



# The transfer of $^{137}\text{Cs}$ , Pu isotopes and $^{90}\text{Sr}$ to bird, bat and ground-dwelling small mammal species within the Chernobyl exclusion zone



N.A. Beresford <sup>a, c, \*</sup>, S. Gaschak <sup>b</sup>, Andrey Maksimenko <sup>b</sup>, M.D. Wood <sup>c</sup>

<sup>a</sup> Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster LA1 4AP, UK

<sup>b</sup> Chernobyl Centre for Nuclear Safety, Radioactive Waste & Radioecology, International Radioecology Laboratory, 77th Gvardiiska Dyviiya str.11, P.O. Box 151, 07100 Slavutych, Kiev Region, Ukraine

<sup>c</sup> School of Environment & Life Sciences, University of Salford, Salford, M5 4WT, UK

## ARTICLE INFO

### Article history:

Received 17 October 2015

Received in revised form

29 December 2015

Accepted 30 December 2015

Available online xxx

### Keywords:

Plutonium

Strontium

Caesium

Chiroptera

Concentration ratio

## ABSTRACT

Protected species are the focus of many radiological environmental assessments. However, the lack of radioecological data for many protected species presents a significant international challenge. Furthermore, there are legislative restrictions on destructive sampling of protected species to obtain such data. Where data are not available, extrapolations are often made from ‘similar’ species but there has been little attempt to validate this approach.

In this paper we present what, to our knowledge, is the first study purposefully designed to test the hypothesis that radioecological data for unprotected species can be used to estimate conservative radioecological parameters for protected species; conservatism being necessary to ensure that there is no significant impact.

The study was conducted in the Chernobyl Exclusion Zone. Consequently, we are able to present data for Pu isotopes in terrestrial wildlife. There has been limited research on Pu transfer to terrestrial wildlife which contrasts with the need to assess radiation exposure of wildlife to Pu isotopes around many nuclear facilities internationally.

Our results provide overall support for the hypothesis that data for unprotected species can be used to adequately assess the impacts for ionising radiation on protected species. This is demonstrated for a range of mammalian and avian species. However, we identify one case, the shrew, for which data from other ground-dwelling small mammals would not lead to an appropriately conservative assessment of radiation impact. This indicates the need to further test our hypothesis across a range of species and ecosystems, and/or ensure adequate conservatism within assessments.

The data presented are of value to those trying to more accurately estimate the radiation dose to wildlife in the Chernobyl Exclusion Zone, helping to reduce the considerable uncertainty in studies reporting dose-effect relationships for wildlife.

A video abstract for this paper is available from: <http://bit.ly/1JesKPC>.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

A necessary component of the tools (e.g. Brown et al., 2008; Coppleson et al., 2001, 2003; USDoE, 2002) now established to estimate the exposure of wildlife to ionising radiations is an ability to predict wholebody activity concentrations of radionuclides in a wide range of biota. Although there are alternative approaches to

predict transfer to wildlife in development, such as the use of taxonomic relationships (e.g. Beresford et al., 2013, 2015), most of the available tools use concentration ratios ( $\text{CR}_{\text{wo-media}}$ ) relating the activity concentrations in plants and animals to those in the appropriate environmental media (soil, air or water) (Beresford et al., 2008a). Whilst databases of  $\text{CR}_{\text{wo-media}}$  values for wild species have been collated (e.g. Beresford et al., 2008b; Coppleson et al., 2013; Hosseini et al., 2008; Howard et al., 2013; Yankovich et al., 2013), data for many radionuclide-organism combinations are sparse or not available. Where data are unavailable, assumptions such as applying data for a ‘similar organism’ (e.g. mammal data for birds) are often made to provide default  $\text{CR}_{\text{wo-media}}$  values

\* Corresponding author. Centre for Ecology & Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster LA1 4AP, UK.

E-mail address: [nab@ceh.ac.uk](mailto:nab@ceh.ac.uk) (N.A. Beresford).

for use in dose assessment tools (Beresford et al., 2008b; Brown et al., 2013).

Protected species are the focus of many assessments (e.g. Copplesstone et al., 2005; Wood et al., 2008). For many protected species, transfer data are lacking and there are legislative restrictions on destructive sampling to obtain data (Wood et al., 2011). For some protected species, there are very few data for the overall taxonomic group appropriate to that species. A good example of this is chiroptera (bats), all species of which are protected in the European Union (HMSO, 1994). For some radionuclides there are many  $CR_{wo-soil}$  data for other animals within the class mammalia and the extent to which these data are applicable to bats needs to be established. Similarly, at many ecologically important sites requiring assessment (e.g. Natura 2000 sites), the most prevalent protected organisms are aves (bird) species (Copplesstone et al., 2003). However, there are very few  $CR_{wo-media}$  values for birds (e.g. ICRP, 2009).

Previously, we have published data on the transfer of  $^{137}Cs$  and  $^{90}Sr$  to a range of bat species sampled from a variety of sites within the Chernobyl Exclusion Zone (CEZ) (Gaschak et al., 2010). The CEZ, which is the area established around the Chernobyl nuclear complex following the 1986 accident, is increasingly viewed as a natural laboratory, and more recently as a radioecological observatory (<https://wiki.ceh.ac.uk/x/NoFsD>). It provides an opportunity to study the transfer of radionuclides to different species of wildlife across different taxonomic groups (e.g. Beresford et al., 2005). In this paper we present a study where species of birds, bats and ground-dwelling small mammals were sampled from a site within the CEZ and analysed for  $^{137}Cs$ , Pu isotopes and  $^{90}Sr$ . To our knowledge, this is the first study purposefully designed to test the hypothesis that radioecological modelling parameters derived from the sampling and analysis of unprotected species (i.e. ground-dwelling small mammals) result in a conservative dose assessment for protected species inhabiting the same site. The paper also makes an important contribution to the available database of Pu isotope data for terrestrial wildlife, few studies having been published previously (e.g. Johansen et al., 2014, 2015).

## 2. Materials and methods

### 2.1. Study sites

In Beresford et al. (2008c) we report a study to determine the

exposure of small mammal species at three forest sites within the CEZ conducted during the summer of 2005. The sites were initially selected to have a range in radionuclide activity concentrations; animal samples from each site were collected within a  $100 \times 100$  m area. In the present study, samples have been collected from one of these sites (termed the 'Medium site' in Beresford et al., 2008c).

The Medium site was approximately 8 km to the west of the Chernobyl power plant complex. The woodland at the Medium site consisted mainly of *Pinus sylvestris* (Scots pine) and *Quercus robur* (Oak), with some *Sorbus aucuparia* (Rowan) and *Tilia platyphyllos* (Large leaved lime). The sparse understorey vegetation included *Pteridium aquilinum* (Bracken). The site had soddy pseudopodzolic sandy and boggy soils on modern alluvial deposits.

Beresford et al. (2008c) describes the collection and analyses of soils ( $n = 23$ ) from the Medium site; soils were collected from an area extended to 50 m beyond the animal sampling area to encompass the likely home ranges of the animal species being trapped (i.e. soils were collected from an area of  $200 \text{ m} \times 200 \text{ m}$  or  $40000 \text{ m}^2$ ). Soil activity concentrations were reported in Beresford et al. (2008c) as:  $43.3 \pm 25.7$ ,  $0.83 \pm 1.49$ ,  $18.6 \pm 14.9 \text{ kBq kg}^{-1}$  dry mass for  $^{137}Cs$ ,  $^{238,239,240}Pu$  and  $^{90}Sr$  respectively. Whilst variable, there was no spatial pattern in soil activity concentrations across the sampling site.

### 2.2. Biota samples

#### 2.2.1. Bird samples

A range of passerine species were collected by mist net at the Medium site during June 2005, euthanised and retained frozen. Species, sample numbers and information on feeding and home range are presented in Table 1.

#### 2.2.2. Bat samples

Three species of bats were collected from the site during the period May–June 2008 using mist nets (Table 1). After being euthanised the samples were stored frozen whilst awaiting analyses.

#### 2.2.3. Ground-dwelling small mammals

In Beresford et al., 2008c, live-monitoring (see approach of Bondarkov et al. (2011) outlined below) results for  $^{90}Sr$  and  $^{137}Cs$  in *Apodemus flavicollis*, *Myodes glareolus* and *Microtus* spp. are

**Table 1**  
Species samples at the study site in the Chernobyl Exclusion Zone.

Species	n	Approximate home range (m <sup>2</sup> )	Diet
<b>Birds</b>			
<i>Erithacus rubecula</i>	7	6000 m <sup>2</sup>	Ground & flying invertebrates, some fruit
<i>Ficedula albicollis</i>	1	6000 m <sup>2</sup>	Flying & ground invertebrates
<i>Ficedula hypoleuca</i>	3	<3000 m <sup>2</sup>	Flying & ground invertebrates, some fruit
<i>Fringilla coelebs</i>	4	7000 m <sup>2</sup>	Seeds, insects (especially caterpillars)
<i>Parus major</i>	2	<20000 m <sup>2</sup>	Insects (especially caterpillars)
<i>Sylvia atricapilla</i>	2	11000 m <sup>2</sup>	Flying & ground invertebrates
<i>Turdus merula</i>	2	Minimum 2000 m <sup>2</sup>	Ground invertebrates, some fruit
<b>Bats</b>			
<i>Nyctalus leisleri</i>	4	Travel up to 13 km from roosts to foraging sites	Flying insects
<i>Pipistrellus pipistrellus</i>	3	May travel up to 5.1 km from roosts	Flying insects
<i>Plecotus auritus</i>	3	Forage close to the roost (usually within 1.5 km)	Flying insects
<b>Ground-dwelling small mammals</b>			
<i>Myodes glareolus</i>	14	400 – 700 m <sup>2</sup>	Plants (including seeds & fruit), some ground invertebrates
<i>Sorex araneus</i>	4	370 – 630 m <sup>2</sup>	Ground invertebrates, carrion
<i>Sylviaemus flavicollis</i>	4	5000 m <sup>2</sup>	Plants (including seeds & fruit), fungi, ground insects

Data sources: Arnold (2004); Holden and Cleaves (2014); Lindblom (2008); Voyinstvensky (1960); [http://www.jstor.org/stable/1934734?seq=6#page\\_scan\\_tab\\_contents](http://www.jstor.org/stable/1934734?seq=6#page_scan_tab_contents); <http://www.snh.gov.uk/docs/C208532.pdf>; [http://en.wikipedia.org/wiki/Common\\_shrew](http://en.wikipedia.org/wiki/Common_shrew); <http://www.mammal.org.uk/species-factsheets/Yellow-necked%20mouse>

**Table 2**

Activity concentrations (kBq kg<sup>-1</sup> fresh mass) in specific bird, bat and ground-dwelling small mammals sampled at a site within the Chernobyl Exclusion Zone. Geometric mean values are presented with the geometric standard deviation given in brackets.

Species	n	<sup>137</sup> Cs	<sup>238,239,240</sup> Pu	<sup>90</sup> Sr
<b>Birds</b>				
<i>Erithacus rubecula</i>	7	3.1E + 3 (3.6)	1.6E-1 (3.4)	2.3E + 3 (3.9)
<i>Ficedula albicollis</i>	1	1.2E + 4	5.8E-2	3.4E + 3
<i>Ficedula hypoleuca</i>	3	1.8E + 3 (2.2)	6.1E-2 (1.4)	1.7E + 3 (2.1)
<i>Fringilla coelebs</i>	4	1.8E + 3 (1.5)	6.4E-2 (2.2)	7.0E + 3 (1.9)
<i>Parus major</i>	2	4.2E + 3 (1.3)	4.4E-2 (2.1)	2.8E + 3 (1.1)
<i>Sylvia atricapilla</i>	2	1.6E + 3 (1.1)	8.2E-2 (2.7)	5.1E + 3 (3.5)
<i>Turdus merula</i>	2	3.8E + 3 (1.1)	6.2E-2 (1.4)	2.9E + 3 (1.0)
<b>Bats</b>				
<i>Nyctalus leisleri</i>	4	1.1E + 3 (1.1)	4.8E-2 (1.8)	3.9E + 3 (2.4)
<i>Pipistrellus pipistrellus</i>	3	2.4E + 2 (1.4)	9.8E-2 (1.3)	1.2E + 4 (2.5)
<i>Plecotus auritus</i>	3	2.6E + 3 (2.9)	7.6E-2 (2.4)	1.2E + 4 (2.1)
<b>Ground-dwelling small mammals</b>				
<i>Myodes glareolus</i>	14	3.4E + 4 (2.4)	2.1E-1 (1.7)	3.7E + 4 (2.0)
<i>Sorex araneus</i>	4	2.4E + 4 (1.4)	3.4 (3.3)	1.6E + 4 (2.3)
<i>Sylvaemus flavicollis</i>	4	8.3E + 4 (3.2)	1.5E-1 (1.1)	5.8E + 4 (2.3)

reported. Some carcasses of *A. flavicollis*, *M. glareolus* and also *Sorex araneus* (Table 1), collected in Sherman humane traps (baited with cereals) during this study, were retained and stored frozen. Some of these have been analysed for the purposes of the present paper.

### 2.3. Analyses

Prior to analysis, samples were defrosted and prepared as follows: bird carcasses were plucked and had the gastrointestinal tract (GIT) removed; bat samples had the GIT removed; and ground-dwelling small mammals had the pelt and GIT removed. All prepared samples were then weighed and washed before

$$CR_{wo-soil} = \frac{\text{whole - organism activity concentration (Bq kg}^{-1} \text{ fresh mass)}}{\text{soil activity concentration (Bq kg}^{-1} \text{ dry mass)}}$$

analyses.

The wholebody <sup>137</sup>Cs and <sup>90</sup>Sr concentrations were determined using the method described by Bondarkov et al. (2011). Prior to counting, the carcasses were placed in a small, disposable, cardboard box (70 × 40 × 40 mm), the upper side of which was made from <0.1 mm thick polyethylene. The box was then placed inside a lead shielded counting container. The detectors comprised a hyper-pure germanium detector and thin-film (1 mm) NaI scintillation detector to measure <sup>137</sup>Cs and <sup>90</sup>Sr, respectively. The <sup>137</sup>Cs spectra were analysed using the Canberra Genie-2000 software package. The activity concentration of <sup>90</sup>Sr was determined from

**Table 3**

Activity concentrations (kBq kg<sup>-1</sup> fresh mass) in birds, bats and ground-dwelling small mammals sampled at a site within the Chernobyl Exclusion Zone. Geometric mean values are presented with the geometric standard deviation given in brackets. For each radioisotope, significant differences between geometric means are indicated by letters; geometric means with different letters are significantly different.

Group	n	<sup>137</sup> Cs	<sup>238,239,240</sup> Pu	<sup>90</sup> Sr
Bat	10	9.1E + 2 (3.0) <sup>a</sup>	6.8E-2 (1.9) <sup>a</sup>	7.6E + 3 (2.6) <sup>b</sup>
Bird	21	2.7E + 3 (2.5) <sup>b</sup>	8.4E-2 (2.5) <sup>a</sup>	3.1E + 3 (2.7) <sup>a</sup>
Ground-dwelling small mammals	22	3.8E + 4 (2.5) <sup>c</sup>	3.3E-1 (3.8) <sup>b</sup>	3.5E + 4 (2.3) <sup>c</sup>

that of its daughter nuclide, <sup>90</sup>Y. The method has previously been calibrated against phantoms containing <sup>137</sup>Cs and <sup>90</sup>Sr; the methodology has been validated against traditional radiochemical extraction and analysis methodologies. Counting times varied from 150 to 1200 s depending upon the radioactivity in the animal. Counting errors were typically <3% for <sup>90</sup>Sr and <7% for <sup>137</sup>Cs.

To determine Pu isotopes, samples were initially dissolved in 65% HNO<sub>3</sub> and <sup>242</sup>Pu was added as a yield tracer. Following anion exchange separation (Bio Rad AG 1 × 8, 100–200 mesh) and coprecipitation, the samples were counted using a planar ion implanted silicon detector. Counting errors were typically <20% for the Pu isotopes.

### 3. Results

Radionuclide activity concentrations summarised by species are presented in Table 2. Given the limited sample numbers of some species we have not attempted any statistical comparison at the species level, focussing instead on group-level comparisons ('bird', 'bat' and 'ground dwelling small mammal') (Table 3). Recognising that radionuclide activity concentration data for wildlife generally follow a lognormal distribution (Wood et al., 2013), the data were log-transformed prior to analysis. The ground-dwelling small mammals had significantly higher activity concentrations of all three radionuclides compared to the other two groups (Generalised Linear Model; p < 0.05). Differences between birds and bats were not consistent between radioisotopes, with <sup>137</sup>Cs activity concentrations being higher in birds and <sup>90</sup>Sr concentrations higher in bats. The <sup>137</sup>Cs:<sup>90</sup>Sr activity concentration ratio in bats was significantly lower than that for both the other groups by a factor of c. 6.

The transfer of radionuclides to wildlife is most commonly described by the whole-organism concentration ratio (CR<sub>wo-soil</sub>) (IAEA, 2014; Beresford et al., 2008a), where for terrestrial animals:

As only a total <sup>238,239,240</sup>Pu activity concentration in soil was available, we calculated Pu CR<sub>wo-soil</sub> values by combining the <sup>238</sup>Pu and <sup>239,240</sup>Pu values for each animal. Concentration ratios are presented by species in Table 4 and by group in Table 5. Significant differences in CR<sub>wo-soil</sub> between the groups (Table 5) were the same as for activity concentrations (Table 3). For all groups the highest CR<sub>wo-soil</sub> values were for <sup>90</sup>Sr which were approximately double those determined for <sup>137</sup>Cs (p < 0.001; paired t-test); the Pu CR<sub>wo-soil</sub> values were two to three orders of magnitude lower than the <sup>137</sup>Cs CR<sub>wo-soil</sub> values (p < 0.001; paired t-test).

**Table 4**  
Concentration Ratios (CR<sub>wo-soil</sub>) for bird, bat and ground-dwelling small mammals sampled at a site within the Chernobyl Exclusion Zone. Geometric mean values are presented with the geometric standard deviation given in brackets.

Species	n	<sup>137</sup> Cs	<sup>238,239,240</sup> Pu	<sup>90</sup> Sr
<b>Birds</b>				
<i>Erithacus rubecula</i>	7	7.2E-2 (3.6)	1.9E-4 (3.4)	1.2E-1 (3.9)
<i>Ficedula albicollis</i>	1	2.7E-1	7.0E-5	1.9E-1
<i>Ficedula hypoleuca</i>	3	4.0E-2 (2.2)	7.3E-5 (1.4)	9.1E-2 (2.1)
<i>Fringilla coelebs</i>	4	4.2E-2 (1.5)	7.8E-5 (2.2)	3.8E-1 (1.9)
<i>Parus major</i>	2	9.6E-2 (1.3)	5.4E-5 (2.1)	1.5E-1 (1.1)
<i>Sylvia atricapilla</i>	2	3.7E-2 (1.1)	9.9E-5 (2.7)	2.7E-1 (3.5)
<i>Turdus merula</i>	2	8.8E-2 (1.1)	7.5E-5 (1.4)	1.6E-1 (1.0)
<b>Bats</b>				
<i>Nyctalus leisleri</i>	4	2.6E-2 (1.1)	5.8E-5 (2.2)	2.1E-1 (2.4)
<i>Pipistrellus pipistrellus</i>	3	5.6E-3 (1.4)	1.2E-4 (1.3)	6.5E-1 (2.5)
<i>Plecotus auritus</i>	3	6.0E-2 (2.9)	9.2E-5 (2.4)	6.3E-1 (2.1)
<b>Ground-dwelling small mammals</b>				
<i>Myodes glareolus</i>	14	7.8E-1 (2.4)	2.5E-4 (1.7)	2.1 (2.0)
<i>Sorex araneus</i>	4	5.6E-1 (1.4)	4.1E-3 (3.3)	8.8E-1 (2.3)
<i>Sylvaemus flavicollis</i>	4	1.9 (3.2)	1.8E-4 (2.2)	3.1 (2.3)

#### 4. Discussion

It is likely that diet contributes to the higher activity concentrations, for all radioisotopes, observed in the ground-dwelling small mammals compared to the birds and bats (Table 2). The diet of all of these ground-dwelling small mammals includes ground living invertebrates. Previous studies have suggested that flying insects (which comprise the diet of study bat species and are an important component of the diet of most of the bird species sampled) generally have lower radionuclide activity concentrations than ground-dwelling invertebrate species collected from the same site (Wood et al., 2009; Barnett et al., 2014). Ground-dwelling invertebrates may contain soil in their digestive tract or be externally contaminated by soil. There is also more potential for the ground-dwelling small mammals to inadvertently ingest contaminated soil.

The CR<sub>wo-soil</sub> for Pu to shrews is 1–2 orders of magnitude higher than those for the other species studied in this paper (Table 4). A similar observation has been made for a number of toxic metals that have been shown to accumulate to higher levels in shrews than in other small mammals (Shore and Rattner, 2001; Tomášková et al., 2005). The high metabolic rate and diet of shrews have been suggested to be the reason for this (Hegstrom and West, 1989; Świergosz-Kowalewska et al., 2005).

Although protected bat species are often the target of assessment (Coppstone et al., 2003), there are very few available data on the transfer of radionuclides to this group of mammals. The only other data that we are aware of are those reported by Gaschak et al. (2010) for bats sampled during 2007–2009 from different areas of the CEZ. Gaschak et al. present transfer of <sup>137</sup>Cs and <sup>90</sup>Sr relative to the deposition in soil rather than as CR<sub>wo-soil</sub> values. For comparison with our data, Table 6 presents CR<sub>wo-soil</sub> values calculated from the data of Gaschak et al. (2010); these data were extracted from the

**Table 5**  
Concentration Ratios (CR<sub>wo-soil</sub>) for birds, bats and ground-dwelling small mammals sampled at a site within the Chernobyl Exclusion Zone. Geometric mean values are presented with the geometric standard deviation given in brackets. For each radioisotope, significant differences between geometric means are indicated by letters; geometric means with different letters are significantly different.

Group	n	<sup>137</sup> Cs	<sup>238,239,240</sup> Pu	<sup>90</sup> Sr
Bat	10	2.1E-2 (3.0) <sup>a</sup>	8.3E-5 (1.9) <sup>a</sup>	4.1E-1 (2.6) <sup>b</sup>
Bird	21	6.3E-2 (2.5) <sup>b</sup>	1.0E-4 (2.5) <sup>a</sup>	1.7E-1 (2.7) <sup>a</sup>
Ground-dwelling small mammals	22	8.7E-1 (2.5) <sup>c</sup>	4.0E-4 (3.8) <sup>b</sup>	1.9 (2.3) <sup>c</sup>

**Table 6**  
Concentration Ratios (CR<sub>wo-soil</sub>) for bats within the Chernobyl Exclusion Zone, calculated from the data discussed in Gaschak et al. (2010) (data extracted from the database described by Coppstone et al., 2013). Geometric mean values are presented with the geometric standard deviation given in brackets.

Species	n	<sup>137</sup> Cs	n	<sup>90</sup> Sr
<i>Eptesicus serotinus</i>	17	2.6E-01 (4.3)	17	4.4E-01 (3.5)
<i>Myotis dasycneme</i>	—	—	1	1.3E-01
<i>Myotis daubentonii</i>	2	1.0E-02 (4.0)	6	1.7E-01 (1.5)
<i>Nyctalus leisleri</i>	5	5.6E-02 (1.6)	6	6.4E-01 (3.0)
<i>Nyctalus noctula</i>	20	9.5E-02 (2.7)	20	4.4E-01 (3.5)
<i>Pipistrellus kuhlii</i>	6	3.4E-01 (15.2)	8	1.7E-01 (3.6)
<i>Pipistrellus nathusii</i>	51	1.0E-01 (4.4)	64	2.6E-01 (3.4)
<i>Pipistrellus pygmaeus</i>	2	2.3E-01 (4.3)	4	6.8E-01 (8.3)

database described by Coppstone et al., 2013. The CR<sub>wo-soil</sub> values presented in the present paper are within the range of those calculated from the Gaschak et al. paper. The only potential exception is that the *Pipistrellus pipistrellus* CR<sub>wo-soil</sub> value for Cs is lower than the range of values presented in the larger dataset of Gaschak et al.. We should acknowledge that, whilst the size of our sampling area was appropriate for the home range of the birds and small ground dwelling mammals, the bat species generally forage over a larger area (Table 1).

The lower <sup>137</sup>Cs:<sup>90</sup>Sr ratio observed in bats compared to the other animal types implies a comparatively high transfer of Sr compared to Cs in bats. The diet of insectivorous bats is limited in calcium (Adams et al., 2003) a strong Sr analogue. It is therefore, likely that the dietary absorption of calcium, and consequently Sr, is higher in bats than in the other species. However, we acknowledge that the <sup>137</sup>Cs:<sup>90</sup>Sr ratio is not consistent across the CEZ (Kashparov et al., 2003) and the greater home range of the bats compared to the other species may contribute to our observation.

Data from previous studies both within the Chernobyl Exclusion Zone and in other areas support our observation that the transfer of Sr is comparatively high compared to Cs (Barnett et al., 2014; Gaschak et al., 2003, 2008; 2009, 2010; Maklyuk et al., 2007; Sheppard, 1991<sup>1</sup>; Sheppard et al., 2004<sup>1</sup>, 2008<sup>1</sup>; 2010<sup>1</sup> Sheppard and Evenden, 1990<sup>1</sup>). Data presented by Beresford et al. (2008c) for small ground-dwelling mammals sampled from the Chernobyl Exclusion Zone in 2005 suggest that the extent of this difference between Sr and Cs transfer was highest at sites with a generally low level of contamination (<10 kBq kg<sup>-1</sup> dry mass <sup>137</sup>Cs). At the most contaminated site, which was located on the western trace (c.100 kBq kg<sup>-1</sup> dry mass <sup>137</sup>Cs), the results of Beresford et al. (2008c) suggest that the transfer of Cs was higher than that for Sr. Gaschak et al. (2010) suggested that for bats sampled throughout the CEZ there was a decreasing transfer of <sup>90</sup>Sr with increasing deposition. Similar observations have been reported for amphibians, small birds and ungulates (Gaschak et al., 2008, 2009; Gashchak, 2009; Gaichenko et al., 2001). This may be because Sr contamination is predominantly in particulate form at the highest contamination sites. Kashparov et al. (1999) showed that the dissolution rate of Sr from particles to the west of the reactor (where the most contaminated site in Beresford et al. was located) was lower than that from other areas.

The data presented in this paper provide an opportunity to test the hypothesis that sampling unprotected species (represented by two species of the ground-dwelling small mammals, *M. glareolus* and *Sylvaemus flavicollis*) and determining activity concentrations in these will allow a conservative estimate of activity

<sup>1</sup> Data from these papers as supplied to the Wildlife Transfer Database described by Coppstone et al., 2013.

concentrations in protected species to be obtained. Table 2 demonstrates that sampling *M. glareolus* and *S. flavicollis* would give higher activity concentration estimates for  $^{137}\text{Cs}$ ,  $^{238,239,240}\text{Pu}$  and  $^{90}\text{Sr}$  than those measured in bats directly. Therefore, using data for these two small ground-dwelling mammals to make an assessment of dose to bats would result in a conservative estimate. Given that many species of birds are also protected, Table 2 also lends confidence to the use of a similar approach to conservatively assessing doses to birds. However, in the case of *S. araneus*, a protected species of ground-dwelling small mammal in the United Kingdom (HMSO, 1981), sampling the *M. glareolus* and *S. flavicollis* would underestimate activity concentrations and, therefore, dose from Pu isotopes given the higher transfer of Pu to this species as discussed previously.

## 5. Conclusions

The data presented in this paper significantly improves the available information on small bird and bat species and also Pu isotope levels in wildlife from the CEZ. The data provide a valuable addition to available transfer databases and will also facilitate more accurate dose assessments for wildlife in the Chernobyl exclusion zone perhaps aiding the debate on reported effects from the area (e.g. Beresford and Copplestone, 2011; Garnier Laplace et al., 2013).

Bats had a high  $^{90}\text{Sr}$ : $^{137}\text{Cs}$  ratio compared to other species; a diet deficient in calcium may contribute to this observation.

The data support the hypothesis that sampling and analyses of small ground-dwelling mammals would provide a conservative estimate of exposure for birds and bats which are often protected and for which there are comparatively few data.

The  $\text{CR}_{\text{wo-soil}}$  value for Pu transfer to shrews (a protected species in the United Kingdom) was 1–2 orders of magnitude higher than those for the other species. This should be taken into account when conducting assessments if using other small mammals as surrogates for shrews.

## Acknowledgements

We would like to acknowledge the support of the following IRL staff in this work: Mikhail Bondarkov (Director of IRL), Valentin Martynenko, Vasily Maksimenko and Sergey Paskevich. The bat study and the analyses of samples for Pu-isotopes was funded under CEH National Capability funding. Manuscript preparation was facilitated by funding from the EU funded COMET project (S. Gaschak & N.A. Beresford; [www.comet-radioecology.org](http://www.comet-radioecology.org)) and the TREE project (M.D. Wood & N.A. Beresford; [www.keh.ac.uk/TREE](http://www.keh.ac.uk/TREE)) funded by the Natural Environment Research Council, the Environment Agency and Radioactive Waste Management Ltd.. We would also like to thank the University of Salford for funding this paper to be published as open access and Prof. Andy Miah (University of Salford) for producing the accompanying video abstract (<http://bit.ly/1JesKPC>).

## References

Adams, R.A., Pedersen, S.C., Thibault, K.M., Jadin, J., Petru, B., 2003. Calcium as a limiting resource to insectivorous bats: can water holes provide a supplemental mineral resource? *J. Zool. Lond.* 260, 189–194.

Arnold, N., 2004. *A Field Guide to the Reptiles and Amphibians of Britain and Europe*. Collins, London.

Barnett, C.L., Beresford, N.A., Walker, L.A., Baxter, M., Wells, C., Copplestone, D., 2014. Transfer parameters for ICRP reference animals and plants collected from a forest ecosystem. *Radiat. Environ. Biophys.* 53, 125–149. <http://dx.doi.org/10.1007/s00411-013-0493-6>.

Beresford, N.A., Wright, S.M., Barnett, C.L., Wood, M.D., Gaschak, S., Arkhipov, A., Sazykina, T.G., Howard, B.J., 2005. Predicting radionuclide transfer to wild animals: an application of a proposed environmental impact assessment framework to the Chernobyl exclusion zone. *Radiat. Environ. Biophys.* 44, 161–168.

Beresford, N.A., Barnett, C.L., Brown, J., Cheng, J.-J., Copplestone, D., Filistovic, V., Hosseini, A., Howard, B.J., Jones, S.R., Kamboj, S., Kryshev, A., Nedveckaite, T., Olyslaegers, G., Saxén, R., Sazykina, T., Vives i Batlle, J., Vives-Lynch, S., Yankovich, T., Yu, C., 2008a. Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota. *Radiat. Environ. Biophys.* 47, 491–514.

Beresford, N.A., Barnett, C.L., Howard, B.J., Scott, W.A., Brown, J.E., Copplestone, D., 2008b. Derivation of transfer parameters for use within the ERICA tool and the default concentration ratios for terrestrial biota. *J. Environ. Radioact.* 99, 1393–1407.

Beresford, N.A., Gaschak, S., Barnett, C.L., Howard, B.J., Chizhevsky, I., Strömman, G., Oughton, D.H., Wright, S.M., Maksimenko, A., Copplestone, D., 2008c. Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – a test application of the ERICA Tool. *J. Environ. Radioact.* 99, 1496–1502.

Beresford, N.A., Copplestone, D., 2011. Effects of ionizing radiation on wildlife: what knowledge have we gained between the Chernobyl and Fukushima accidents? *Integr. Environ. Assess. Manag.* 7, 371–373. <http://dx.doi.org/10.1002/ieam.238>.

Beresford, N.A., Yankovich, T.L., Wood, M.D., Fesenko, S., Andersson, P., Muikku, M., Willey, N.J., 2013. A new approach to predicting environmental transfer of radionuclides: a demonstration for freshwater fish and caesium. *Sci. Total Environ.* 463–464, 284–292.

Beresford, N.A., Wood, M.D., Vives i Batlle, J., Yankovich, T.L., Bradshaw, C., Willey, N., 2015. Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models. *J. Environ. Radioact.* <http://dx.doi.org/10.1016/j.jenvrad.2015.03.022>.

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D., Pröhl, G., Ulanovsky, A., 2008. The ERICA tool. *J. Environ. Radioact.* 99, 1371–1383.

Brown, J.E., Beresford, N.A., Hosseini, A., 2013. Approaches to providing missing transfer parameter values in the ERICA tool - How well do they work? *J. Environ. Radioact.* 126, 399–411. <http://dx.doi.org/10.1016/j.jenvrad.2012.05.005>.

Bondarkov, M.D., Maksimenko, A.M., Gaschak, S., Zheltonozhsky, V.A., Jannik, G.T., Farfán, E.B., 2011. Method for simultaneous  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  in-vivo measurements of small animals and other environmental media developed for the conditions of the Chernobyl exclusion zone. *Health Phys.* 101, 383–392. <http://dx.doi.org/10.1097/HP.0b013e318224bb2b>.

Copplestone, D., Bielby, S., Jones, S.R., Patton, D., Daniel, P., Gize, I., 2001. *Impact Assessment of Ionising Radiation on Wildlife*. R&D Publication 128. Environment Agency, Bristol.

Copplestone, D., Wood, M.D., Bielby, S., Jones, S.R., Vives, J., Beresford, N.A., 2003. *Habitat Regulations for Stage 3 Assessments: Radioactive Substances Authorisations*. R&D Technical Report P3-101/SP1a. Environment Agency, Bristol.

Copplestone, D., Wood, M.D., Merrill, P.C., Allott, R., Jones, S.R., Vives, J., Beresford, N.A., Zinger, I., 2005. Impact assessment of ionising radiation on Wildlife: meeting the requirements of the EU birds and habitat directives. *Radioprotection* 40, S893–S898. <http://dx.doi.org/10.1051/radiopro:2005s1-131>.

Copplestone, D., Beresford, N.A., Brown, J., Yankovich, T., 2013. An international database of radionuclide Concentration ratios for wildlife: development and uses. *J. Environ. Radioact.* 126, 288–298. <http://dx.doi.org/10.1016/j.jenvrad.2013.05.007>.

Gaichenko, V.A., Koval, G.M., Titar, V.M., 2001. Features of uptake and biogenic redistribution of radionuclides, their migration in trophic chains and making dose burden in wild animals. In: *Collection of Scientific Works: Chernobyl Exclusion Zone*. Naukova Dumka, Kiev, (Ukrainian), pp. 299–316.

Garnier-Laplace, J., Geras'kin, S., Della-Vedova, C., Beaugelin-Seiller, K., Hinton, T.G., Real, A., Oudalova, A., 2013. Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates. *J. Environ. Radioact.* 121, 12–21. <http://dx.doi.org/10.1016/j.jenvrad.2012.01.013>.

Gaschak, S., Chizhevsky, I., Arkhipov, A., Beresford, N.A., Barnett, C.L., 2003. The transfer of Cs-137 and Sr-90 to wild animals within the Chernobyl exclusion zone. In: *International Conference on the Protection of the Environment from the Effects of Ionizing Radiation*. IAEA, Vienna, pp. 200–202. IAEA-CN-109 (Stockholm).

Gashchak, S.P., Maklyuk, Y.A., Maksimenko, A.M., Maksimenko, V.M., Martynenko, V.I., Chizhevsky, I.V., Bondarkov, M.D., Mousseau, T.A., 2008. Features of radioactive contamination of small birds in the Chernobyl zone in 2003–2005. *Radiobiol. Radioecol.* 48, 28–47 (Russian).

Gashchak, S.P., 2009. Main points of radioecology of big mammals in Chernobyl zone. In: *Problems of Chernobyl Exclusion Zone*, 9, pp. 125–140 (Russian).

Gashchak, S.P., Maklyuk, Y.A., Maksimenko, A.M., Bondarkov, M.D., 2009. Radioecology of amphibians in Chernobyl zone. In: *Problems of Chernobyl Exclusion Zone*, 9, pp. 76–86 (Russian).

Gaschak, S., Beresford, N.A., Maksimenko, A., Vlaschenko, A.S., 2010. Strontium-90 and caesium-137 activity concentrations in bats in the Chernobyl exclusion zone. *Radiat. Environ. Biophys.* 49, 635–644. <http://dx.doi.org/10.1007/s00411-010-0322-0>.

Hegstrom, L.J., West, S.D., 1989. Heavy metal accumulation in small mammals following sewage sludge application to forest. *J. Environ. Qual.* 18, 345–349.

Her Majesty's Stationary Office (HMSO), 1981. *Wildlife and Countryside Act 1981*. HMSO, London. [http://www.legislation.gov.uk/ukpga/1981/69/pdfs/ukpga-19810069\\_en.pdf](http://www.legislation.gov.uk/ukpga/1981/69/pdfs/ukpga-19810069_en.pdf).

- Her Majesty's Stationary Office (HMSO), 1994. Agreement on the Conservation of Bats in Europe. London, December 1991. Treaty Series No. 9(1994). HMSO, London. [http://www.eurobats.org/sites/default/files/documents/pdf/Agreementtexts/FCO\\_Agreement\\_Text\\_engl.pdf](http://www.eurobats.org/sites/default/files/documents/pdf/Agreementtexts/FCO_Agreement_Text_engl.pdf).
- Holden, P., Cleeves, T., 2014. RSPB Handbook of British Birds, fourth ed. Bloomsbury Publishing plc, London, ISBN 978-1-4729-1010-3.
- Hosseini, A., Thørring, H., Brown, J.E., Saxén, R., Illus, E., 2008. Transfer of radionuclides in aquatic ecosystems - default concentration ratios for aquatic biota in the ERICA Tool. *J. Environ. Radioact.* 99, 1408–1429.
- Howard, B.J., Beresford, N.A., Copplestone, D., Telleria, D., Proehl, G., Fesenko, S., Jeffree, R., Yankovich, T., Brown, J., Higley, K., Johansen, M., Mulye, H., Vandenhove, H., Gashchak, S., Wood, M.D., Takata, H., Andersson, P., Dale, P., Ryan, J., Bollhöfer, A., Doering, C., Barnett, C.L., Wells, C., 2013. The IAEA handbook on radionuclide transfer to wildlife. *J. Environ. Radioact.* 121, 55–74. <http://dx.doi.org/10.1016/j.jenvrad.2012.01.027>.
- International Atomic Energy Agency (IAEA), 2014. Handbook of Parameter Values for the Prediction of Radionuclide Transfer to Wildlife. Technical Reports Series No. 479. IAEA, Vienna. [http://www-pub.iaea.org/MTCD/Publications/PDF/Trs479\\_web.pdf](http://www-pub.iaea.org/MTCD/Publications/PDF/Trs479_web.pdf).
- International Commission on Radiological Protection (ICRP), 2009. Environmental Protection: transfer parameters for reference animals and plants. ICRP Publication 114 Ann. ICRP 39 (6). Elsevier. <http://www.icrp.org/publication.asp?id=ICRP%20Publication%20114>.
- Johansen, M.P., Child, D.P., Davis, E., Doering, C., Harrison, J.J., Hotchkis, M.A.C., Payne, T.E., Thiruvoth, S., Twining, J.R., Wood, M.D., 2014. Plutonium in wildlife and soils at the Maralinga legacy site: persistence over decadal timescales. *J. Environ. Radioact.* 131, 72–80.
- Johansen, M.P., Child, D.P., Caffrey, E.A., Davis, E., Harrison, J.J., Hotchkis, M.A.C., Ikeda-Ohno, A., Thiruvoth, S., Twining, J.R., Beresford, N.A., 2015. Accumulation of plutonium in mammalian wildlife tissues following dispersal by accidental-release tests. *J. Environ. Radioact.* <http://dx.doi.org/10.1016/j.jenvrad.2015.03.031>.
- Kashparov, V.A., Oughton, D.H., Zvarich, S.I., Protsak, V.P., Levchuk, S.E., 1999. Kinetics of fuel particles weathering and <sup>90</sup>Sr mobility in the Chernobyl 30-km exclusion zone. *Health Phys.* 76, 251–259.
- Kashparov, V.A., Lundin, S.M., Zvarych, S.I., Yoshchenko, V.I., Levchuk, S.E., Khomutinin, Y.V., Maloshtan, I.M., Protsak, V.P., 2003. Territory contamination with radionuclides representing the fuel component of Chernobyl fallout. *Sci. Tot. Environ.* 317, 105–119.
- Lindblom, H., 2008. Competition for Space as a Mechanism for Density- and Frequency-dependent Selection on Bank Vole (*Myodes Glareolus*) Females. MSc. Thesis. University of Jyväskylä.
- Maklyuk, Y.A., Maksimenko, A.M., Gaschak, S.P., Bondarkov, M.D., Chizhevsky, I.V., 2007. Long-term dynamic of radioactive contamination (<sup>90</sup>Sr, <sup>137</sup>Cs) of small mammals in Chernobyl zone. *Ecology* 38, 198–206 (Russian).
- Sheppard, S.C., Evenden, W.G., 1990. Characteristics of plant concentration ratios assessed in a 64-site field survey of 23 elements. *J. Environ. Radioact.* 11, 15–36.
- Sheppard, S.C., 1991. A field and literature survey, with interpretation, of elemental concentrations in blueberry (*Vaccinium angustifolium*). *Can. J. Bot.* 69, 63–77.
- Sheppard, S.C., Sheppard, M.I., Sanipelli, B., Tait, J., 2004. Background Radionuclide Concentrations in Major Environmental Compartments of Natural Terrestrial Ecosystems. Contract No. 87055020215 of the Canadian Nuclear Safety Commission.
- Sheppard, S.C., Sheppard, M.I., Ilin, M., Tait, J.C., Sanipelli, B.L., 2008. Primordial radionuclides in Canadian background sites: secular equilibrium and isotopic differences. *J. Environ. Radioact.* 99, 933–946.
- Sheppard, S.C., Long, J.M., Sanipelli, B., 2010. Measured elemental transfer factors for boreal hunter/gatherer scenarios: fish, game and berries. *J. Environ. Radioact.* 101, 902–909.
- Shore, R.F., Rattner, B.A., 2001. *Ecotoxicology of Wild Mammals*. John Wiley & Sons Ltd., Chichester.
- Świergosz-Kowalewska, R., Gramatyka, M., Reczyński, W., 2005. Metals distribution and interaction in tissues of shrews (*Sorex* spp.) from copper- and zinc-contaminated areas in Poland. *J. Environ. Qual.* 34, 1519–1529.
- Tomášková, L., Bejček, V., Sedláček, F., Štastný, K., Tkadlec, E., Zima, J., 2005. Population biology of shrews (*Sorex araneus* and *S. minutus*) from a polluted area in central Europe. In: Merritt, J.F., et al. (Eds.), *Advances in the Biology of Shrews II*. Int. Soc. Shrew Biologists, pp. 189–197.
- USDoE (United States Department of Energy), 2002. A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota Voluntary Consensus Technical Standard DOE-STD-1153-2002. USDoE, Washington, D.C.
- Voyinstvensky, M.A., 1960. *Useful Wild Birds of the Ukraine*. State Publishing House, Kiev (Ukrainian).
- Wood, M.D., Marshall, W.A., Beresford, N.A., Jones, S.R., Howard, B.J., Copplestone, D., Leah, R.T., 2008. Application of the ERICA integrated approach at the Drigg coastal sand dunes. *J. Environ. Radioact.* 99, 1484–1495.
- Wood, M.D., Leah, R.T., Jones, S.R., Copplestone, D., 2009. Radionuclide transfer to invertebrates and small mammals in a coastal sand dune ecosystem. *Sci. Tot. Environ.* 407, 4062–4074. <http://dx.doi.org/10.1016/j.scitotenv.2009.03.011>.
- Wood, M.D., Beresford, N.A., Yankovich, T.L., Semenov, D.V., Copplestone, D., 2011. Addressing current knowledge gaps on radionuclide transfer to reptiles. *Radioprotection* 46, S521–S527. <http://dx.doi.org/10.1051/radiopro/20116792s>.
- Wood, M.D., Beresford, N.A., Howard, B.J., Copplestone, D., 2013. Evaluating summarised radionuclide concentration ratio datasets for wildlife. *J. Environ. Radioact.* 126, 314–325.
- Yankovich, T.L., Beresford, N.A., Fesenko, S., Fesenko, J., Phaneuf, M., Dagher, E., Outola, I., Andersson, P., Thiessen, K., Ryan, J., Wood, M.D., Bollhöfer, A., Barnett, C.L., Copplestone, D., 2013. Establishing a database of radionuclide transfer parameters for freshwater wildlife. *J. Environ. Radioact.* 126, 299–313.