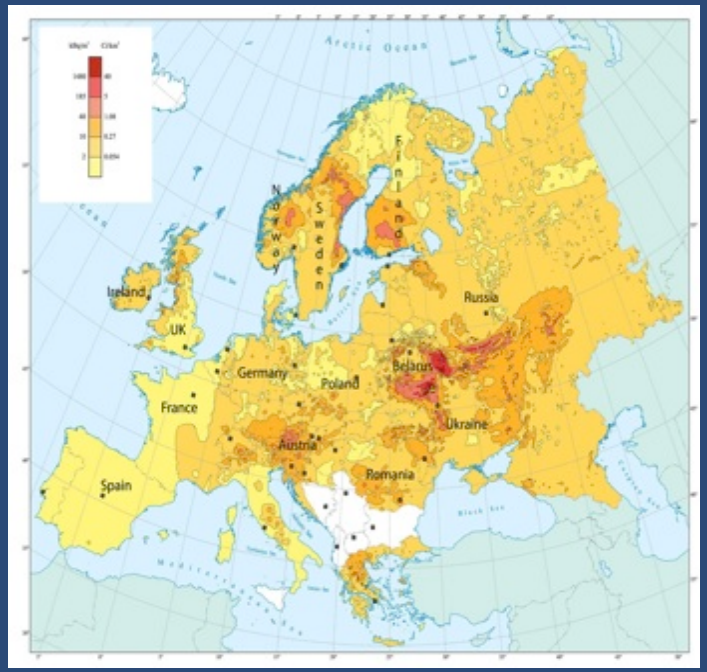
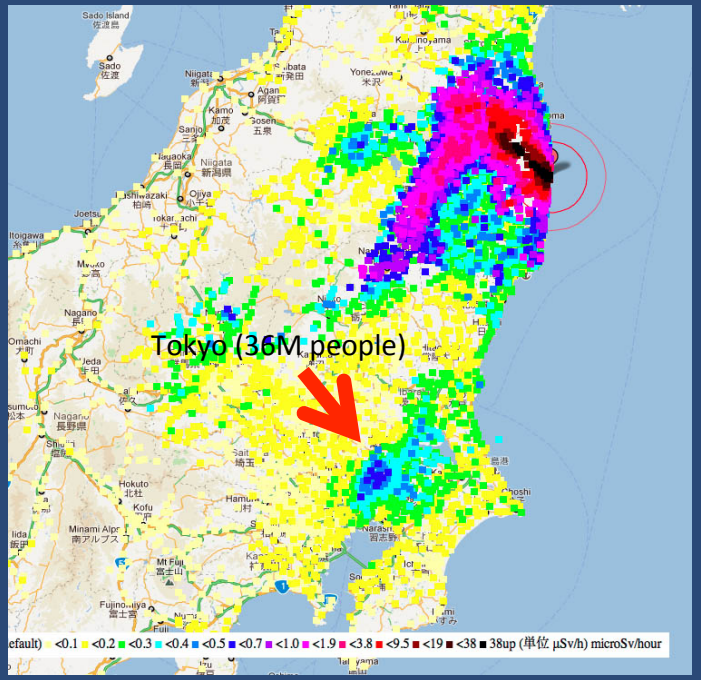
The Consequences of Radiation for Wildlife: Of Blind Mice and Bird Brains

Timothy A. Mousseau, PhD

Professor of Biological Sciences

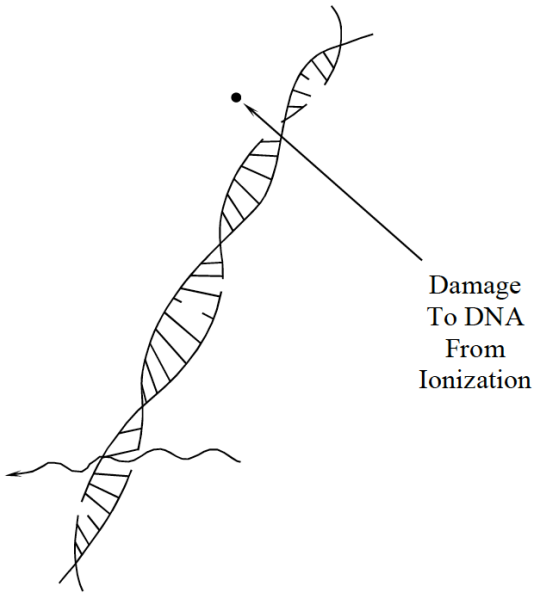
University of South Carolina





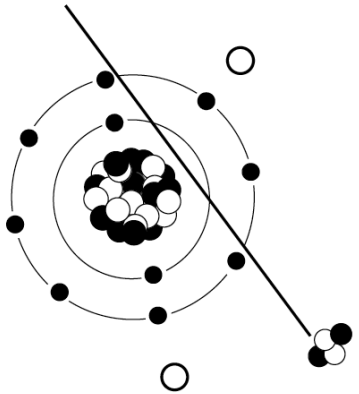
Radiation Causes Genetic Damage

Direct Effect



If radiation interacts with the atoms of the DNA molecule, or some other cellular component critical to the survival of the cell, it is referred to as a direct effect. Such an interaction may affect the ability of the cell to reproduce and, thus, survive. If enough atoms are affected such that the chromosomes do not replicate properly, or if there is significant alteration in the information carried by the DNA molecule, then the cell may be destroyed by "direct" interference with its life-sustaining system.

Indirect Effect



Radiolytic Decomposition of Water in a Cell

If a cell is exposed to radiation, the probability of the radiation interacting with the DNA molecule is very small since these critical components make up such a small part of the cell. However, each cell, just as is the case for the human body, is mostly water. Therefore, there is a much higher probability of radiation interacting with the water that makes up most of the cell's volume.

When radiation interacts with water, it may break the bonds that hold the water molecule together, producing fragments such as hydrogen (H) and hydroxyls (OH). These fragments may recombine or may interact with other fragments or ions to form compounds, such as water, which would not harm the cell. However, they could combine to form toxic substances, such as hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.

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SUBJECT AREAS:
ECOLOGICAL GENETICS
EVOLUTIONARY GENETICS

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Strong effects of ionizing radiation from Chernobyl on mutation rates

Anders Pape Møller[1] & Timothy A. Mousseau[2]

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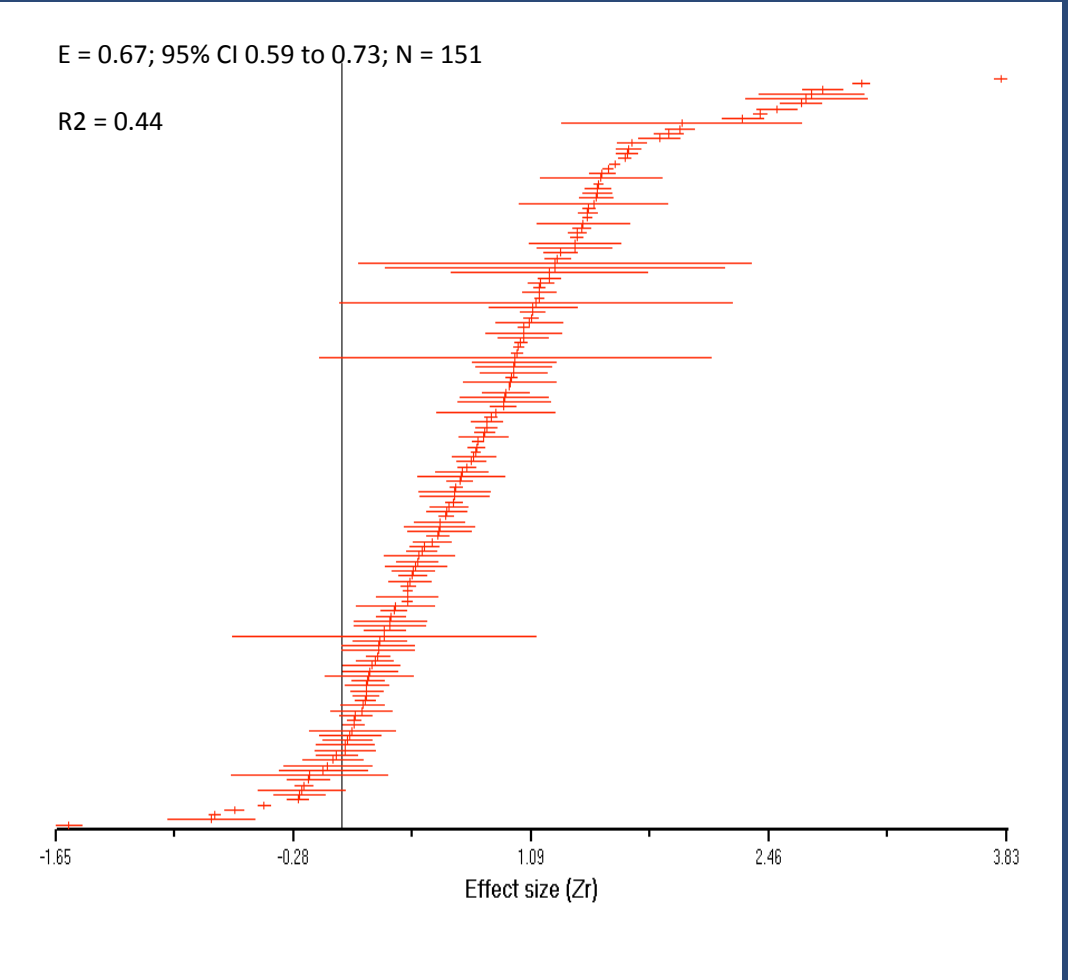
In this paper we use a meta-analysis to examine the relationship between radiation and mutation rates in Chernobyl across 45 published studies, covering 30 species. Overall effect size of radiation on mutation rates estimated as Pearson's product-moment correlation coefficient was very large ($E = 0.67$; 95% confidence intervals (CI) 0.59 to 0.73), accounting for 44.3% of the total variance in an unstructured random-effects model. Fail-safe calculations reflecting the number of unpublished null results needed to eliminate this average effect size showed the extreme robustness of this finding (Rosenberg's method: 4135 at $p = 0.05$). Indirect tests did not provide any evidence of publication bias. The effect of radiation on mutations varied among taxa, with plants showing a larger effect than animals. Humans were shown to have intermediate sensitivity of mutations to radiation compared to other species. Effect size did not decrease over time, providing no evidence for an improvement in environmental conditions. The surprisingly high mean effect size suggests a strong impact of radioactive contamination on individual fitness in current and future generations, with potentially significant population-level consequences, even beyond the area contaminated with radioactive material.

Chernobyl: Radiation and Mutation, a Meta-Analysis



A. P. Møller, T. A. Mousseau. 2015. Strong effects of ionizing radiation on mutation rates from Chernobyl. Nature Scientific Reports .

Science of the Total Environment 548–549 (2016) 463–471

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Ionizing radiation, antioxidant response and oxidative damage: A meta-analysis

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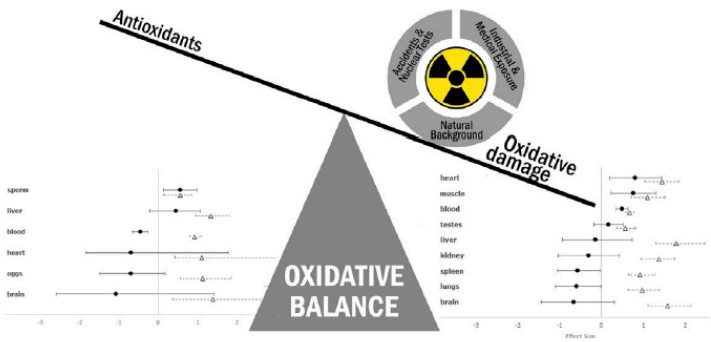
HIGHLIGHTS

- There is interest in variation in metabolic effects of chronic low-dose ionizing radiation
- A random effect meta-analysis of effect sizes of radioactive contamination was performed
- We found significant effects of radiation on oxidative damage and antioxidant response
- We found significant heterogeneity among biological matrices, species and age classes

GRAPHICAL ABSTRACT



Radiation, Genetic Damage, and Oxidative Stress Cause Many Effects on Development and Morphology

- **Sperm morphology, swimming performance, and sterility**
- **Cataracts in eyes of birds and rodents**
- **Tumors in birds and rodents**
- **Brain size in birds and mammals**
- **Many other developmental malformations in birds, rodents, insects, plants**

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PLOS ONE

Aspermy, Sperm Quality and Radiation in Chernobyl Birds

Anders Pape Møller[1]*, Andrea Bonisoli-Alquati[2], Timothy A. Mousseau[2], Geir Rudolfsen[3]

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Abstract

Background: Following the Chernobyl nuclear power plant accident, large amounts of radionuclides were emitted and spread in the environment. Animals living in such contaminated areas are predicted to suffer fitness costs including reductions in the quality and quantity of gametes.

Methodology/Principal Findings: We studied whether aspermy and sperm quality were affected by radioactive contamination by examining ejaculates from wild caught birds breeding in areas varying in background radiation level by more than three orders of magnitude around Chernobyl, Ukraine. The frequency of males with aspermy increased logarithmically with radiation level. While 18.4% of males from contaminated areas had no sperm that was only the case for 3.0% of males from uncontaminated control areas. Furthermore, there were negative relationships between sperm quality as reflected by reduced sperm velocity and motility, respectively, and radiation.

Conclusions/Significance: Our results suggest that radioactive contamination around Chernobyl affects sperm production and quality. We are the first to report an interspecific difference in sperm quality in relation to radioactive contamination.

Citation: Møller AP, Bonisoli-Alquati A, Mousseau TA, Rudolfsen G (2014) Aspermy, Sperm Quality and Radiation in Chernobyl Birds. PLoS ONE 9(6): e100296. doi:10.1371/journal.pone.0100296

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High frequency of albinism and tumours in free-living birds around Chernobyl

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Population decline
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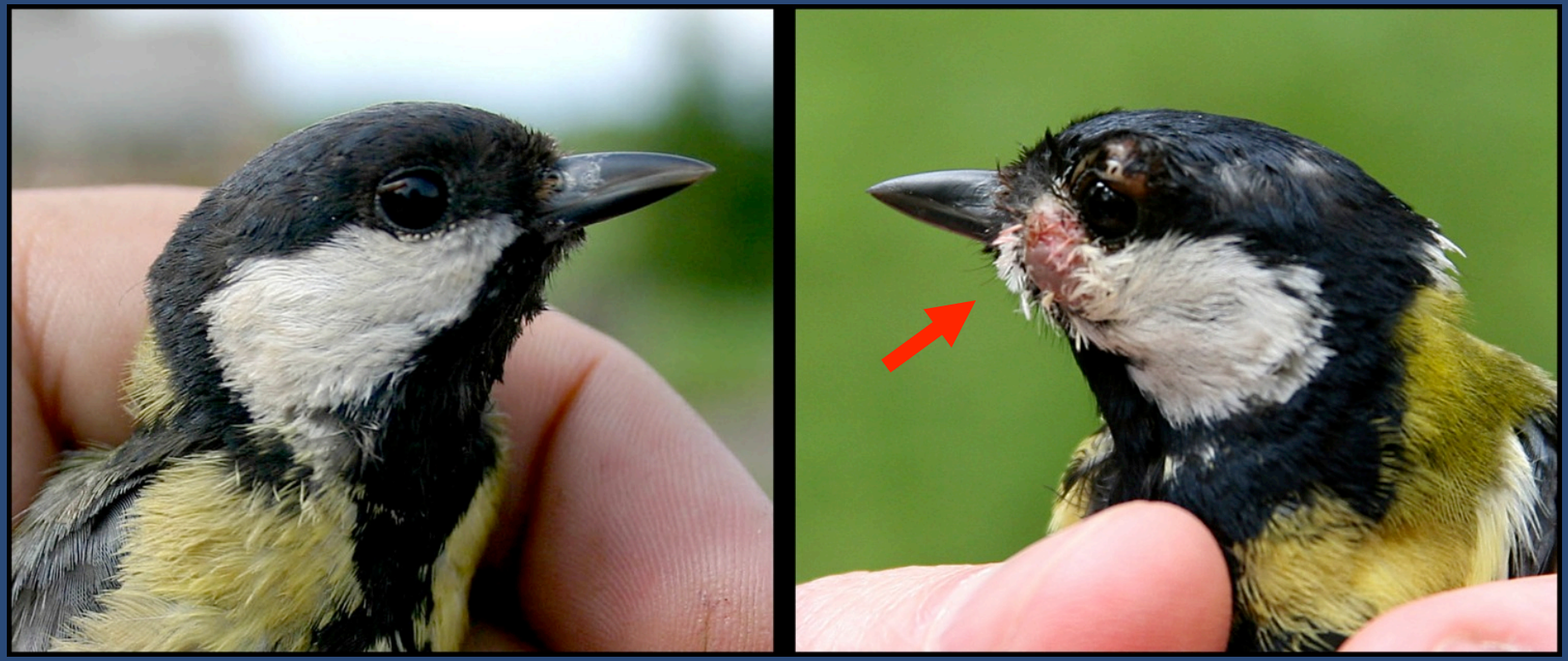
Tumours

ABSTRACT

The effects of radioactive contamination on the phenotype of free-living organisms are poorly understood, mainly because of the difficulty of capturing the large numbers of individual specimens that are required to quantify rare events such as albinism and tumour formation. We hypothesized that the frequency of abnormalities like albinism and the frequency of radiation-induced diseases like cancer would increase with the level of background radiation, that the two markers of radiation would be positively correlated, and that the reduction in abundance of animals would be greater in species with a higher frequency of albinism and tumour formation, if these markers reliably reflected poor viability. Here we analyzed the frequency of albinistic feathers and tumours in a sample of 1669 birds captured during 2010–2012 at eight sites around Chernobyl that varied in level of background radiation from 0.02 to more than 200 μSv/h. We recorded 111 cases of partial albinism and 25 cases of tumour formation. Nominal logistic models were used to partition the variance into components due to species and background radiation. Radiation was a strong predictor of the two markers in birds, with a small, but significant effect of species for albinism. The slope of the relationship between abundance and radiation in different bird species was significantly inversely correlated with the frequency of albinism and tumours, as was to be expected if a common underlying cause (i.e. radiation) affects both variables. These findings are consistent with the hypothesis that background radiation is a cause of albinism and tumours, that albinism and tumours are biomarkers of radiation exposure, and that high frequencies of albinism and tumours were present despite the low viability of birds with these conditions.

Great tit, *Parus major*



Tumor around eye

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PLOS ONE

Elevated Frequency of Cataracts in Birds from Chernobyl

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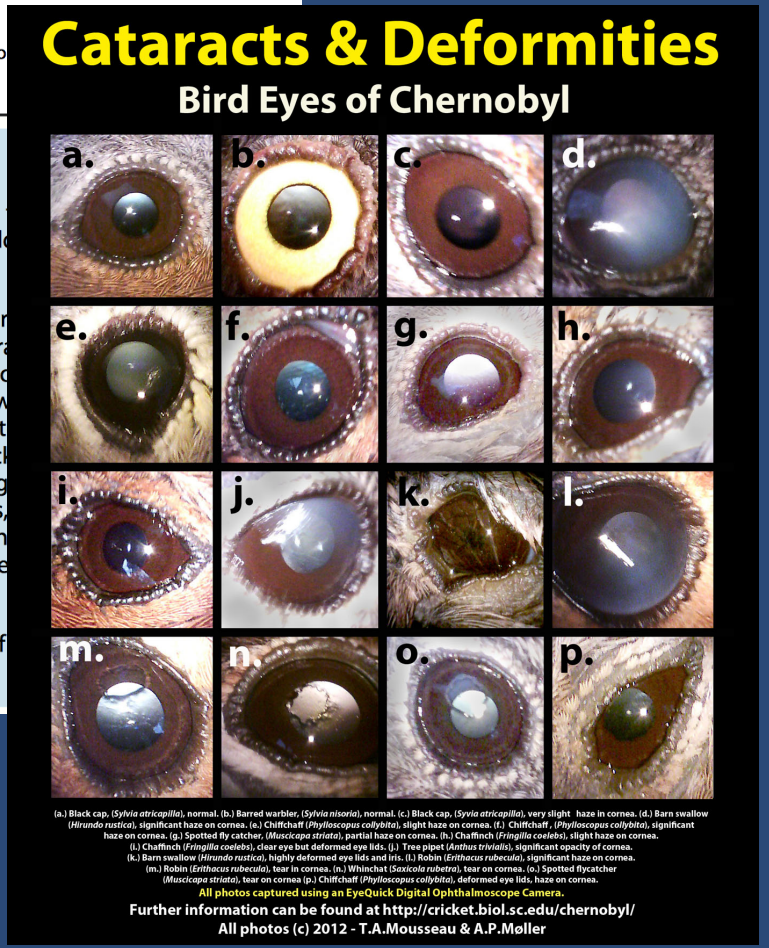
1 Department of Biological Sciences, University of South Carolina, Columbia, South Carolina, United States of America, **2** Labo
Evolution, CNRS UMR 8079, Université Paris-Sud, Orsay, France

Abstract

Background: Radiation cataracts develop as a consequence of the effects of ionizing radiation on
lens of the eye with an opaque lens reducing or eliminating the ability to see. Therefore, we woul
associated with reduced fitness in free-living animals.

Methodology/Principal Findings: We investigated the incidence of lens opacities typical of catar
free-living birds in the Chernobyl region in relation to background radiation. The incidence of catar
of background radiation both in analyses based on a dichotomous score and in analyses of continuo
cataracts. The odds ratio per unit change in the regressor was 0.722 (95% CI 0.648, 0.804), which w
from investigations of radiation cataracts in humans. The relatively small odds ratio may be due t
birds with cataracts. We found a stronger negative relationship between bird abundance and bac
the frequency of cataracts was higher, but also a direct effect of radiation on abundance, suggesting
affects abundance negatively through an increase in the frequency of cataracts in bird populations,
effects of radiation on other diseases, food abundance and interactions with other species. Th
incidence of cataracts with increasing age, suggesting that yearlings and older individuals were
typical of radiation cataract.

Conclusions/Significance: These findings suggest that cataracts are an under-estimated cause of
birds and, by inference, other vertebrates in areas contaminated with radioactive materials.



www.nature.com/scientificreports

SCIENTIFIC REPORTS

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Fitness costs of increased cataract frequency and cumulative radiation dose in natural mammalian populations from Chernobyl

Received: 11 June 2015
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Philipp Lehmann[1,2], Zbyszek Boratyński[3], Tapio Mappes[1], Timothy A. Mousseau[4] & Anders P. Møller[5]

A cataract is a clouding of the lens that reduces light transmission to the retina, and it decreases the visual acuity of the bearer. The prevalence of cataracts in natural populations of mammals, and their potential ecological significance, is poorly known. Cataracts have been reported to arise from high levels of oxidative stress and a major cause of oxidative stress is ionizing radiation. We investigated whether elevated frequencies of cataracts are found in eyes of bank voles *Myodes glareolus* collected from natural populations in areas with varying levels of background radiation in Chernobyl. We found high frequencies of cataracts in voles collected from different areas in Chernobyl. The frequency of cataracts was positively correlated with age, and in females also with the accumulated radiation dose.

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PLoS one

Chernobyl Birds Have Smaller Brains

Anders Pape Møller[1]*, Andea Bonisoli-Alquati[2], Geir Rudolfsen[3], Timothy A. Mousseau[2]

1 Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Orsay, France, **2** Department of Biological Sciences, University of South Carolina, Columbia, South Carolina, United States of America, **3** Norwegian Radiation Protection Authority (NRPA), Department of Environmental Radioactivity, The Polar Environmental Center, Tromsø, Norway

Abstract

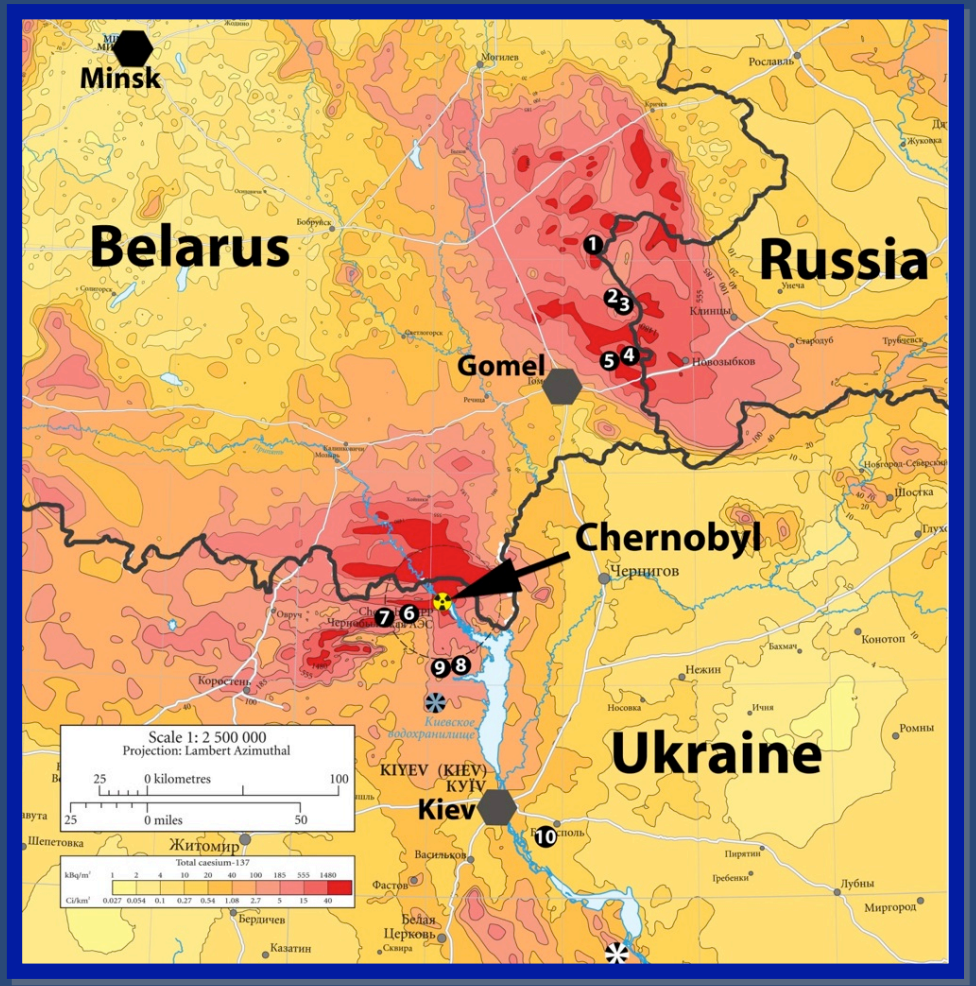
Background: Animals living in areas contaminated by radioactive material from Chernobyl suffer from increased oxidative stress and low levels of antioxidants. Therefore, normal development of the nervous system is jeopardized as reflected by high frequencies of developmental errors, reduced brain size and impaired cognitive abilities in humans. Alternatively, associations between psychological effects and radiation have been attributed to post-traumatic stress in humans.

Methodology/Principal Finding: Here we used an extensive sample of 550 birds belonging to 48 species to test the prediction that even in the absence of post-traumatic stress, there is a negative association between relative brain size and level of background radiation. We found a negative association between brain size as reflected by external head volume and level of background radiation, independent of structural body size and body mass. The observed reduction in brain size in relation to background radiation amounted to 5% across the range of almost a factor 5,000 in radiation level. Species differed significantly in reduction in brain size with increasing background radiation, and brain size was the only morphological character that showed a negative relationship with radiation. Brain size was significantly smaller in yearlings than in older individuals.

Conclusions/Significance: Low dose radiation can have significant effects on normal brain development as reflected by brain size and therefore potentially cognitive ability. The fact that brain size was smaller in yearlings than in older individuals implies that there was significant directional selection on brain size with individuals with larger brains experiencing a viability advantage.

Injury to Individuals Causes Population, Community, and Ecosystem Effects

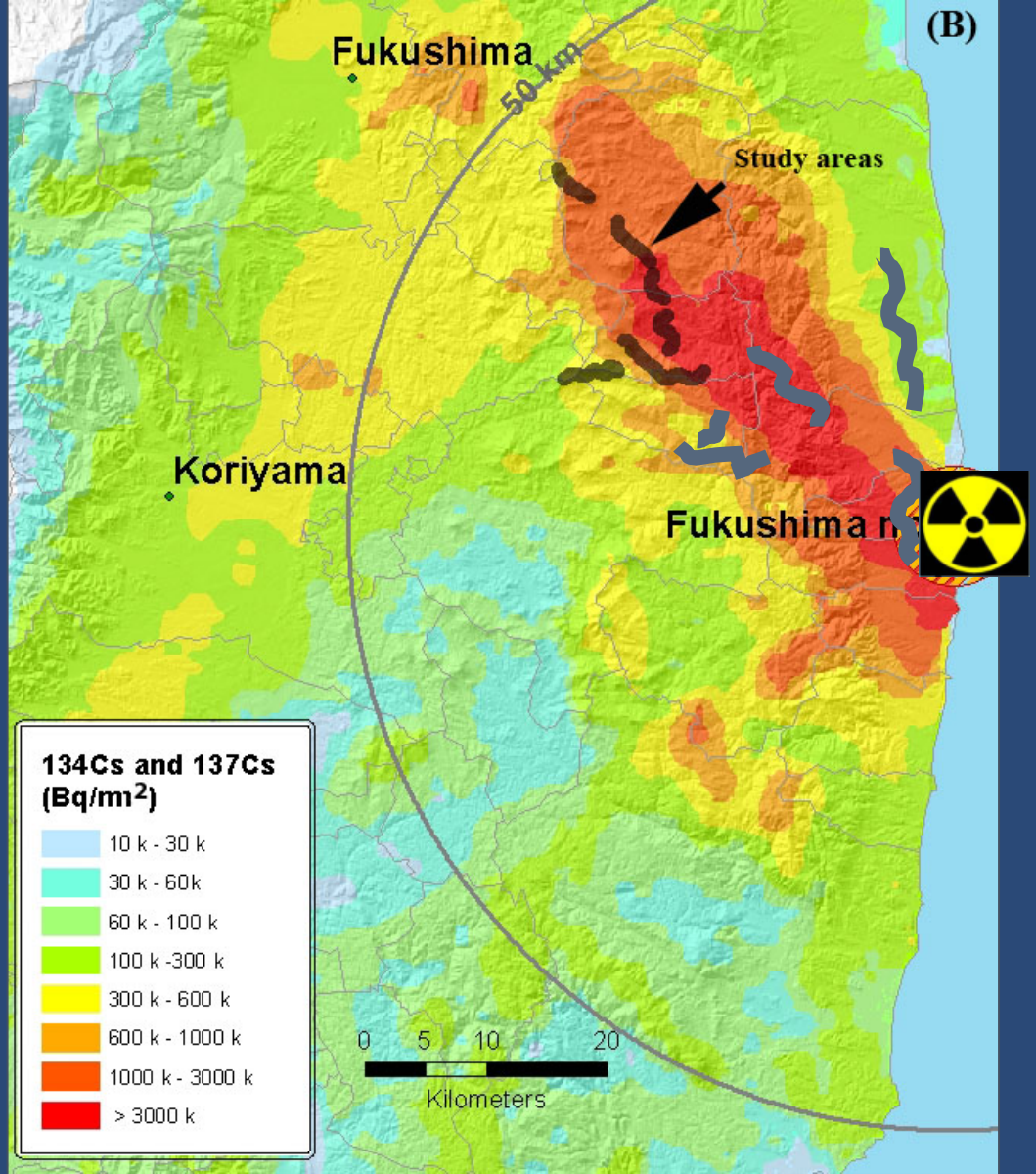
Most of our research includes areas of the highest contamination in addition to control areas. Patchiness of deposition permits disentanglement of radiation, distance from source, and other environmental factors that influence abundance and biodiversity.



- 896 bird and insect surveys from about 300 locations in Ukraine and Belarus

Control Populations:

- Italy (Milan)
- Spain (Badajoz)
- Denmark (Aalborg)
- Ukraine



Surveys of birds and insects from 400 discrete locations, 1500 inventories in total to date.

Massively Replicated Biotic Inventories

(1500 in Fukushima, 896 in Chernobyl)

+

Measures of Multiple Environmental Variables

(e.g. meteorology, hydrology, geology, plant community, Habitat type, land use history, plant coverage amount and type, altitude, meteorological conditions, time, date, distance to nearest water source, etc)

+

Field Measures of Residential Radiation Levels

+

GIS

+

Multivariate Statistics

=

Predictive Models of Radiation Effects on Populations

All Major Groups of Organisms Surveyed at Chernobyl Show Significant Declines in Areas of High Radiation

Birds, mammals, insects, spiders, amphibians, etc

SCIENTIFIC REPORTS

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Radiological dose reconstruction for birds reconciles outcomes of Fukushima with knowledge of dose-effect relationships

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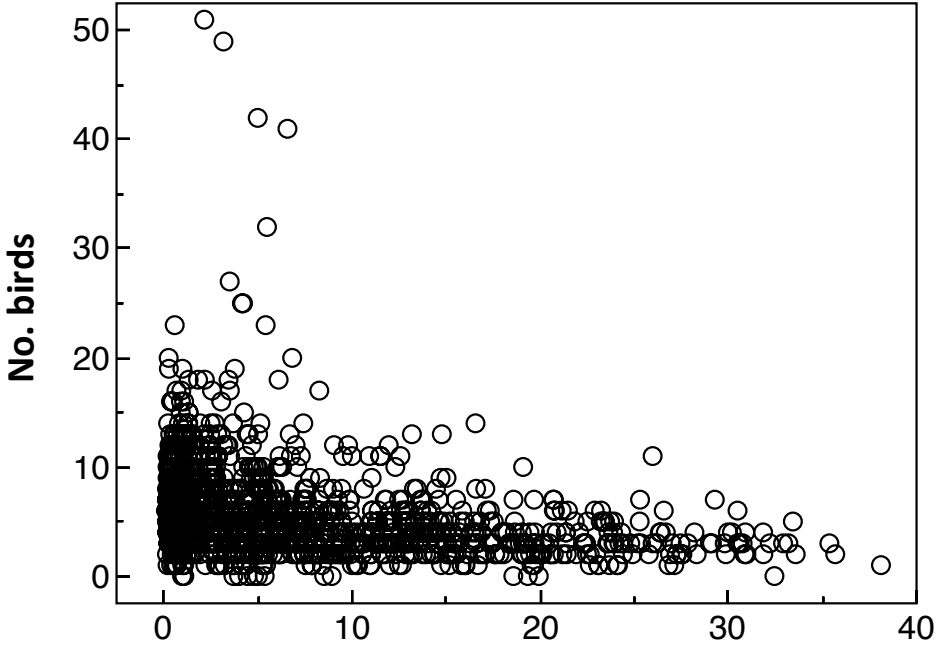
Accepted: 15 October 2015
Published: xx xx xxxx

Jacqueline Garnier-Laplace[1], Karine Beaugelin-Seiller[1], Claire Della-Vedova[1], Jean-Michel Métivier[1], Christian Ritz[2], Timothy A. Mousseau[3] & Anders Pape Møller[4]

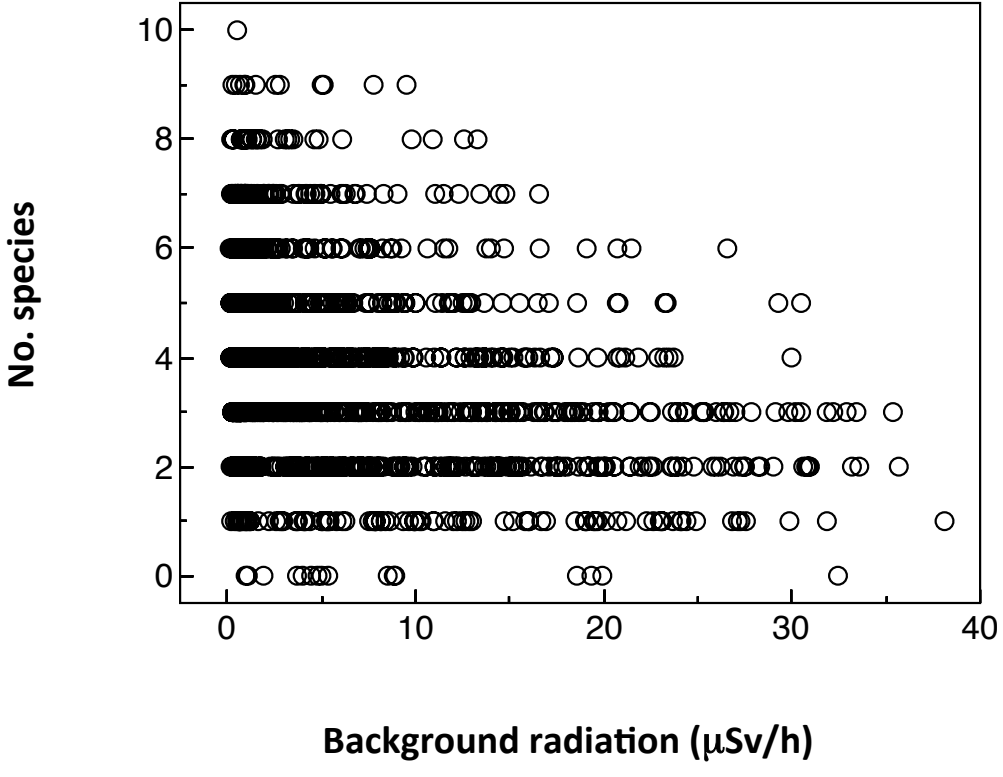
We reconstructed the radiological dose for birds observed at 300 census sites in the 50-km northwest area affected by the accident at the Fukushima Daiichi nuclear power plant over 2011–2014. Substituting the ambient dose rate measured at the census points (from 0.16 to 31 μGy h^{-1}) with the dose rate reconstructed for adult birds of each species (from 0.3 to 97 μGy h^{-1}), we confirmed that the overall bird abundance at Fukushima decreased with increasing total doses. This relationship was directly consistent with exposure levels found in the literature to induce physiological disturbances in birds. Among the 57 species constituting the observed bird community, we found that 90% were likely chronically exposed at a dose rate that could potentially affect their reproductive success. We quantified a loss of 22.6% of the total number of individuals per increment of one unit log_{10}-tansformed total dose (in Gy), over the four-year post-accident period in the explored area. We estimated that a total dose of 0.55 Gy reduced by 50% the total number of birds in the study area over 2011–2014. The data also suggest a significant positive relationship between total dose and species diversity.

Abundance and radiation – Fukushima Birds 2011-14

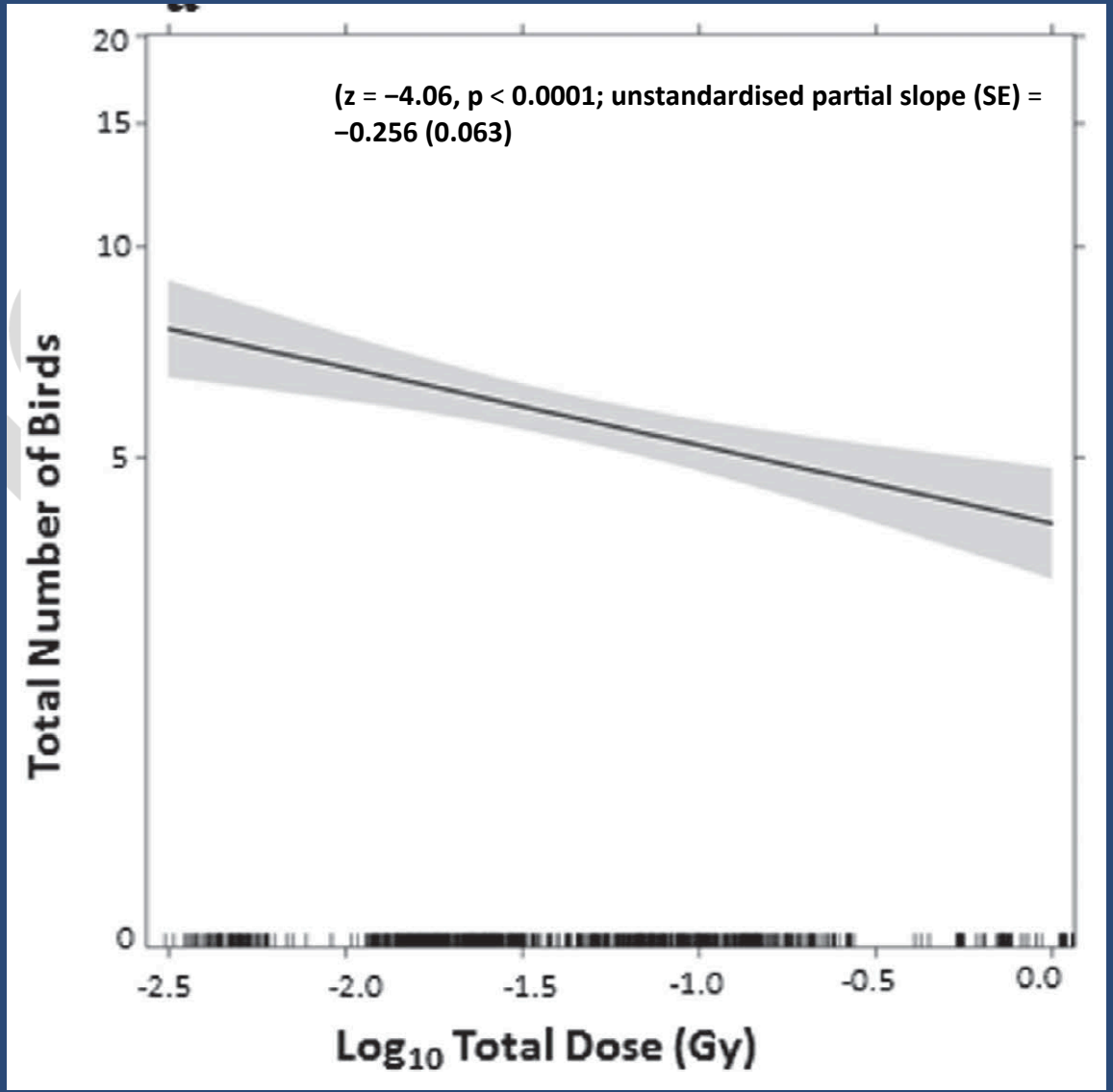


$\chi^2 = 241.93$, $P < 0.0001$

Species richness and radiation - Fukushima Birds 2011-14



$\chi^2 = 100.30$, $P < 0.0001$



Fukushima 2011-2014

Trees
DOI 10.1007/s00468-013-0891-z

ORIGINAL PAPER

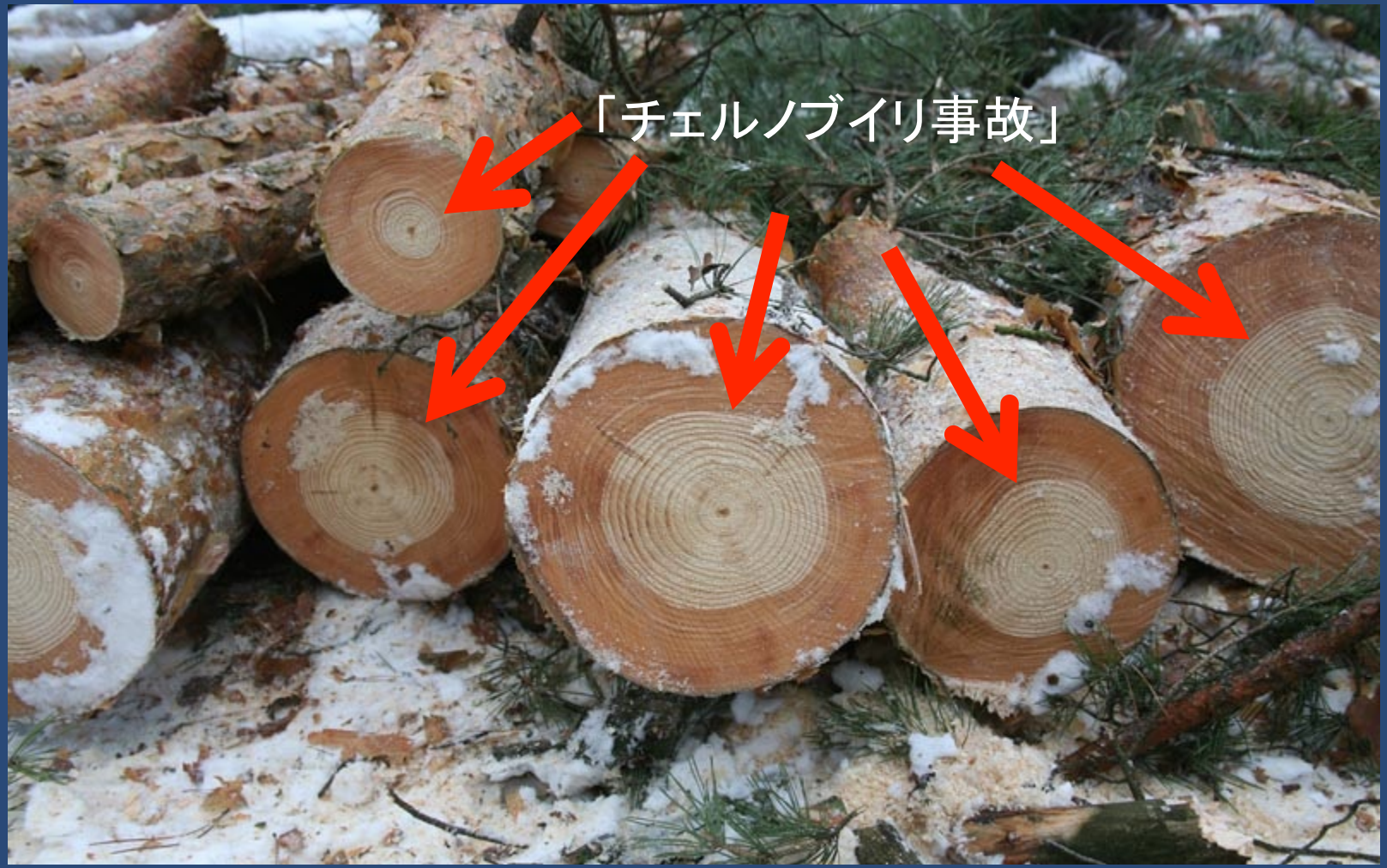
Tree rings reveal extent of exposure to ionizing radiation in Scots pine *Pinus sylvestris*

Timothy A. Mousseau · Shane M. Welch · Igor Chizhevsky · Oleg Bondarenko · Gennadi Milinevsky · David J. Tedeschi · Andrea Bonisoli-Alquati · Anders Pape Møller

Received: 14 December 2012 / Revised: 12 April 2013 / Accepted: 30 May 2013

Abstract Tree growth has been hypothesized to provide a reliable indicator of the state of the external environment. Elevated levels of background ionizing radiation may impair growth trajectories of trees by reducing the annual drought or their interactions with background radiation. Elevated temperatures suppressed individual growth rates in particular years. Finally, the negative effects of radioactive contaminants were particularly pronounced in

放射線と樹木の生長



Oecologia
DOI 10.1007/s00442-014-2908-8

GLOBAL CHANGE ECOLOGY - ORIGINAL RESEARCH

Highly reduced mass loss rates and increased litter layer in radioactively contaminated areas

Timothy A. Mousseau · Gennadi Milinevsky · Jane Kenney-Hunt · Anders Pape Møller

Received: 24 June 2013 / Accepted: 13 February 2014

Abstract The effects of radioactive contamination from Chernobyl on decomposition of plant material still remain unknown. We predicted that decomposition rate would be reduced in the most contaminated sites due to an absence or reduced densities of soil invertebrates. If microorganisms were the main agents responsible for decomposition, exclusion of large soil invertebrates should not affect decomposition. In September 2007 we deposited 572 bags loss was 40 % lower in the most contaminated sites relative to sites with a normal background radiation level for Ukraine. Similar reductions in litter mass loss were estimated for individual litter bags, litter bags at different sites, and differences between litter bags at pairs of neighboring sites differing in level of radioactive contamination. Litter mass loss was slightly greater in the presence of large soil invertebrates than in their absence. The thickness of the for-

Trends in Ecology & Evolution

CellPress

Review

Are Organisms Adapting to Ionizing Radiation at Chernobyl?

Anders Pape Møller[1,2,*] and Timothy Alexander Mousseau[3]

Numerous organisms have shown an ability to survive and reproduce under low-dose ionizing radiation arising from natural background radiation or from nuclear accidents. In a literature review, we found a total of 17 supposed cases of adaptation, mostly based on common garden experiments with organisms only deriving from typically two or three sampling locations. We only found one experimental study showing evidence of improved resistance to radiation. Finally, we examined studies for the presence of hormesis (i.e., superior fitness at low levels of radiation compared with controls and high levels of radiation), but found no evidence to support its existence. We conclude that rigorous experiments based on extensive sampling from multiple sites are required.

Trends

In total,17 studies have suggested that they have demonstrated adaptation to ionizing radiation from Chernobyl, while in fact only two of these fulfill the criteria for evolutionary adaptation.

Lack of evidence of adaptation mainly derived from the lack of replication and of rigorous experimental design.

There was no evidence of hormesis, with organisms at low levels of radiation

What does this all mean?

- Contrary to governmental and media reports, there is now an abundance of information demonstrating consequences (i.e. injury) to individuals, populations, species, and ecosystem function stemming from the low dose radiation due to the Chornobyl and Fukushima disasters.
- Effects appear to be proportional to dose.
- There is no evidence for any kind of threshold below which effects are not seen.

Acknowledgments – My Deepest Thanks

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K. Wakamatsu

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