Environmental Pollution 164 (2012) 36–39

Contents lists available at SciVerse ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Rapid communication

Abundance of birds in Fukushima as judged from Chernobyl

Anders Pape Møller[a,*], Atsushi Hagiwara[b], Shin Matsui[c], Satoe Kasahara[c], Kencho Kawatsu[d], Isao Nishiumi[e], Hiroyuki Suzuki[f], Keisuke Ueda[c], Timothy A. Mousseau[g]

[a] Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France
[b] Laboratory of Aquaculture Biology, Faculty of Fisheries, Nagasaki University, Nagasaki 852-8521, Japan
[c] Department of Life Sciences, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan
[d] Graduate School of Symbiotic Systems Science and Technology, Fukushima University, 1 Kanayagawa, Fukushima City 960-1296, Japan
[e] Department of Zoology, National Museum of Nature and Science, 3-23-1 Haykunin-cho, Shinjuku-ku, Tokyo 169-0073, Japan
[f] Value Frontier Co., Ltd., 4-13-7, Minamiazabu, Minato, Tokyo 106-0047, Japan
[g] Department of Biological Sciences, University of South Carolina, Columbia, SC 29208, USA

ARTICLE INFO

Article history:
Received 6 November 2011
Received in revised form
11 January 2012
Accepted 12 January 2012

Keywords:
Birds
Chronic radiation
Population trends
Radiation

ABSTRACT

The effects of radiation on abundance of common birds in Fukushima can be assessed from the effects of radiation in Chernobyl. Abundance of birds was negatively related to radiation, with a significant difference between Fukushima and Chernobyl. Analysis of 14 species common to the two areas revealed a negative effect of radiation on abundance, differing between areas and species. The relationship between abundance and radiation was more strongly negative in Fukushima than in Chernobyl for the same 14 species, demonstrating a negative consequence of radiation for birds immediately after the accident on 11 March 2011 during the main breeding season in March–July, when individuals work close to their maximum sustainable level.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Animal abundances provide reliable early warning signals of the impact of environmental perturbations on biological systems (e.g. Voříšek et al., 2010). For example, a wide range of animals show reduced abundance in areas with high background radiation near Chernobyl (Møller and Mousseau, 2011a; Mousseau and Møller, 2011), allowing us to use the relationship between abundance and radiation in Chernobyl as a yardstick for assessing the magnitude of other nuclear accidents such as that at the Fukushima-Daiichi Nuclear Power Plant on 11 March 2011. The nuclear accidents at both Chernobyl and Fukushima contaminated large areas in the neighborhood of the reactors (Fig. 1), but also many neighboring countries. While the magnitude of the nuclear disaster has been assessed as seven on the official IAEA INES scale (on par with Chernobyl (http://www.iaea.org/Publications/Factsheets/English/ines.pdf)), the biological magnitude of nuclear disasters has so far eluded assessment.

Previous studies of the effects of low-dose radiation on animals and plants have been extremely limited, and when it comes to extensive surveys that use standardized, widely approved census methods to relate abundance of free-living organisms to the level of background radiation, there are only a handful of such studies available (Krivolutsky and Pokarshevsky, 1992; Maksimova, 2002; Møller and Mousseau, 2006, 2007; Galván et al., 2011). These studies consistently show negative relationships between abundance and radiation, even when statistically controlling for potentially confounding habitat factors and other variables. The results are repeatable among observers (Møller and Mousseau, 2011a), they are repeatable among areas (Ukraine vs. Belarus) (Møller and Mousseau, 2011a), and they are repeatable among years (Møller and Mousseau, 2011a), showing that similarly negative effects can be demonstrated using stringent methodology. The nuclear accident at Fukushima-Daiichi provides a novel opportunity to assess previously reported effects by increasing the level of replication, which is a hallmark of scientific enquiry. Obviously, Chernobyl and Fukushima differ in terms of environmental conditions, the amount and composition of radionuclides, prevailing weather and time since the nuclear accident. However, vast amounts of radioactivity remain in areas surrounding Chernobyl, due to the long half-lives of plutonium, cesium and strontium, making a comparison of the effects of a given level of radiation on abundance of any group of organisms possible and justifiable. Furthermore, the two disaster zones show similarities by both being heavily contaminated, both

* Corresponding author.
E-mail address: anders.moller@u-psud.fr (A.P. Møller).

0269-7491/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2012.01.008

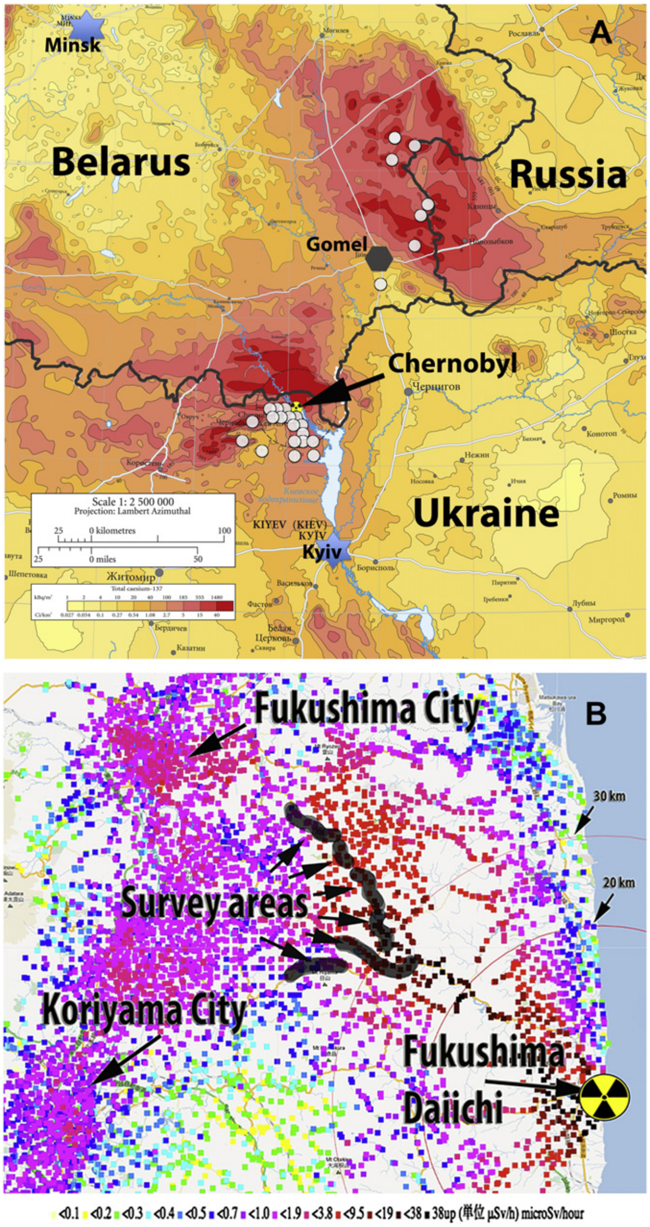

Fig. 1. Location of bird census areas around (A) Chernobyl, Ukraine and Belarus (blue dots) and (B) Fukushima, Japan (black dots). (A) was adapted from Shestopalov (1996) and (B) from http://www.nnistar.com/gmap/fukushima, generated by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and local government. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

being composed of farmland and forests, and both being located in temperate climates in the same zoogeographic region. If there were similar negative relationships between abundance and a given level of background radiation in the vicinity of Chernobyl and Fukushima, we could conclude that the underlying factor responsible for these effects was most likely the same. Chernobyl and Fukushima are both located in the Palearctic zoogeographic region, implying that numerous taxa occur in both areas despite the areas being separated by a distance of more than 7000 km. We explicitly exploited that situation by investigating the response of the same set of species in Chernobyl and Fukushima to low-dose radiation.

Here we assessed the predictions that (i) the effects of radiation on abundance of birds would be negative; (ii) the effect would be stronger in the area more recently exposed to radiation; and that (iii) species would show species-specific responses that differed between areas. We tested these predictions by conducting extensive breeding bird censuses in Chernobyl during four years 2006–2009 and in Fukushima in 2011, using exactly the same methods, procedures and individuals to conduct the censuses. In addition, we compare the response of the same 14 species that co-occur in both areas to radiation, allowing for stringent tests that would be independent of differences in ecology and evolutionary history.

2. Material and methods

Breeding bird censuses were conducted within the Chernobyl Exclusion Zone or adjacent areas on the southern and western borders with a permit from the Ukrainian authorities and in areas in southern Belarus around Gomel during the breeding seasons 2006–2009 (Fig. 1A). We conduced similar censuses at a total of 300 sampling points in forested areas west of the exclusion zone around the Fukushima Daiichi power plants in 2011 (Fig. 1B). Information on census methods, confounding variables, repeatability of density estimates, radiation measurements and statistical analyses are reported in Electronic Supplementary Material 1.

3. Results and discussion

Radioactive contamination can negatively affect the abundance of living beings through the toxic effects of radionuclides or through effects related to the accumulation of mutations (Møller and Mousseau, 2006). We related bird abundance to background radiation level after controlling statistically for potentially confounding effects of time of day, weather and habitat on abundance of birds (Møller and Mousseau, 2011a; Electronic Supplementary Material 2). Bird abundances showed a significant decline with increasing background radiation both in Chernobyl and Fukushima ($F_{1,1194} = 66.49$, $P < 0.0001$, slope (SE) $= -0.092$ (0.011)), with no significant effect of study area (Chernobyl or Fukushima: $F_{1,1194} = 0.43$, $p = 0.51$) or difference in effect of radiation between areas (interaction between radiation and area: $F_{1,1194} = 1.45$, $P = 0.23$). This implies that for the **same** level of radiation we found a similar decline in abundance with increasing level of radiation. This result implies that differences between the two disaster zones are much less important than the similarities, most likely caused by radioactive contamination.

Most species had reduced population density at higher levels of background radiation (Fig. 2), after controlling for potentially confounding variables (Møller and Mousseau, 2011a; Electronic Supplementary Material 2). The slope describing the relationship between abundance and radiation was on average strongly negative both in Chernobyl (-0.063 (SE $= 0.007$), $N = 80$ species, one-sample t-test, $t_{79} = -8.69$, $P < 0.0001$) and in Fukushima (-0.040 (SE $= 0.008$), $N = 45$ species, one-sample t-test, $t_{44} = -4.81$, $P < 0.0001$). Thus, the effect of radiation on abundance was stronger in species breeding in Chernobyl than in Fukushima ($F_{1,123} = 3.80$, $r^2 = 0.03$, $P = 0.040$).

We used extensive and unique data obtained from large-scale censuses of breeding birds in the vicinity of Chernobyl in Ukraine and Belarus and in the vicinity of Fukushima in Japan to test for an effect of radiation on abundance. There was extensive evidence consistent with the hypothesis that low-dose radiation has significant negative consequences for birds because most species had suppressed populations in more contaminated areas (Fig. 2). A direct comparison of these negative effects in the two disaster zones revealed for 80 species in Chernobyl a more strongly negative effect of radiation on abundance than for the 45 species recorded in Fukushima. These effects were independent of habitat, weather and time of day when the censuses were conducted, making it unlikely that any uncontrolled, additional variables could be the underlying cause for the negative relationships. Our previous studies in the

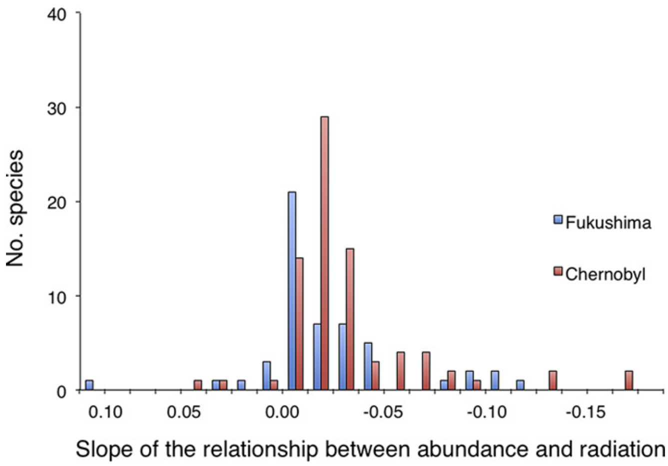

Fig. 2. Frequency distribution of the number of bird species with different slopes of the relationship between abundance and background radiation level, after controlling statistically for the potentially confounding effects of habitat variables, weather, and time of day. See Materials and methods for further details. Note that there are many more negative slopes than would be expected by chance alone, implying that most species have declines in abundance in more heavily contaminated areas.

vicinity of Chernobyl have also revealed very similar results independent of statistical control for effects of potentially confounding variables (Møller and Mousseau, 2011a).

To further assess the possible effects of radiation, we analyzed the 14 bird species that were breeding both in Fukushima and Chernobyl, relating their abundance to radiation without the potentially confounding effects of differences in ecology among species and different phylogenetic histories that could have affected the analyses of all species. In these 14 bird species there was a significant negative relationship between abundance and radiation (Table 1), as found for all bird species, and there was also a significant difference between areas, with density being higher in Fukushima than in Chernobyl (Table 1). Species differed significantly in abundance (Table 1). The radiation effect differed between areas, as shown by the interaction between radiation and area (Table 1). The mean slope of the relationship between abundance and radiation for the 14 species of birds in Fukushima (−0.067 (SE = 0.011)) was more negative than the mean slope for the same 14 species in Chernobyl (−0.008 (0.001); paired t-test, $t_{13} = -3.32$, $P = 0.0055$). This difference in effect between Fukushima and Chernobyl is unbiased by effects due to ecology and common phylogenetic descent and is therefore more reliable than the apparently stronger effect for Chernobyl than for Fukushima, when analyzing all species (see above). The stronger negative effect for the same level of background radiation on abundance of exactly the same bird species in Fukushima than in Chernobyl may be interpreted as being due to (1) selection already having eliminated individuals with accumulated mutations in Chernobyl to a greater extent than in Fukushima; (2) the composition of radionuclides being more dangerous for birds in Fukushima than in Chernobyl (perhaps an unlikely explanation); or (3) the higher density in Fukushima than in Chernobyl increasing the intensity of intraspecific competition and therefore the negative effects of radiation. The relationship between abundance and radiation also differed significantly among species, as shown by the interaction between radiation and species (Table 1). The difference in abundance between Chernobyl and Fukushima differed among species, as shown by the significant area by species interaction (Table 1). Finally, the different effect of radiation on species was not the same in the two areas, as shown by the interaction between radiation, area and species (Table 1).

Table 1
Abundance of the same 14 species of birds in Chernobyl and Fukushima in relation to radiation level at 1198 census points (898 in Chernobyl and 300 in Fukushima). The overall model had the statistics $F_{55,16716} = 47.60$, $r^2 = 0.14$, $P < 0.0001$.

	Sum of squares	d.f.	F	P	Estimate (SE)
Radiation (R)	1.019	1	136.81	<0.0001	−0.011 (0.0014)
Area (A)	0.412	1	55.29	<0.0001	0.013 (0.0011)
Species (S)	7.102	13	73.36	<0.0001	
R × A	0.240	1	32.28	<0.0001	−0.008 (0.0014)
R × S	1.354	13	13.99	<0.0001	
A × S	6.846	13	70.72	<0.0001	
R × A × S	1.210	13	12.50	<0.0001	
Error	124.47	16,716			

Although Chernobyl and Fukushima are located more than 7000 km apart, they still share a large number of species due to the fact that the two sites are both located in the Palearctic zoogeographic region. We identified 14 species of birds that were common to the two sites, allowing us to conduct a particularly stringent test of the hypothesis that radiation would differ negative impact on abundance even when comparing populations of the same species in the two areas. Detailed analyses of species common to the two disaster zones revealed a more strongly negative relationship between abundance and radiation at Fukushima than at Chernobyl, demonstrating an immediate negative consequence of radiation for birds during the main breeding season March–July 2011, when individual birds are known to work close to their maximum sustainable level (Drent and Daan, 1980). Previous research at Chernobyl has shown that bird species with high metabolic rates and hence high rate of use of antioxidants suffer disproportionately from the negative effects of radiation on the production of free radicals (Galván et al., 2011; Bonisoli-Alquati et al., 2010b). A reduction in the level of free radicals will have consequences for damage to DNA (Bonisoli-Alquati et al., 2010a), the ability to reproduce and survive (Møller et al., 2005), and normal development of neurological tissues (e.g. brains) (Almond et al., 2007; Møller et al., 2011).

In conclusion, the data presented here constitute the first investigation of initial biological community responses to the radioactive fallout from the Fukushima disaster. The parallels and contrasts with prior results from Chernobyl suggest that organismal responses to radionuclides can be immediate and large. The prolonged, relatively larger impacts on Chernobyl communities point to possible sustained, longer term impacts on organisms that may reflect cumulative, multigenerational consequences of mutation accumulation within populations, as suggested by Møller and Mousseau (2011a,b). The disaster at Chernobyl, and now Fukushima, provide unique opportunities to assess the risks and hazards of prolonged exposure to mutagenic contaminants that likely have relevance for other communities inhabiting the regions affected by these disasters.

Acknowledgments

We gratefully acknowledge logistic support and help by I. Chizhevsky and G. Milinevski. We also acknowledge support from the US National Science Foundation, the University of South Carolina School of the Environment, the NATO CLG program, the CNRS, the CRDF, the Fulbright Program, the National Geographic Society, and the Samuel Freeman Charitable Trust for research in Chernobyl, and the University of South Carolina, the CNRS and Qiagen GmbH for research in Japan.

Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envpol.2012.01.008.

References

Almond, D., Edlund, L., Palmer, M., 2007. Chernobyl's subclinical legacy: prenatal exposure to radioactive fallout and school outcomes in Sweden. National Bureau of Economic Research 13347, 1–50.

Bonisoli-Alquati, A., Voris, A., Mousseau, T.A., Møller, A.P., Saino, N., Wyatt, M., 2010a. DNA damage in barn swallows (*Hirundo rustica*) from the Chernobyl region detected by use of the Comet assay. Comparative Biochemistry and Physiology C 151, 271–277.

Bonisoli-Alquati, A., Mousseau, T.A., Møller, A.P., Caprioli, M., Saino, N., 2010b. Increased oxidative stress in barn swallows from the Chernobyl region. Comparative Biochemistry and Physiology A 155, 205–210.

Drent, R.H., Daan, S., 1980. The prudent parent. Ardea 68, 225–252.

Galván, I., Mousseau, T.A., Møller, A.P., 2011. Bird population declines due to radiation exposure at Chernobyl are stronger in species with pheomelanin-based coloration. Oecologia 165, 827–835.

Krivolutsky, D.A., Pokarshevsky, A.D., 1992. Effects of radioactive fallout on soil animals populations in the 30 km zone of the Chernobyl atomic power plant. Science of the Total Environment 112, 69–77.

Maksimova, S., 2002. The effect of radioactive contamination caused by the Chernobyl nuclear accident on Diplopoda communities. Acta Zoologica Lituanica 12, 90–94.

Møller, A.P., Bonisoli-Alquati, A., Rudolfsen, G., Mousseau, T.A., 2011. Chernobyl birds have smaller brains. Public Library of Science One 6 (2), e16862.

Møller, A.P., Mousseau, T.A., 2006. Biological consequences of Chernobyl: 20 years after the disaster. Trends in Ecology and Evolution 21, 200–207.

Møller, A.P., Mousseau, T.A., 2007. Species richness and abundance of birds in relation to radiation at Chernobyl. Biology Letters 3, 483–486.

Møller, A.P., Mousseau, T.A., 2011a. Efficiency of bio-indicators for low-level radiation under field conditions. Ecological Indicators 11, 424–430.

Møller, A.P., Mousseau, T.A., 2011b. Conservation consequences of Chernobyl and other nuclear accidents. Biological Conservation 114, 2787–2798.

Møller, A.P., Mousseau, T.A., Milinevsky, G., Peklo, A., Pysanets, E., Szép, T., 2005. Condition, reproduction and survival of barn swallows from Chernobyl. Journal of Animal Ecology 74, 1102–1111.

Mousseau, T.A., Møller, A.P., 2011. Landscape portrait: a look at the impacts of radioactive contaminants on Chernobyl's wildlife. Bulletin of Atomic Scientists 67, 38–46.

Shestopalov, V.M., 1996. Atlas of Chernobyl Exclusion Zone. Ukrainian Academy of Science, Kiev, Ukraine.

Voříšek, P., Klvanova, A., Wotton, S., Gregory, R.D., 2010. A Best Practice Guide for Wild Bird Monitoring Schemes. European Union, Bruxelles, Belgium.