have more exposure to metals than granivorous birds due to their higher trophic levels and the potential accumulation in invertebrate species (Dauwe et al., 2004; Fritsch et al., 2012; Swaileh and Sansur, 2006; Zhuang et al., 2009), especially invertebrates known as ‘hyper-accumulators’, such as Lumbricidae (Qiu et al., 2014). Although several monitoring studies have presented actual metal residues for a few terrestrial songbird species (Cooper et al., 2017), the exposure to and risks posed by metals to a wide range of species are still poorly understood (Godwin et al., 2016).

For passerine birds, data on the effects of metals are limited when compared with small mammals. Non-essential metals' effects on birds include and are not-limited to: for Cd, anaemia, intestinal damage, impaired digestion, kidney damage, changes to bone mineralization, diseases and oxidative and histopathological damage, reduced reproductive success and endocrine disruption (Wayland and Scheuhammer, 2011); for Pb, anaemia, renal and haematological toxicity, possible brain damage, weight loss, immunosuppression, lesions of tissues, lethargy, ataxia, neurological effects, reduced reproductive success, and possibly death (Franson and Pain, 2011). Thus, multiple fitness-related traits can be affected by Pb and Cd, but not all studies report such effects in birds living in contaminated areas (Eeva et al., 2014; Rainio et al., 2015; Ruuskanen et al., 2015). In addition, since oxidative stress can affect the fitness of bird population (growth, survival, and reproduction), metal-related oxidative stress could affect populations of free-living birds (Koivula and Eeva, 2010). Cu and Zn, in contrast, are essential elements to all vertebrates, and are under homeostatic control. At normal physiological concentrations, Cu binds to the blood protein ceruloplasmin but excess Cu is carried ‘free’ in the blood and causes oxidative stress and intracellular oxidative damage by increasing ROS formation (Brewer, 2010); (Berglund et al., 2007). Chronic Zn toxicity is not well studied in wild or captive birds (Beyer, 2006), with just a few studies on waterfowl (Taggart et al., 2006), which can be exposed from acid mine drainage (Gasaway and Buss, 1972). Zn toxic effects can decrease the pancreas and the body mass (Koivula and Eeva, 2010). As flying vertebrates that require high levels of motor-control and muscular activity, the physiological effects of exposure to metals may be critical to birds. Indeed, flight performance is known to be a sensitive indicator of environmental perturbations, such as a poor quality diet (Larcombe et al., 2008).

Sex and age can alter both the exposure to and consequences of metal residues. In wild and captive birds, females have been shown to be more sensitive (Eeva et al., 2009b) and/or simply accumulate metals at varying rates in different organs than males (Taggart et al., 2006) but see (Cooper et al., 2017). Juveniles are known to be more sensitive to damage due to Pb and other pollutants than adults, for example due to their immature digestion, and especially underdeveloped blood–brain barrier (Scheuhammer, 1987). Pb poisoning effects, including chick deformities and reductions in fertility, are well documented in waterfowl as they are often exposed to lead shots (Fisher et al., 2006). Nestlings also seem to be more exposed to Pb than adult birds through the diet and because they are unable to escape polluted sites (e.g. (Grue and Franson, 1986).

To investigate the potential risks of soil-associated metals to a large range of songbird species at a national scale, we applied a previously developed modelling framework to 30 insectivorous songbird species (strictly speaking passerines that include invertebrates in their diet but we use ‘insectivorous’ for brevity) breeding in England and Wales. This modelling framework was initially developed to assess the risks of metal to bats and uses a risk characterization approach (Hernout et al., 2013). The model has been evaluated for insectivorous bats against monitoring data which showed that the model provides satisfactory predictions (Hernout et al., 2015; Hernout et al., 2013). Of our focal species, several are on the British Trust for Ornithology's (BTO) red or amber lists of high conservation concern in the UK (Eaton et al., 2009). To improve our knowledge on the potential risks of metal exposure to insectivorous passerine birds, our aims were to parameterize and apply a modelling framework to insectivorous passerine birds in order to: 1) identify which species are the most exposed to metals and which diet items and metals drive exposure risk; 2) investigate age-related effects on exposure risks and 3) map spatial variation in toxicity risk from individual metals at a national level to identify areas for further investigation.