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Species richness and abundance of forest birds in relation to radiation at Chernobyl

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The effects of low-level radiation on the abundance of animals are poorly known, as are the effects on ecosystems and their functioning. Recent conclusions from the UN Chernobyl forum and reports in the popular media concerning the effects of radiation from Chernobyl on animals have left the impression that the Chernobyl exclusion zone is a thriving ecosystem, filled with an increasing number of rare species. Surprisingly, there are no standardized censuses of common animals in relation to radiation, leaving the question about the ecological effects of radiation unresolved. We conducted standardized point counts of breeding birds at forest sites around Chernobyl differing in level of background radiation by over three orders of magnitude. Species richness, abundance and population density of breeding birds decreased with increasing level of radiation, even after controlling statistically for the effects of potentially confounding factors such as soil type, habitat and height of the vegetation. This effect was differential for birds eating soil invertebrates living in the most contaminated top soil layer. These results imply that the ecological effects of Chernobyl on animals are considerably greater than previously assumed.

Keywords: census; ecosystem effects; population density; radiation at Chernobyl; species richness

1. INTRODUCTION

The ecological consequences of radiation from the Chernobyl catastrophe are poorly known (Zakharov & Krysanov 1996; Møller & Mousseau 2006). Without scientific justification, the Chernobyl exclusion zone has been promoted as a thriving ecosystem with a number of uncommon species having appeared in increasing numbers in recent years (Chernobyl Forum 2005a,b; Mycio 2005; Rosenthal 2005; Stephan 2005; UN Chernobyl Forum Expert Group 2005).

Surprisingly, there are little data on how the abundance of animals varies with levels of radiation, and there has been no effort to census animals in relation to local levels of radiation around Chernobyl.

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Since 1990, we have collected information suggesting a reduced and continuously declining abundance of birds in the most contaminated areas. This prompted us to conduct standard censuses in relation to local levels of radiation.

During May to June 2006, we censused breeding birds using standard point count census (Møller 1983; Bibby *et al.* 2005), while simultaneously recording levels of background radiation at these forest sites. Species richness and abundance of animals can be affected by numerous environmental factors other than radiation, and, therefore, we controlled statistically for a range of potentially confounding variables that could affect our assessment of the relationship between species richness and abundance of animals and the level of background radiation by including variables reflecting habitat, soil type, weather and several other factors in the statistical models. Most radiation around Chernobyl is currently in the topmost layer of the soil (Shestopalov 1996; European Union 1998), where soil invertebrates are abundant. Therefore, we predicted that the abundance of bird species eating soil invertebrates would be particularly depressed in the most contaminated areas.

2. MATERIAL AND METHODS

APM (wearing a radiation protection suit) conducted standard point counts during 29 May to 9 June 2006, with each count lasting 5 min during which all bird species seen or heard were recorded (Møller 1983; Bibby *et al.* 2005). The census was conducted within the Chernobyl exclusion zone with a permit from the Ukrainian authorities. Two hundred and fifty-four points were located at a distance of approximately 100 m intervals within forested areas (excluding successional stages of secondary forest due to abandoned farming (these areas are still almost exclusively open grassland)) of the Chernobyl exclusion zone or in areas adjacent to the southern and western borders.

Point counts of birds provide highly reliable estimates of species richness and abundance (Møller 1983; Bibby *et al.* 2005). We directly tested the reliability of our counts for a sample of 10 points where two persons performed the counts. The second person performing the counts was unaware of the purpose of his counts. The Pearson product–moment correlation between species richness in these two series of counts was $r = 0.99$, $t = 42.06$, d.f. $= 8$, $p < 0.0001$, and for abundance it was equally high: $r = 0.99$, $t = 12.47$, d.f. $= 8$, $p < 0.0001$. Species eating soil invertebrates were distinguished from all other species (table 1 in the electronic supplementary material).

(a) *Confounding variables*

Bird abundance estimates can be affected by numerous potentially confounding variables (Møller 1983; Bibby *et al.* 2005), and, therefore, it is crucial to control such variables statistically to assess the underlying relationship between radiation and animal species richness or abundance. We quantified habitat (agricultural habitats with grassland or shrub (either currently or previously cultivated), deciduous forest or coniferous forest estimated to the nearest 10% of ground coverage within a distance of 50 m from the observation point). Agricultural habitat thus also controlled statistically for any effects of edge habitat. Maximum height of trees was estimated to the nearest 5 m, and soil type was recorded as loam/clay or sand. The presence of open water within a distance of 50 m was also recorded. Weather conditions can affect animal activity and hence census results (Møller 1983; Bibby *et al.* 2005), and we recorded cloud cover at the start of each point count (to the nearest eighth, range 0–1 during the censuses), temperature (degree Celsius, range 12–22°C) and wind force (Beaufort, range 0–4 during the censuses). For each point count, we recorded time of day when the count was started (to the nearest minute). Since bird activity may show a curvilinear relationship with time of day, with high levels of activity in the morning and to a lesser extent in the evening (Møller 1983; Bibby *et al.* 2005), we also included time squared as an additional variable.
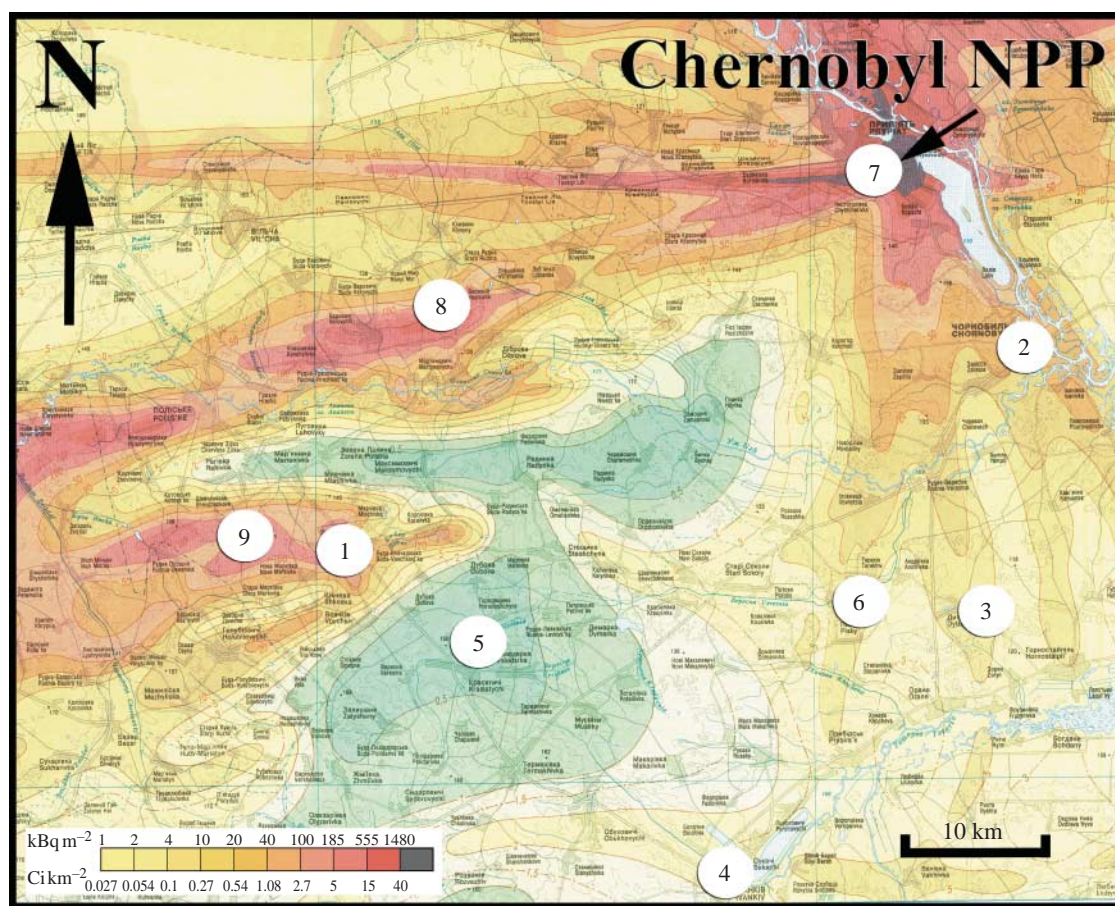
Figure 1. Locations of census areas in the Chernobyl area of northern Ukraine: (1) Bobor, (2) Chernobyl, (3) Dytiaku, (4) Ivankov, (5) Mikhivshchyna, (6) Pisky, (7) Red Forest, (8) Vesniane and (9) Yasen. Adapted from Shestopalov (1996).

(b) *Measuring background radiation levels*

We obtained radiation estimates from our measurements and cross-validated these with measurements by the Ministry of Emergencies. We measured α, β and γ radiation at ground level directly at each point where we censused birds using a handheld dosimeter (Model: Inspector, SE International, Inc., Summertown, TN, USA). We measured levels several (2–3) times at each site and averaged the measurements. Our data were validated with correlation against data from the governmental measurements published by Shestopalov (1996), estimated as the midpoint of the ranges published. This analysis revealed a strong positive relationship (linear regression on log–log transformed data: $F_{1,252} = 1546.49$, $r^2 = 0.86$, $p < 0.0001$, slope (s.e.) = 1.28 (0.10)), suggesting that our estimates of radiation provided the same ranking of levels of radiation as did published estimates. The measurements by the Ministry of Emergencies were obtained by repeated standardized measurement of radiation at the ground level in a large number of different localities in Ukraine. Radiation levels vary considerably at very short geographical distances due to heterogeneity in the deposition of radiation after the Chernobyl accident (figure 1; Shestopalov 1996). Our measurements at the census points ranged from 0.04 to 135.89 mR h^{-1}.

(c) *Statistical methods*

Radiation level was $\log_{10}$-transformed, while coverage with farmland, deciduous forest and coniferous forest was square-root arcsine-transformed. We also included radiation level squared to account for nonlinear relationships between species richness and abundance and radiation. We developed best-fit statistical models to assess the relationship between species richness and abundance (dependent variables) and radiation, assuming a Poisson distribution, after inclusion of the potentially confounding variables, as implemented in the statistical software JMP (SAS Institute 2000). Population density was analysed using abundance as the dependent variable, with species richness as an additional independent variable. Model selection was based on Akaike's information criterion (AIC), using the criterion of delta AIC < 2.00 for the exclusion of variables (Burnham & Anderson 2002).

The frequency distribution of the counts of birds was skewed, with a disproportionate number of zeros. Therefore, we repeated the analyses using Kendall rank–order correlation and partial

rank–order correlation (controlling for the confounding variables in table 2 in the electronic supplementary material), and the conclusions remained unchanged (electronic supplementary material).

3. RESULTS

We recorded 1570 individuals representing 57 species of birds (see table 1 in the electronic supplementary material). Species richness of birds was reduced by more than half when comparing sites with the highest and normal background level of radiation within the study areas (figure 2a). In addition, there were independent effects of time of day and habitat on the number of species recorded (table 2 in the electronic supplementary material). Total abundance of all species decreased by almost two-thirds between sites with the highest levels and the normal background levels of radiation within the study areas (figure 2b; table 2 in the electronic supplementary material). The effect of radiation level remained after controlling statistically for the effects of time of day, weather and farmland habitat (table 2 in the electronic supplementary material). Finally, population density of birds, defined as total abundance of all species divided by species richness, decreased significantly with increasing radiation level (figure 2c; table 2 in the electronic supplementary material).

The abundance of bird species eating soil invertebrates decreased considerably with radiation level (figure 2b; $F_{1,252} = 115.76$, $r^2 = 0.31$, $p < 0.0001$, slope (s.e.) = -0.114 (0.011)). In contrast, there was no significant relationship between the abundance of the
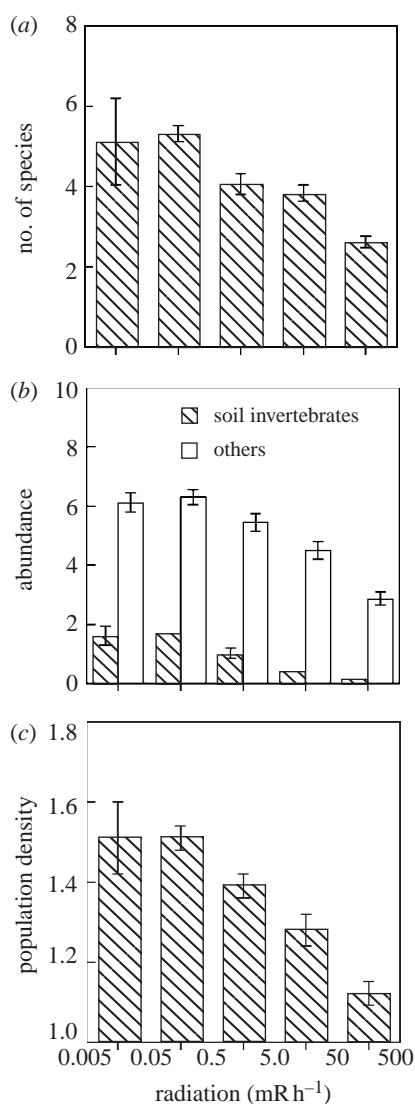
Figure 2. (*a*) Mean species richness (s.e.) of birds, (*b*) mean abundance (s.e.) of birds and (*c*) mean (s.e.) population density of birds in relation to background radiation level (mR h^{-1}) for forested locations around Chernobyl. The partial effects for radiation were (*a*) $F_{1,249} = 55.63$, $r^2 = 0.18$, $p < 0.0001$, (*b*) $F_{1,247} = 62.07$, $r^2 = 0.20$, $p < 0.0001$ and (*c*) $F_{1,246} = 51.88$, $r^2 = 0.17$, $p < 0.0001$.

remaining species and radiation ($F_{1,252} = 1.53$, $r^2 = 0.006$, $p = 0.22$, slope (s.e.) $= -0.014$ (0.013)). A similar conclusion was reached when the potentially confounding variables reflecting weather, habitat and time of day were included.

4. DISCUSSION

Species richness of birds in forests around Chernobyl decreased by more than 50% with increasing level of radiation, and this effect was independent of potentially confounding factors such as time of day, weather, soil type, age of tree stands and habitat. Abundance of birds decreased by 66% between the most contaminated sites and sites with normal background radiation (within the study areas). These results are the first census data reported from Chernobyl, and they indicate dramatic effects on species richness and

abundance of birds that play important roles in ecosystem functioning.

We found strong declines in species richness, abundance and population density of birds associated with elevated levels of background radiation near Chernobyl. The conclusions were similar when based on parametric or non-parametric analyses, controlling for potentially confounding variables. We had relatively few observations in the range of 1–10 mR h^{-1} (figure 2). However, the negative relationships were prominent both among data points with a radiation level below and above 5 mR h^{-1} (figure 2), showing that even radiation levels below 5 mR h^{-1} were associated with reduced abundance. Most radiation around Chernobyl is currently in the topmost layer of the soil (Shestopalov 1996; European Union 1998), where soil invertebrates live. Bird species consuming soil invertebrates decreased in abundance more strongly than other species, suggesting that radiation had differential effects on specific functional ecological groups.

We suggest three mechanisms underlying these observed patterns of species richness and abundance of birds in relation to level of radiation. First, radiation may directly reduce survival rates and fecundity, thereby causing extinction or reducing population sizes, as shown previously for the barn swallow *Hirundo rustica* (Møller *et al.* 2005). Second, birds may avoid radioactively contaminated areas because such areas are suboptimal habitats for birds (Møller & Mousseau 2007). Third, birds may be less abundant and species richness may be reduced in contaminated areas owing to reduced abundance of invertebrates that constitute the most common food of many species.

We have previously demonstrated significant negative impacts of Chernobyl-related fallout on barn swallow mutation rates, survival and reproduction (Møller 1983; Ellegren *et al.* 1997; Møller *et al.* 2005). Here, we extend our observations to document extensive reductions in the species richness, abundance and population density of birds in general with increasing levels of radiation around Chernobyl. These effects are likely to have important implications for other parts of the ecosystem and for overall ecosystem functioning.

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