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Interspecies variation in the risks of metals to bats

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ABSTRACT

A modeling framework was used to assess the risk of four metals to UK bat species. Eight species of bats were predicted to be "at risk" from one or more of the metals in over 5% of their ranges. Species differed significantly in their predicted risk. Contamination by Pb was found to pose the greatest risk, followed by Cu, Cd and Zn. A sensitivity analysis identified the proportion of invertebrates ingested as most important in determining the risk. We then compared the model predictions with a large dataset of metals concentrations in the tissues (liver, kidney) of *Pipistrellus sp*. from across England and Wales. Bats found in areas predicted to be the most "at risk" contained higher metal concentrations in their tissues than those found in areas predicted "not at risk" by the model. Our spatially explicit modeling framework provides a useful tool for further environmental risk assessment studies for wildlife species.

1. Introduction

Declines in many bat populations (e.g. *Pipistrellus pipistrellus*, *Rhinolophus hipposideros*, *Rhinolophus ferrumequinum* and *Myotis myotis*) have been observed across Europe (Jones et al., 2009; Dietz et al., 2009). Population declines can be the result of a number of factors including: environmental and climate change, changes in resources e.g. water, prey availability and quality, roost loss, disturbance, urbanization and industrialization, agricultural intensification, the increase in wind turbines, the pressure of disease and also exposure to chemicals in the environment (Frick et al., 2010; Jones et al., 2009; Walker et al., 2007; Wickramasinghe et al., 2003). Bats are long-lived mammals and consume a large amount of prey each night during their foraging period, and are thought to be particularly exposed to chemicals (Clark and Shore, 2001). Exposure to environmental contaminants, such as metals, may be considered as additional stressors to bats, although very few studies have considered the effects of metals on bat species (Clark and Shore, 2001).

Environmental contamination by metal compounds has been widespread across Europe since the industrial revolution. In England and Wales, more than 80% of contaminated land sites have been reported to be contaminated by metals and metalloids (Environment Agency, 2009). In addition, as metals do not degrade, they are highly likely to accumulate in mammalian body tissues, especially for top predators and long-lived species such as bats (Dietz et al., 2009). Metals can elicit a range of toxic effects on wildlife, including induction of tremors, spasms, lethargy, lack of control in body movement, as well as sublethal effects at the biochemical, physiological and histological levels (e.g., oxidative stress, DNA damage, tissue damage including inclusion bodies), and, in some cases, can cause mortality (Clark and Shore, 2001; Hoffman et al., 2001; Hurley and Fenton, 1980; Sánchez-Chardi et al., 2009). As flying mammals depend upon exceptional levels of motor-control and muscular activity, bats may show particular vulnerability to the physiological effects of exposure to metals.

To explore the potential risks of chemical exposure to bats, we previously developed and applied a spatial modeling framework using a risk characterization approach, to assess the risks from soil-associated metals (cadmium, copper, lead and zinc) to the health of population of *P. pipistrellus* in England and Wales (Hernout et al., 2013). However, in our previous study, we only looked at one bat

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species and the modeling framework was not evaluated against monitoring data.

The exposure of different bat species to metals is likely to vary due to differences in factors such as their food intake, dietary composition and distribution. For example, bats specializing in consuming prey with a high metal accumulation capacity, which have a high food intake and a spatial range restricted to polluted areas, might be expected to have higher exposure than others. Studies monitoring metal residues in bats show that renal metal concentrations differ across bat species, which may reflect differences in dietary exposure (Walker et al., 2007). As observed for passerine birds, interspecific differences in metal exposure may be linked with their diet (Berglund et al., 2011). For example, it was shown that the pied flycatcher (*Ficedula hypoleuca*) accumulated more metals than great tits (*Parus major*) as the diet composition of pied flycatchers is composed of a large proportion of insects from higher trophic levels than the great tits (Berglund et al., 2011).

When using modeling frameworks of the type described by Hernout et al. (2013), it is also important to understand the sensitivity of a framework to changes in model input parameters. This knowledge can be invaluable in informing the parameterisation process and guiding the model development. Sensitivity analyses are strongly recommended for use in Environmental risk assessment (ERA) (Schmolke et al., 2010), and emphasized by many institutions (e.g. EFSA Journal, 2009; Health Canada Contaminated Sites Division, 2005). However, the literature remains scarce. The analyses consist in examining how outputs vary as inputs are varied, to understand how the risk predictions are dependent on the variability and the uncertainty of the factors contributing to the risk (Grimm and Railsback, 2005; Risk assessment guidance for superfund, 2001). Complex approaches, as we have used, involve mathematical and statistical techniques and can include the effect of the combination of several factors having different statistical distributions (Risk Assessment Guidance for Superfund, 2001). Sensitivity analyses have been used previously in ecological modeling exercises such as an agent-based model, simulating skylark (*Alauda arvensis*) population response to landscape change (Parry et al., 2013). The most important parameters were identified for the model parameterization process or subsequent empirical studies. Model evaluation is also strongly recommended in modeling practise, although relatively scarce (Schmolke et al., 2010).

In this study, to improve our knowledge of the potential threat of metal contamination to bats, we: (1) used the modeling framework which is based on a basic risk characterization approach (Hernout et al., 2013) to explore the risks of metal exposure for 14 bat species and identify the species most at risk from exposure to four metals; (2) used the modeling framework to determine the most important parameters affecting the predicted exposure, which are the main drivers in exposure risk, and to understand why certain species may be more vulnerable to metal exposure than others, and finally (3) compared levels of metals in different tissues (liver and kidney) of *Pipistrellus sp*. from across England and Wales (internal exposure) with our model predictions (based on oral exposure estimations) to evaluate our model.

2. Methods

2.1. Risk of UK bat species to metal exposure

The modeling framework method described by Hernout et al. (2013) was applied to estimate the risks of four metals to 14 bat species present in the UK, namely: *Barbastella barbastellus*, *Eptesicus serotinus*, *Myotis bechsteinii*, *Myotis daubentonii*, *Myotis mystacinus*, *Myotis nattereri*, *Nyctalus leisleri*, *Nyctalus noctula*, *Pipistrellus sp*. (*P. pipistrellus* and *Pipistrellus pygmaeus*), *Pipistrellus nathusii*, *Plecotus auritus*, *Pl. austriacus*, *Rhinolophus ferrumequinum*, *R. hipposideros*. The model used a risk characterization approach where the daily oral dose is compared with a ‘safe’ dose value to derive a ratio. The comparison of the ratio with a trigger value (of 1) indicates whether the risk is acceptable or not (using a resolution of 5×5 km^2 cell) (Hernout et al., 2013).

The modeling framework requires information on concentrations of metals in soils, soil-insect accumulation factors, bat diet, bat distribution and toxicity data on the metal studied. Concentrations of Cd, Cu, Pb and Zn in soil in England and Wales were obtained from NSRI (National Soil Resources Institute) at a 5×5 km^2 resolution. Ecological data on bats (bat diet composition, foraging distance and weight) were gathered from the literature (Table S1, Table S2). Daily food intakes and no observed effect levels (NOAELs) were estimated based on the average bat weight for each species and were derived using the allometric relationships described in Nagy, 1987 and Sample et al., 1996, respectively (Table S2) (Hernout et al., 2013). The experimental studies used to derive the NOAELs considered a reproductive endpoint and chronic effects (Sample et al., 1996). Further details on the experimental studies are presented in Table S3. The NOAEL was divided by an uncertainty factor of five to calculate the “safe dose” (Hernout et al., 2013). Biota accumulation factor (BAF) data were obtained from the literature for each of the invertebrate orders listed in the bat diet for the four metals studied (Table S4). The bat distribution dataset (presence/absence data) was provided by the Bat Conservation Trust for each bat species (Data derived from the National Bat Monitoring Programme; NBMP). The spatial analysis was done using Geographic Information System (ArcGIS, ArcMap Version 9.3.1) (ESRI, Redlands Calif., USA).

The final output was a risk characterization ratio (RCR) for each 5×5 km^2 cell defined by the ratio between the daily dose of metal that a bat receives (mg/g body weight/d) and predicted safe daily dose for the metal (mg/g body weight/d), within the spatial distribution of the bat (Hernout et al., 2013). The percentage of areas at risk for each species and metal, as well as for the groups of metals combined were derived from the number of cells where a species was found to be at risk (i.e. with an RCR$\geq$1) divided by the total number of cells in which the bat species is present (Hernout et al., 2013).

2.2. Identification of key drivers of risk

A number of analyses were performed to identify the key factors that drive the risk of metals to bats as determined in the model. Distributions of selected model input parameters (Table 1) covering all species were used alongside the model to identify which of these were the most important in determining the risk values calculated. The Emulator GEM-SA 1.1 (Gaussian Emulation Machine for Sensitivity Analysis, Kennedy, 2005) was used to determine the effect of each individual input, or pairs of inputs on the output value. Further details on the emulation process are given is Text S2 (Supplemental data). The different input parameters and their respective ranges are shown in Table 1.

The sensitivity analyses cannot integrate spatial components and therefore we did not include the spatial range in which the bat species reside. As each bat distribution is unique, the ranges of metal concentrations in soils will also vary for each bat species (Figure S1). Thus, the sensitivity analyses used a simplified generic distribution to represent all bats, representing the whole of England and Wales based on the totality of soil metal concentrations available for this area (see overall UK map soil concentrations in Hernout et al., 2013).

The differences of RCRs across metals and bat species were tested using the non-parametric Kruskal–Wallis test. To explore