There are 438 operational nuclear reactors worldwide, and nuclear power production is expected to grow over the coming decades (IAEA 2014). As this industry expands, so too does the need to fully understand the ecological consequences of its production and associated accidents. Although nuclear energy production has strict protocols to protect human health and maximize safety, the potential for a nuclear accident capable of causing catastrophic, ecosystem-level radiation contamination (eg Chernobyl and Fukushima) is always present. The consequences of such accidents are costly from an economic, human health, and ecological perspective, and can render affected regions uninhabitable to humans for centuries. Thus, the potential long-term ecological effects of nuclear disasters are of global interest to international organizations and the public.

Chernobyl is a prime location for investigating such effects on wildlife populations. The 1986 accident at the Chernobyl Nuclear Power Plant resulted in the release of large amounts of radioactivity into the atmosphere. In response, humans were evacuated from a roughly 4300-km² area spanning the modern borders of Ukraine and Belarus, an area now referred to as the “Chernobyl Exclusion Zone” (CEZ). Following the accident, radioactive material suspended in the air began to “fall out” and settle onto the landscape, depending upon local wind and rainfall patterns (Smith and Beresford 2005). Radionuclides were deposited in a spatially heterogeneous manner across the landscape surrounding Chernobyl, and contaminant exposure rates in wildlife species are therefore highly dependent on an individual animal’s diet, behavior, and location within that landscape. Despite this contamination, many wildlife species have continued to inhabit the CEZ with little to no human manipulation; in some cases, wildlife were intentionally introduced into the zone by humans (ie European bison [Canis lupus], raccoon dog [Nyctereutes procyonoides], Eurasian boar [Sus scrofa], and red fox [Vulpes vulpes]), we found no evidence to suggest that their distributions were suppressed in highly contaminated areas within the CEZ. These data support the results of other recent studies, and contrast with research suggesting that wildlife populations are depleted within the CEZ.

Although nearly 30 years have passed since the Chernobyl Nuclear Power Plant accident near the town of Pripyat, Ukraine, the status and health of mammal populations within the Chernobyl Exclusion Zone (CEZ) remain largely unknown, and are of substantial scientific and public interest. Information regarding the response of flora and fauna to chronic radiation exposure is important in helping us understand the ecological consequences of past (eg Chernobyl and Fukushima) and potential future nuclear accidents. We present the results of the first remote-camera scent-station survey conducted within the CEZ. We observed individuals of 14 mammalian species in total; for those species with sufficiently robust visitation rates to allow occupancy to be modeled (gray wolf [Canis lupus], raccoon dog [Nyctereutes procyonoides], Eurasian boar [Sus scrofa], and red fox [Vulpes vulpes]), we found no evidence to suggest that their distributions were suppressed in highly contaminated areas within the CEZ. These data support the results of other recent studies, and contrast with research suggesting that wildlife populations are depleted within the CEZ.

Where the wild things are: influence of radiation on the distribution of four mammalian species within the Chernobyl Exclusion Zone

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Although nearly 30 years have passed since the Chernobyl Nuclear Power Plant accident near the town of Pripyat, Ukraine, the status and health of mammal populations within the Chernobyl Exclusion Zone (CEZ) remain largely unknown, and are of substantial scientific and public interest. Information regarding the response of flora and fauna to chronic radiation exposure is important in helping us understand the ecological consequences of past (eg Chernobyl and Fukushima) and potential future nuclear accidents. We present the results of the first remote-camera scent-station survey conducted within the CEZ. We observed individuals of 14 mammalian species in total; for those species with sufficiently robust visitation rates to allow occupancy to be modeled (gray wolf [Canis lupus], raccoon dog [Nyctereutes procyonoides], Eurasian boar [Sus scrofa], and red fox [Vulpes vulpes]), we found no evidence to suggest that their distributions were suppressed in highly contaminated areas within the CEZ. These data support the results of other recent studies, and contrast with research suggesting that wildlife populations are depleted within the CEZ.

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including sperm deformities and increases in mutation rates, morbidity, and mortality (Møller et al. 2005). However, controversy has surrounded some studies that documented severe health effects in wildlife, due to questions regarding field methods, analyses, and methods of estimating radiation doses (Beresford and Copplestone 2011). Furthermore, few studies have examined organisms occupying high trophic levels within the Chernobyl ecosystem, and so little is known about how chronic radiation exposure may be affecting mid- to large-sized mammals.

Specifically, there are large knowledge gaps pertaining to occupancy trends and densities of mammals in the CEZ, and it is unclear what effects chronic radiation exposure may have on their population status and distribution; such data are vital for informing future management or protection of wildlife inhabiting contaminated landscapes. Recent evidence suggests that populations of several large mammal species increased within the CEZ during the first decade after the accident, and that large mammal distributions are uncorrelated with severity of radiation contamination (Deryabina et al. 2015), in contrast to previous findings from a more limited spatial and temporal study (Møller and Mousseau 2013). Thus, additional research that more clearly records wildlife distribution, abundance, and health is needed. The goal of our study was, for the first time, to use scent stations coupled with remote cameras to determine whether the probability of mammal occurrences are correlated to the intensity of radionuclide contamination within the CEZ.

Methods

Study area

We conducted our study in the 2162-km² Polesie State Radioecological Reserve (PSRER) in southern Belarus. The reserve was created in 1988 by the regional government to encompass the portion of the CEZ located within the Belarusian Soviet Socialist Republic (which at that time was a component of the Soviet Union but is now independent Belarus). Approximately 51% of the PSRER is forested, with the remaining 49% composed of abandoned agricultural and developed land (deserted villages, farms, and transportation systems), open fields, and seasonal wetlands. The PSRER is bisected by the Pripyat River, and human access to the reserve is strictly regulated. Levels of cesium-137 ($^{137}$Cs) within the PSRER remain very high, and as of 2009 soil contaminant densities ranged from 40 kilobecquerels per square meter (kBq m$^{-2}$) to $>7500$ kBq m$^{-2}$ across the reserve (Figure 1; Izrael and Bogdevich 2009). Because radionuclides are unevenly distributed across the landscape, exposure rates will differ widely among wildlife species.

Field sampling

We deployed scent stations throughout the PSRER from October–November 2014. Scent stations consisted of a plaster tab infused with fatty acid scent (US Department of Agriculture, Pocatello, ID) placed in a 0.9-meter diameter circle of soil cleared of vegetation. Stations were sited a minimum of ~3 km apart, to reduce the chances of individuals visiting multiple stations within a single survey period. In addition, we placed all stations <10 m from a road, given that many carnivores use roads as a means of travel (Macdonald 1980). We affixed an infrared remote camera (Moultrie m990i Infrared Game Camera, EBSCO Industries Inc) to a tree or other vertical structure within 3 m of each station. Cameras were programmed to take three pictures each time they were triggered by nearby movement, with a 5-second delay between events. Stations were active

![Image of Polesie State Radioecological Reserve (PSRER) with scent station locations](image-url)

**Figure 1.** The Polesie State Radioecological Reserve (PSRER) has considerable heterogeneity in $^{137}$Cs soil contaminant density, ranging from 40 kBq m$^{-2}$ to $>7500$ kBq m$^{-2}$, as derived from imagery reported by Izrael and Bogdevich (2009) and imported to ArcGIS 10.2, georectified, and digitized. Green dots represent the locations of the scent stations.
for 7 days, and were revisited on day 3 or 4 to replace scent tabs if tampered with, to minimize variation in detection probability throughout the sampling period.

**Quantifying habitat**

Using GPS technology, we demarcated 42 sites located in various habitat types to obtain representative data for each habitat type that occurs within the reserve. GPS-based positions were used in a supervised classification (ArcGIS 10.2.1, ESRI, Redlands, CA) of LANDSAT imagery obtained from GLOVIS (US Geological Survey Global Visualization Viewer, http://glovis.usgs.gov). We reclassified the content of the resulting map into five habitat types: pine forest, hardwood [deciduous] forest, seasonal marsh, dry field, and water. Anthropogenic structures (eg roads, houses, public buildings) were not considered barriers to movement or occupancy because of the lack of continuous human presence within the PSRER over the past 30 years. We used the Geospatial Modelling Environment (Spatial Ecology LLC, www.spatial ecology.com/gme) platform to quantify habitat cover within circular buffers with radii of 250 m and 1000 m at each sampling location; these distances were chosen in order to capture both fine and landscape-level scales of potential habitat selection for our species of interest. Within each circular buffer, we calculated area-weighted mean soil activity densities of \(^{137}\text{Cs}\) (“Rad”); kBq m\(^{-2}\); based on geo-rectified imagery data from Izrael and Bogdevich 2009), as well as area of forest (“Forest”), area of open field (“DryField”), area of seasonal wetland (“Marsh”), quantity of edge habitat (length, in meters, of intersection of open and forested habitats; “Edge”), distance of sampling location to the Pripyat River (“Water”), and distance of sampling location to the CEZ border as an indicator of sensitivity to anthropogenic pressures (“Border”).

**Data analysis**

On the basis of average home-range sizes of carnivores detected in our camera surveys, we considered each station as an independent sample for each species of interest, excluding gray wolves, which have average home-range sizes of 600 km\(^2\) to 900 km\(^2\) in the region (Theuerkauf et al. 2003). We divided the survey period into seven 24-hour sampling occasions during deployment of scent stations and used these data to create species-specific binary detection histories for each station. We used an occupancy modeling approach to quantify the influence of radiation and habitat attributes on the distribution of surveyed wildlife throughout the PSRER. This approach (McKenzie et al. 2002) relies on detection/non-detection data and maximum likelihood estimation to quantify the probability of site occupancy (ie probability of a given animal being present at a site during the period of sampling, denoted as \(\Psi\)) and detection probability (probability of detecting a species at an occupied site) while incorporating our detection/non-detection data as well as covariates of interest. We used a single-season occupancy analysis and developed models only for species that met a minimum threshold of 10 detections (the number of visitations to stations required for modeling to be successful). We did not model temporal variation in detection probabilities as a function of survey-specific variables (eg weather events), but rather we made the assumption that, based on our sampling design, no survey-specific variables influenced detection probability throughout the 7-night survey period.

To avoid multicollinearity, we examined correlations among the environmental variables at both spatial scales (250 m and 1000 m) by deriving a matrix of all possible Pearson correlation coefficient values. Any variables with a significant correlation \((r^2 \geq 0.2; P \leq 0.05)\) were not simultaneously included in the same model in subsequent analyses. Preliminary analyses revealed models containing \(\geq 3\) uncorrelated variables failed to converge for every species; we therefore limited our analyses to models including \(\leq 2\) environmental variables. We developed a suite of 15 candidate models at each habitat scale that incorporated all combinations of uncorrelated variables and used them for every species.

We conducted all analyses using R (R Development Core Team, www.r-project.org) and fitted the model using the package “unmarked” (Fiske and Chandler 2011), which accounts for potential autocorrelation of data when calculating both detection probabilities and site occupancy probability, but assumes spatial independence between survey locations. We calculated Akaike Information Criterion (AIC) values for all models, and ranked models based on \(\Delta\text{AIC}\) and \(\text{AIC}\) weights \((\omega_j)\) to determine which model best fit the capture history data (Burnham and Anderson 2002). We used the chi-square \((\chi^2)\) method for site-occupancy models to ensure model validity (MacKenzie and Bailey 2004).

We averaged all models within two AIC units and derived parameter beta estimates from the averaged model. Uninformative parameters were identified by calculating 85% confidence intervals (CIs) for model-averaged parameter estimates for each species and scale (Arnold 2010).

**Results**

We deployed 98 scent stations over a 5-week period in October–November 2014. Of these stations, four were excluded due to camera malfunctions, making our effective sample size 94. We detected 14 mammal species (including seven carnivores) at scent stations,
four of which – gray wolf (Canis lupus), raccoon dog (Nyctereutes procyonoides), red fox (Vulpes vulpes), and Eurasian boar (Sus scrofa) - had sufficient detection thresholds to successfully model occupancy (Table 1; Figure 2; WebFigure 1). Although carnivores were the main focus of this study, visitation rates by the omnivorous Eurasian boar (an artiodactyl species) were adequately robust to model visitation and therefore this species was included in the analyses. Supported models varied among species across both spatial scales, although several models contained uninformative parameters that were removed from biological interpretation (WebTable 1).

Radiation did not negatively affect occupancy probability (Ψ) for any species or spatial scale examined. For red foxes, all variables within supported models were uninformative at the 250-m scale. At the 1000-m scale, “Water” (β = 4.02, CI = 0.38 – 7.65) and “Marsh” (β = –2.07, CI = –4.05 – –0.09) had a positive and negative influence on Ψ, respectively (WebTable 2). For Eurasian boars, distance to the CEZ border negatively influenced Ψ at both habitat scales (β = –2.21, CI = –3.64 – –0.77; WebTable 2); all other parameters in supported models were uninformative. For raccoon dogs, “Rad+Water” was the most supported model at both spatial scales, with both of these parameters having a positive influence on Ψ (WebTable 2). Additionally, at the 1000-m scale, “DryField” negatively influenced Ψ (β = –1.62, CI = –3.1 – –0.14). For gray wolves, no measured environmental attributes were informative for estimating Ψ, but we anticipated this possibility, given that the model assumption of independence of sampling stations was violated for this species due to their large home-range sizes.

**Discussion**

Our results provide the first quantitative analysis on the distribution of carnivores within the CEZ based on remote-camera surveys. The data suggest that the current distribution of wildlife within the CEZ is unaffected by 137Cs contaminant densities. However, we did not examine the health effects of radiation exposure at the individual level, and contaminant densities of 137Cs may not directly correlate to absorbed dose rate due to a multitude of factors (e.g. movement, behavior, diet). Long-term, chronic exposure to radiation may possibly affect animal health, although our findings indicate that current levels of exposure are not limiting the distributions of gray wolf, red fox, raccoon dog, or Eurasian boar. Moreover, if individual-level effects were severe, we would expect a negative correlation between occupancy probability and radiation contaminant density, particularly for species with restricted home-range sizes (e.g. raccoon dog, red fox), a pattern not supported by our data.

Indeed, individuals of all four species included in our analyses were detected at stations <500 m from areas with the highest contaminant densities of 137Cs in the PSRER (≥7500 kBq m⁻²). These species included raccoon dogs and red foxes, which have home-range sizes of only 1.5–2.0 km² (Drygala and Zoller 2012), and are therefore highly influenced by local radiation levels. The occupancy probability for raccoon dogs was positively correlated with radiation contaminant density at both spatial scales measured, as well as with distance to the Pripyat River. A positive correlation with radiation level is unexpected, and most likely due to environmental factors not measured in our study (e.g. prey base, interspecific competition). Similarly, red foxes were unaffected by 137Cs contaminant density, and had a higher probability of occupying areas farther from the Pripyat River and areas with less seasonal marsh, consistent with habitat requirements for this species.

Eurasian boars also have relatively small home ranges (3–15 km²; Baskin and Danell 2003) and so are likely to be affected by local radiation levels. However, our data do not indicate that populations of Eurasian boars were suppressed in highly contaminated regions of the CEZ, as only distance to the CEZ border was found to influence boar occupancy probability. This correlation,

<table>
<thead>
<tr>
<th>Species detected</th>
<th>Number of stations occupied</th>
<th>Total detections**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black grouse (Tetrao tetrix)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Domestic dog (Canis familiaris)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Eurasian badger (Meles meles)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Eurasian bison (Bison bonasus)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Eurasian boar (Sus scrofa)</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>Eurasian jay (Garrulus glandarius)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Eurasian magpie (Pica pica)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Eurasian red squirrel (Sciurus vulgaris)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>European hare (Lepus europaeus)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Gray wolf (Canis lupus)*</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>Least weasel (Mustela nivalis)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Moose (Alces alces)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Pine marten (Martes martes)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Raccoon dog (Nyctereutes procyonoides)*</td>
<td>31</td>
<td>60</td>
</tr>
<tr>
<td>Red deer (Cervus elaphus)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Red fox (Vulpes vulpes)**</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Roe deer (Capreolus capreolus)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Notes:** *species included in modeling analysis; **detections = number of 24-hour sampling occasions in which species was observed at scent stations.
which was negative at both habitat scales, most likely exists because the landscape immediately outside the CEZ is predominantly composed of agricultural crops. Eurasian boars use agricultural crops as a food resource, so areas adjacent to the CEZ border probably support higher densities of boars because they offer increased foraging opportunities. Although this trend coincides with boars being more likely to be found in areas of lower radiation, $^{137}\text{Cs}$ contaminant density was not found to influence occupancy, and boars were detected at stations in the most contaminated regions of our study area.

Gray wolves were unique among the species considered in that no measured environmental parameters were found to be influential at either scale. We expected that the effects of $^{137}\text{Cs}$ contaminant density on their occupancy probability would be limited because of their large home-range size and high mobility through spatially heterogeneous regions of radiation contamination. Although our data support this hypothesis, we acknowledge that our interpretations are limited for wolves, as our study design was based on the assumption that an individual animal cannot visit multiple stations in a single sampling occasion; this assumption should not hold true for members of this species, given their characteristically extensive home ranges.

Overall, our findings indicate that the severity of radiation contamination has no discernible impact on the current distribution of selected mid- to large-sized carnivores, or of Eurasian boars, within the CEZ. Rather, other habitat-related and anthropogenic factors (e.g., agricultural lands, human presence) appear to be driving occupancy. Thus, despite severe impacts on some wildlife immediately after the nuclear accident (Alexakhin and Geras’kin 2013), our results corroborate the conclusions of Baker et al. (1996) and Deryabina et al. (2015), and suggest that robust populations of numerous mammals now occur throughout much of the CEZ, including areas with radiation levels exceeding 7500 kBq m$^{-2}$. Such data contribute to an improved scientific understanding of the long-term ecological consequences of nuclear accidents, and can be applied by policy makers to establish effective management and safety protocols for wildlife in highly contaminated landscapes elsewhere. However, further studies are needed to elucidate whether, and to what extent, critical attributes of wildlife populations (e.g., abundance, genetic diversity) or individuals (e.g., genetic mutations, fecundity, survival) are affected by chronic radiation exposure.

**Acknowledgements**

We thank PM Kudan, Y Bondar, S Kutschel, S Smalovski, and the staff at the PSRER for their assistance; I Filipkova and A Bundtzen for their invaluable knowledge and hard work with this research; and J-M Metivier (IRSN) for digitizing $^{137}\text{Cs}$ data from contamination maps of the PSRER. Funding was provided by the US Department of Energy (Award Number DE-FC09-07SR22506 to the University of Georgia Research Foundation), the National Geographic Society, the Institut de Radioprotection et de Sûreté Nucleaire, and the Norwegian Radiation Protection Authority. None of these funding sources were involved in the design, implementation, or analysis of this research.

**References**


**Supporting Information**

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi:10.1002/fee.1227/supinfo