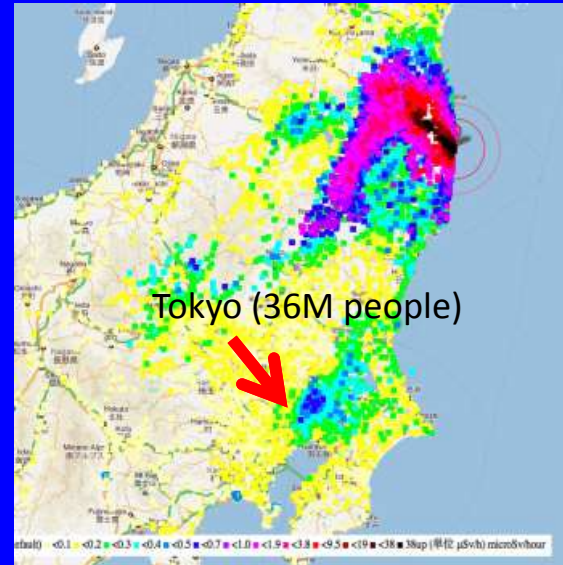


# Do nuclear accidents generate a “Garden of Eden” for wildlife? Lessons from the Chernobyl and Fukushima disasters

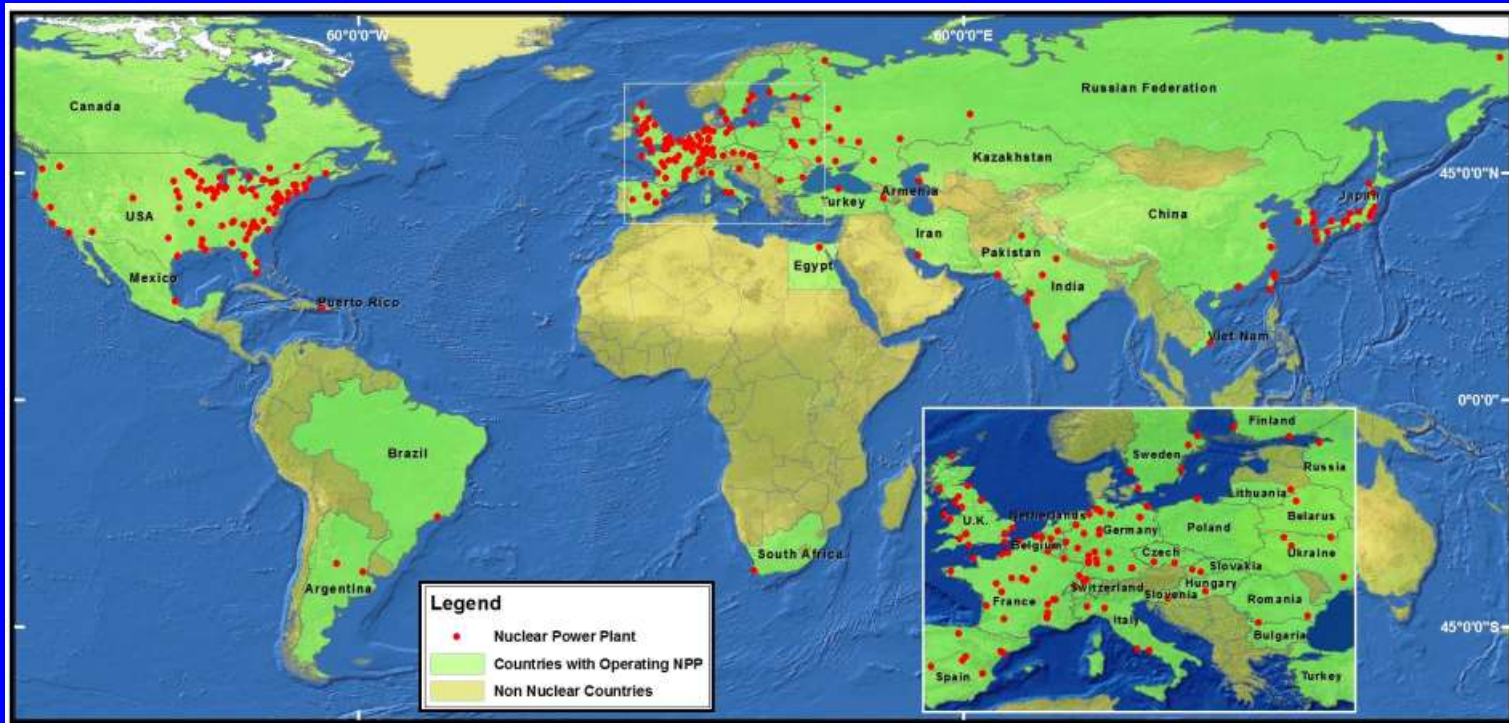
Timothy A. Mousseau  
Anders Pape Møller  
Tapio Mappes  
Andrea Bonisoli-Alquati

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National Science Foundation, National Geographic Society, CRDF, NATO CLG**



- 438 Nuclear reactors in operation around the World
- 65 under construction (22 in China)
- 165 on order or planned, 325 proposed







Enormous quantities of radioisotopes released as a part of normal operations.

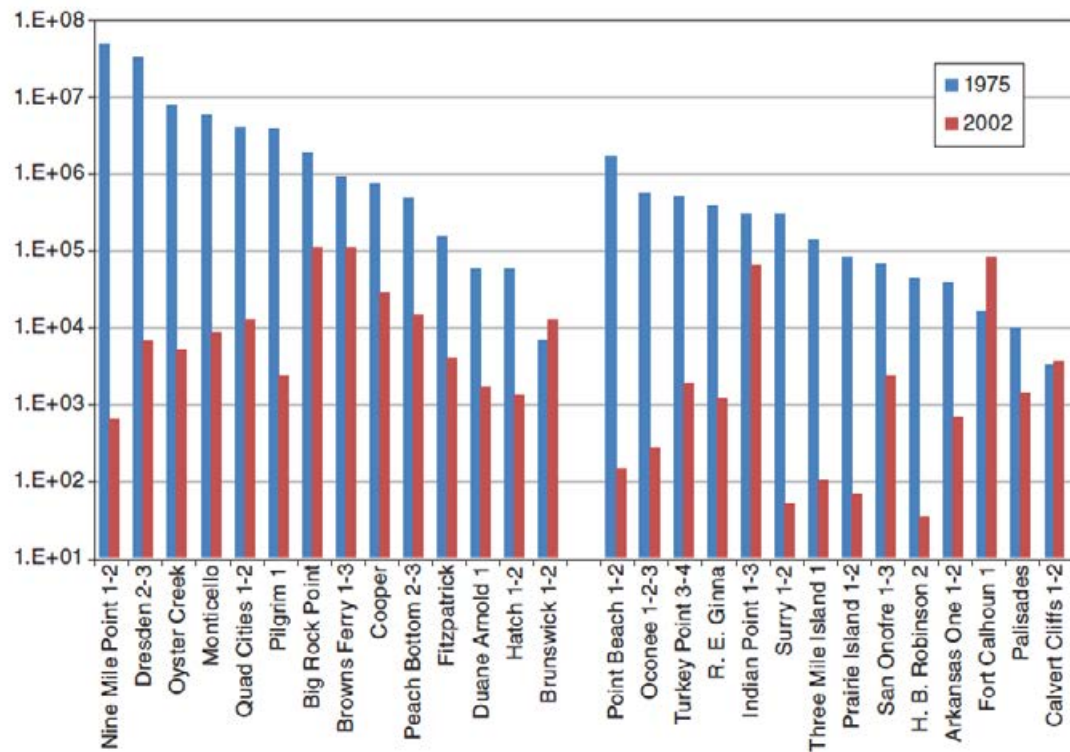


FIGURE 2.5 Comparison of atmospheric releases of noble gases for selected BWRs (left) and PWRs (right) in the United States. The units on the vertical scale are in gigabecquerels (GBq = 0.03 Ci). SOURCE: Data from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

Burris, J.E.,....., T. Mousseau, et. al. 2012. Analysis of Cancer Risks in Populations Near Nuclear Facilities: Phase I. **Nuclear and Radiation Studies Board, The National Academies Press**, Washington, D.C., 412pp.

<b>Country</b>	<b>Spent Fuel Inventory (tons of heavy metal) end of 2007</b>	<b>Spent Fuel Policy</b>
Canada	37,300	Direct disposal
Finland	1,600	Direct disposal
France	13,500	Reprocessing
Germany	5,850	Direct disposal (now)
Japan	19,000	Reprocessing
Russia	13,000	Some reprocessing
South Korea	10,900	Storage, disposal undecided
Sweden	5,400	Direct disposal
United Kingdom	5,850	Reprocessing but future unclear
United States	61,000	Direct disposal

**Table 2.** Spent fuel inventories in cooling ponds and dry-cask storage at the end of 2007 for the 10 countries in the present study.



## VPR News



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### New Developments Disclosed On Tritium Contamination At Vermont Yankee

Friday, 01/28/11 5:50pm

[LISTEN \(2:06\)](#) | [MP3](#) | [Download MP3](#)

John Dillon - Montpelier, Vt.



AP File Photo/Jason R. Henske

A Yankee spokesperson examines a monitoring well in March, 2010.

(Host) There are more developments on radioactive tritium contamination at the Vermont Yankee plant.

The plant disclosed today that another well is contaminated. And, as VPR's John Dillon reports, Yankee also confirmed that it couldn't test for tritium for two weeks.

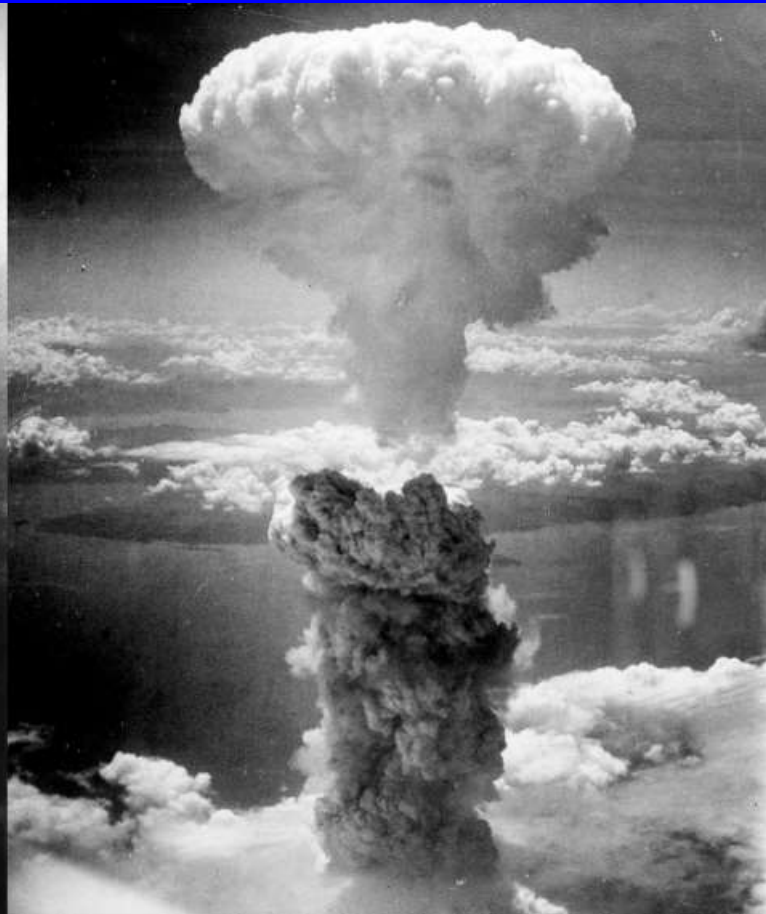
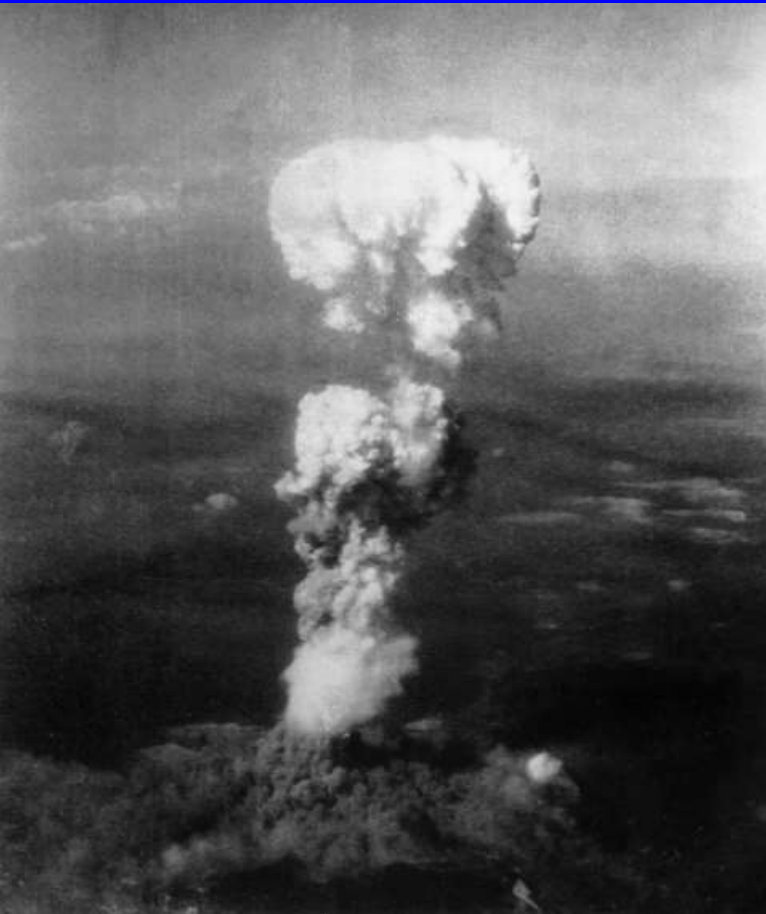
(Dillon) An underground plume of water laced with tritium has been tracked by Yankee officials and government regulators since about this time last year.

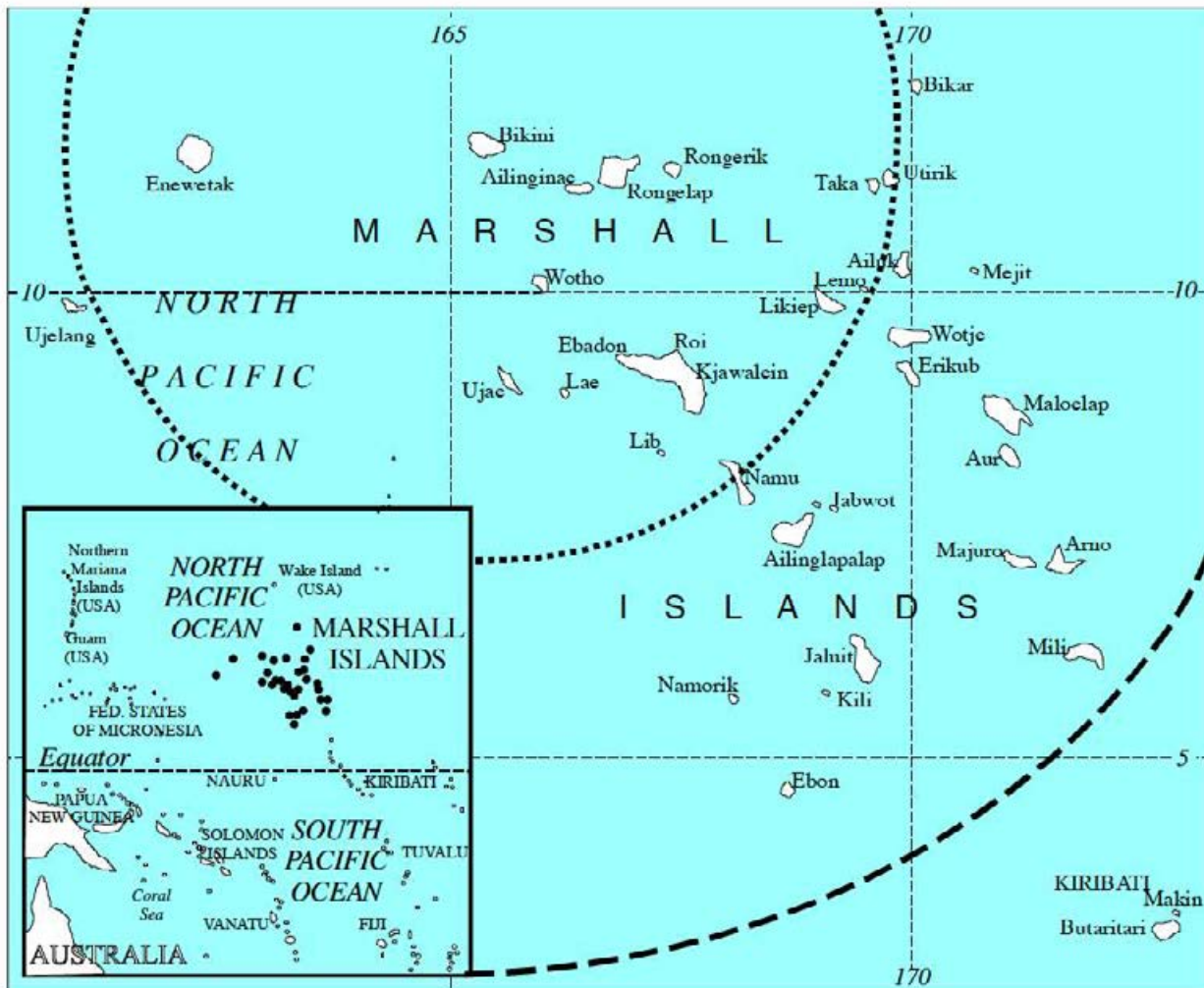
The tritium was traced to leaking underground pipes that Yankee had not previously disclosed existed.

There hadn't been any additional discoveries for months. Until last week. That's when Yankee said it had found another well containing the radioactive isotope.

How many NPP's are leaking tritium? (>37 in USA reported in the last few years)

# Atomic Bombs at Nagasaki and Hiroshima

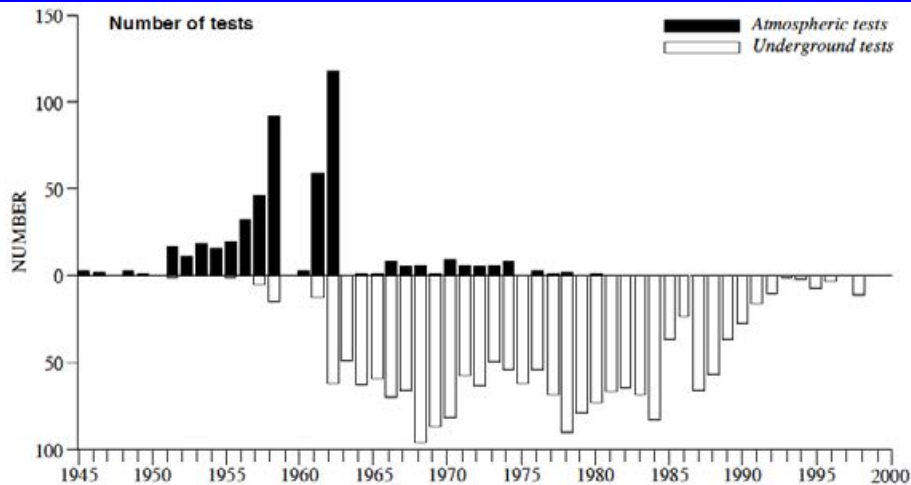




**Figure XII. Bikini and Enewetak test sites.**

*The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1,000 km from the test sites.*





1193 atmospheric  
1517 underground  
2710 total

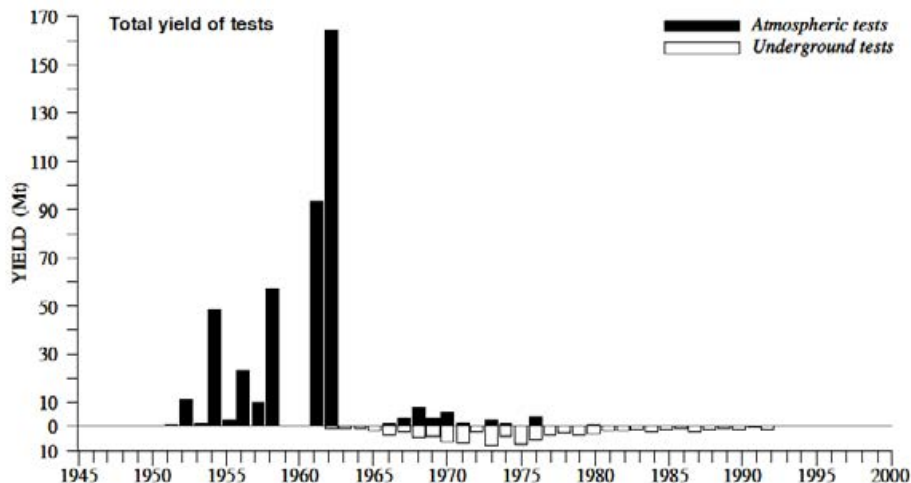


Figure I. Tests of nuclear weapons in the atmosphere and underground.

# NUCLEAR TERRORISM

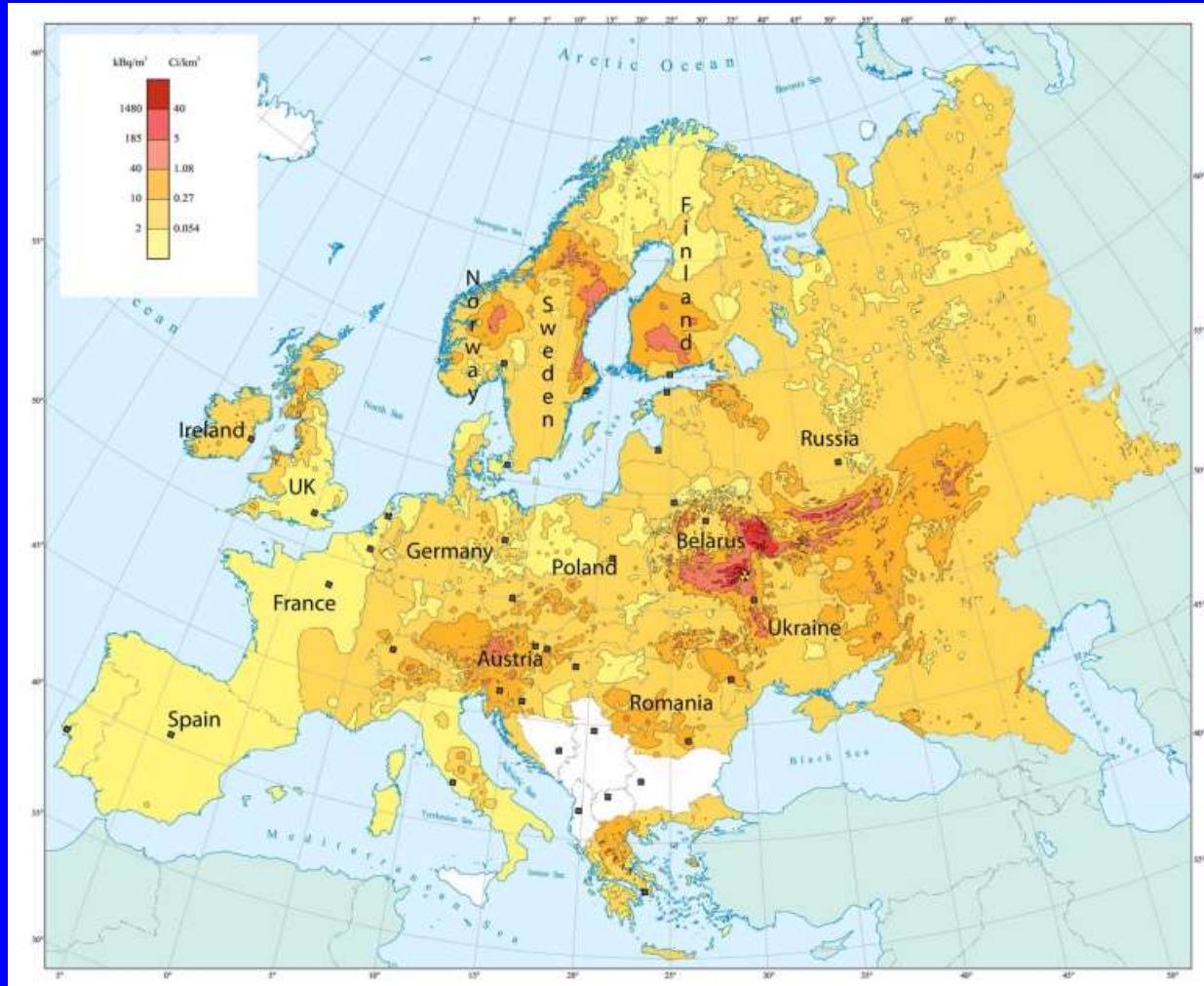
THE ULTIMATE  
PREVENTABLE  
CATASTROPHE

GRAHAM ALLISON

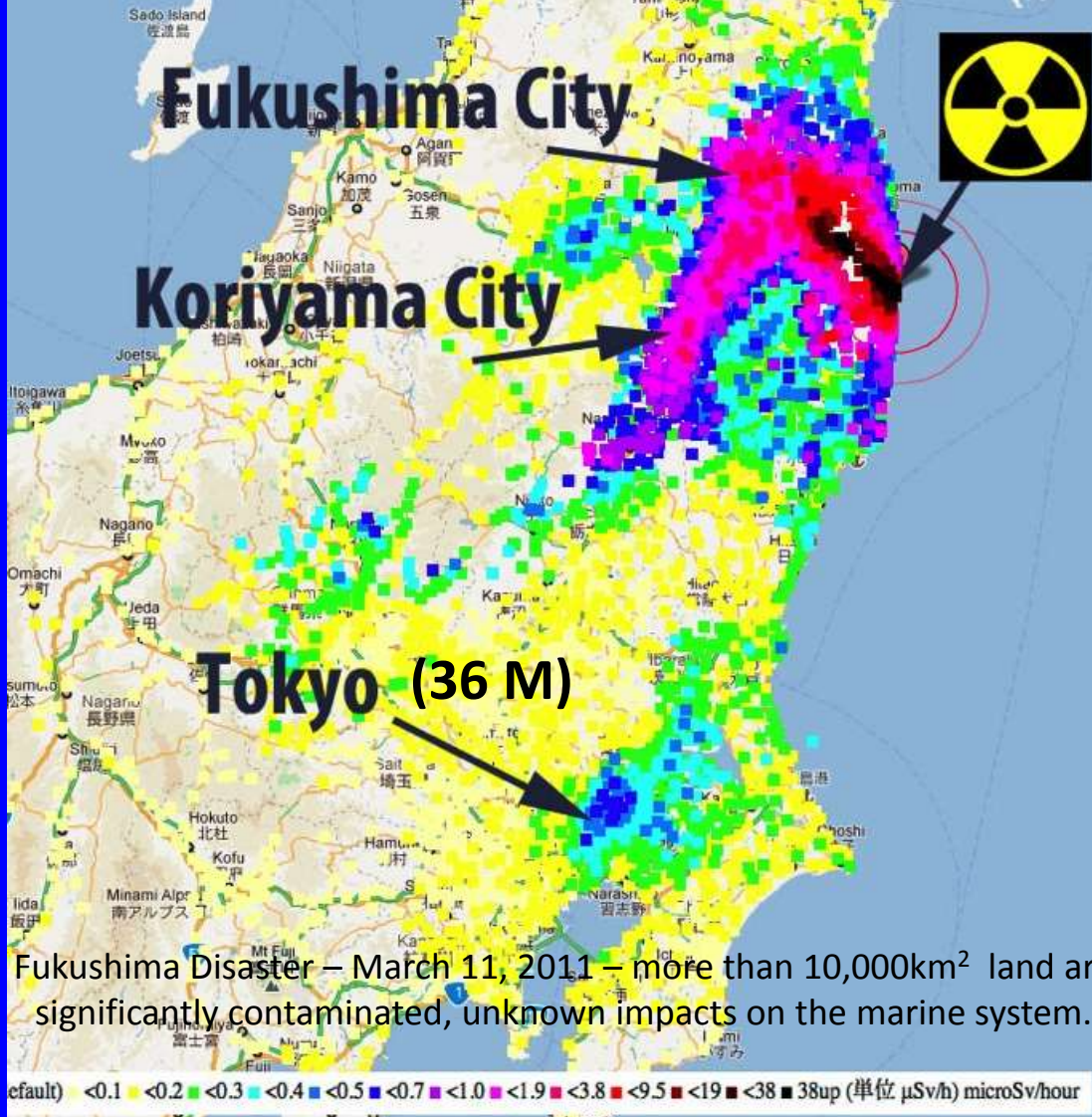


## Chernobyl disaster – April 26, 1986 – nuclear fire burned for 10 days

- More than 200,000 km<sup>2</sup> significantly contaminated land or about half the land area of Japan

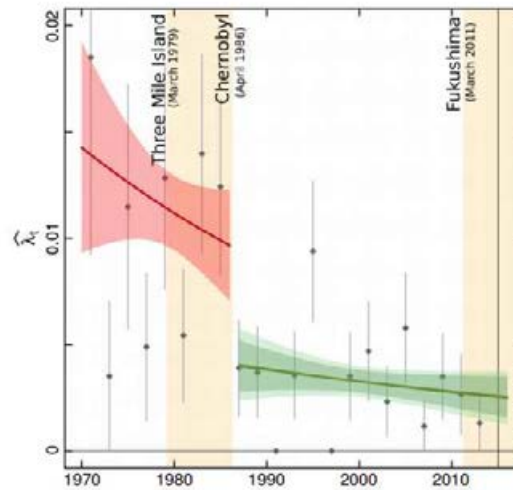






## The Chances of Another Chernobyl Before 2050? 50%, Say Safety Specialists

And there's a 50:50 chance of a Three Mile Island-scale disaster in the next 10 years, according to the largest statistical analysis of nuclear accidents ever undertaken.



Wheatley et al. 2015.

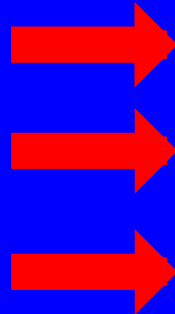
The catastrophic disasters at Chernobyl and Fukushima are among the worst humankind has had to deal with. Both were the result of the inability of scientists and engineers to foresee how seemingly small problems can snowball into disasters of almost unimaginable scale.

## Hypotheses and questions addressed:

- **Do low (and high) doses result in measureable, elevated mutation rates in natural populations?**
- **Are there phenotypic consequences to elevated mutation rates?**
- **Are there fitness consequences to elevated mutation rates? (i.e. survival, reproduction, or disease).**
- **Is there evidence for adaptation?**
- **Are there effects on population abundances and biodiversity?**
- **Are there ecosystem consequences?**



# How do we know the radiation dose received by an animal?





**“TLD” dosimeters to  
measure external radiation  
dose.**



Gamma radiation spectrometry in the field is used to determine internal dose to birds and rodents without hurting them.





- **T.A. Mousseau (South Carolina) and A.P. Møller (France) – first field expedition together in 2000.**
- **Research in Fukushima beginning July 2011**
- **Studies of natural populations of birds, insects, microbes, mammals, and plants.**
- **More than 35 research expeditions to Chernobyl, and 14 expeditions to Fukushima.**
- **More than 80 scientific publications related to low-dose radiation effects (Most available at <http://cricket.biol.sc.edu>)**
- **We are *independent* evolutionary biologists; our primary interest is in documenting adaptation and impacts of elevated mutation rates on population processes. We are not activists.**

OPEN

## Strong effects of ionizing radiation from Chernobyl on mutation rates

Anders Pape Møller<sup>1</sup> & Timothy A. Mousseau<sup>2</sup>

SUBJECT AREAS:  
ECOLOGICAL GENETICS  
EVOLUTIONARY GENETICS

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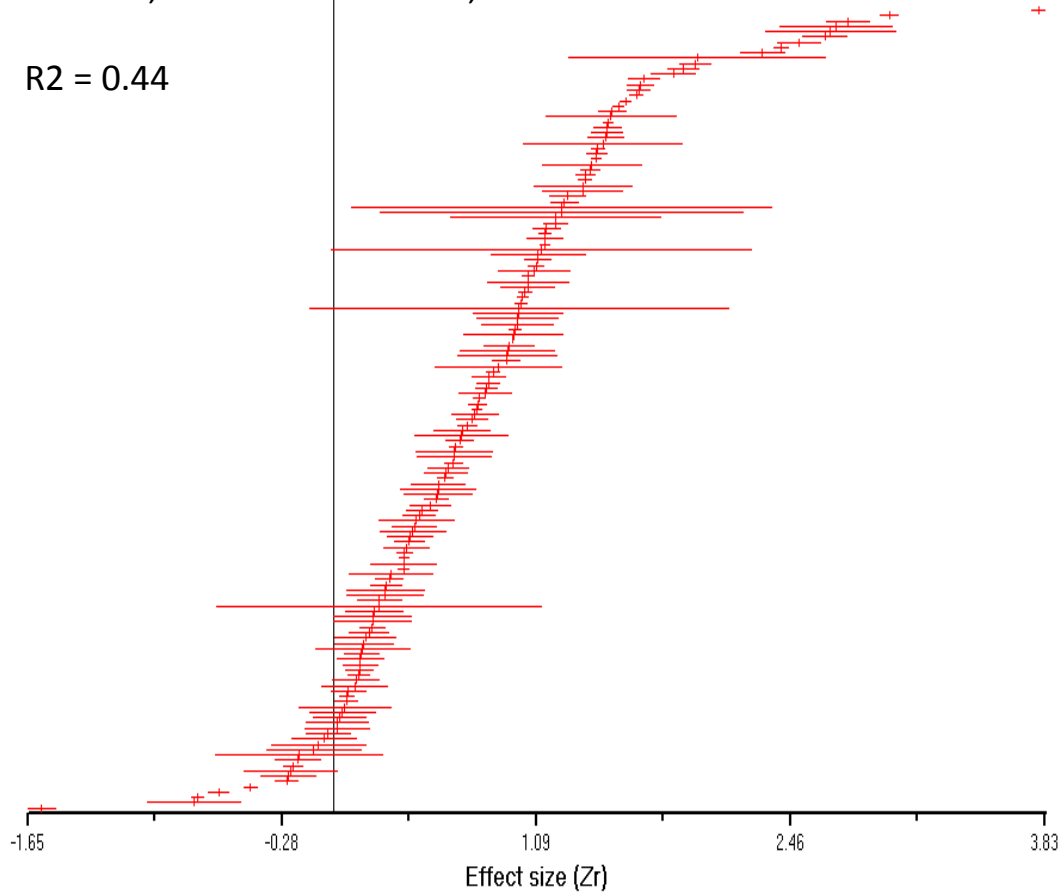
<sup>1</sup>Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France, <sup>2</sup>Department of Biological Sciences, University of South Carolina, Columbia SC 29208, USA.

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

$E = 0.67$ ; 95% CI 0.59 to 0.73;  $N = 151$

$R^2 = 0.44$



# Aspermy, Sperm Quality and Radiation in Chernobyl Birds

Anders Pape Møller<sup>1\*</sup>, Andrea Bonisoli-Alquati<sup>2</sup>, Timothy A. Mousseau<sup>2</sup>, Geir Rudolfson<sup>3</sup>

**1** Laboratoire d'Ecologie, Systématique et Evolution, CNRS Unité Mixte de Recherche 8079, Université Paris-Sud, Bâtiment 362, Orsay Cedex, France, **2** University of South Carolina, Department of Biological Sciences, Columbia, South Carolina, United States of America, **3** Department of Arctic and Marine Biology, University of Tromsø, Tromsø, Norway

## Abstract

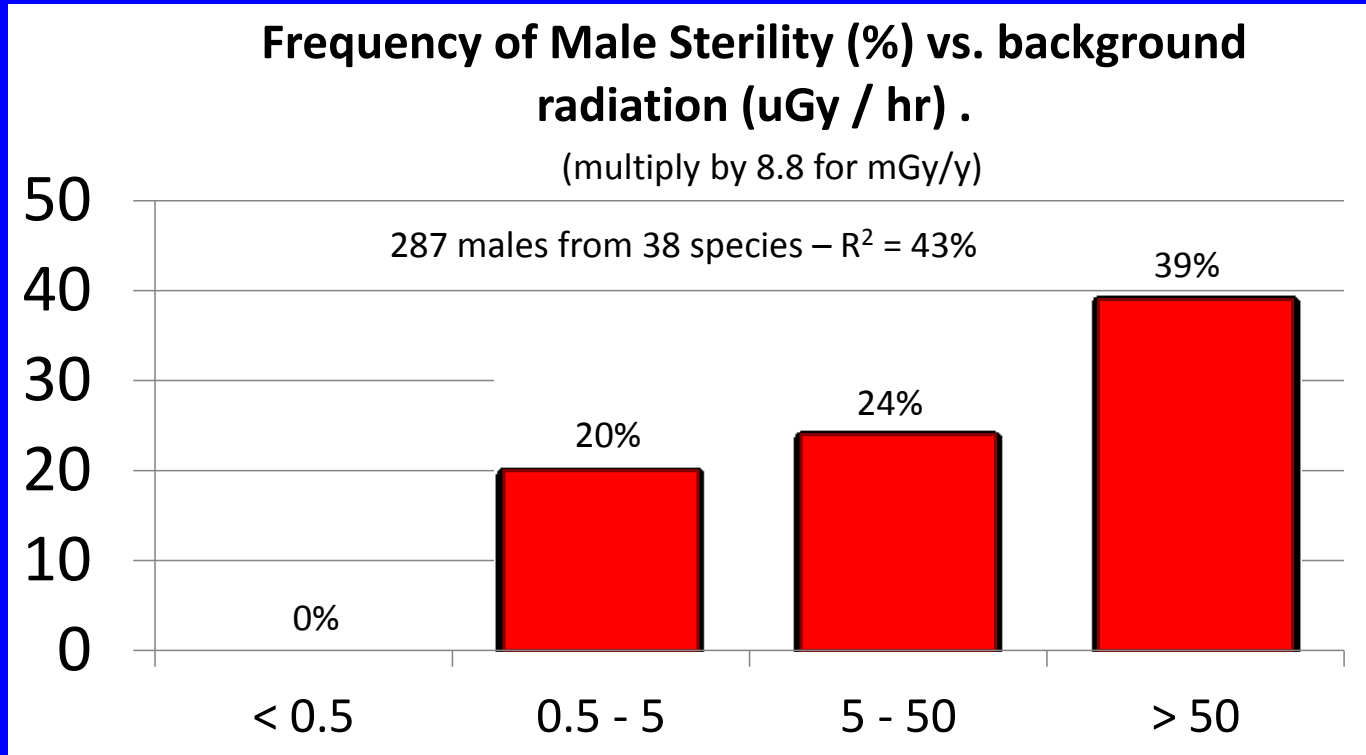
**Background:** Following the Chernobyl nuclear power plant accident, large amounts of radionuclides were emitted and spread in the environment. Animals living in such contaminated areas are predicted to suffer fitness costs including reductions in the quality and quantity of gametes.

**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.



# Proportion of male birds with no sperm Or only dead sperm in Chernobyl.



Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

# Mutation Research/Genetic Toxicology and Environmental Mutagenesis

journal homepage: [www.elsevier.com/locate/gentox](http://www.elsevier.com/locate/gentox)Community address: [www.elsevier.com/locate/mutres](http://www.elsevier.com/locate/mutres)

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

A.P. Møller<sup>a,\*</sup>, A. Bonisoli-Alquati<sup>b</sup>, T.A. Mousseau<sup>b</sup><sup>a</sup> *Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France*<sup>b</sup> *Department of Biological Sciences, University of South Carolina, Columbia, SC 29208, USA*

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### 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  $\mu\text{Sv/h}$ . 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**





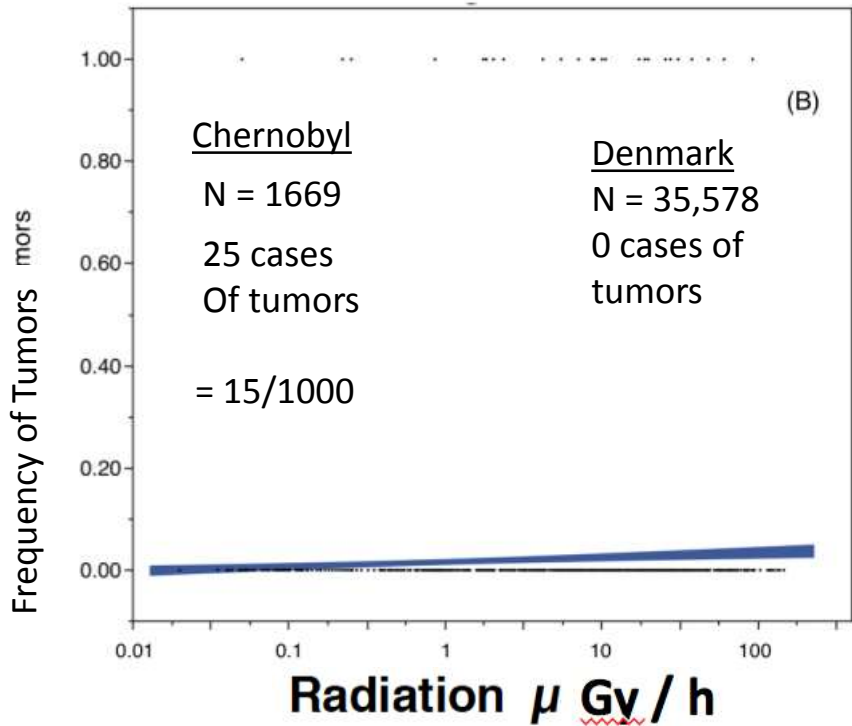


# Tumors and other developmental abnormalities



Møller, A.P., A. Bonisoli-Alquati, and T.A. Mousseau. 2013. High frequencies of albinism and tumors in free-living birds at Chernobyl. **Mutation Research**.

# Chernobyl Birds Have Significantly Higher Rates of Tumors



Møller, A.P., A. Bonisoli-Alquati, and T.A. Mousseau. 2013. High frequencies of albinism and tumors in free-living birds at Chernobyl. **Mutation Research.**

**Table 1**

Nominal logistic regression models of albinism and tumours in relation to background radiation and species.  $R^2$  was 0.20 and 0.06 for the two models. Odds ratios and their 95% confidence interval are also shown.

Variable	Chi-square	d.f.	P	Estimate (SE)	Odds ratio	95% CI for odds ratio
<b>Albinism</b>						
Species	146.97	61	<0.0001			
Radiation	33.82	1	<0.0001	0.660 (0.120)	0.309	0.162, 0.577
<b>Tumours</b>						
Radiation	15.06	1	0.0001	0.722 (0.210)	0.061	0.011, 0.271

# 原爆白内障

放射線によって目の中の水晶体(レンズ)の後ろ中心部が白くにがり、視力が低下する症状です。被爆して数か月から数年後に多発しました。

## A-bomb Cataracts

Radiation can cause the center posterior part of the lens to become white and cloudy, leading to loss of sight. Cataracts occurred several months to several years after exposure.



## 原爆白内障患者の目

1966 (昭和41)年4月撮影 広島大学医学部眼科教室提供

爆心地から820メートルで被爆し、  
両眼に白濁があります。

写真の中央にある黒い部分が原爆白内障によるにごりです。

## The eye of an A-bomb cataract patient

Taken in April 1966

Courtesy of the Department of Ophthalmology, Faculty of Medicine,  
Hiroshima University

The patient was exposed 820m from the hypocenter and had white cloudiness in both eyes.

The dark area in the center of this photo is the cloudiness caused by an A-bomb cataract.



# Elevated Frequency of Cataracts in Birds from Chernobyl

Timothy Alexander Mousseau<sup>1</sup>, Anders Pape Møller<sup>2\*</sup>

**1** Department of Biological Sciences, University of South Carolina, Columbia, South Carolina, United States of America, **2** Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Orsay, France

## Abstract

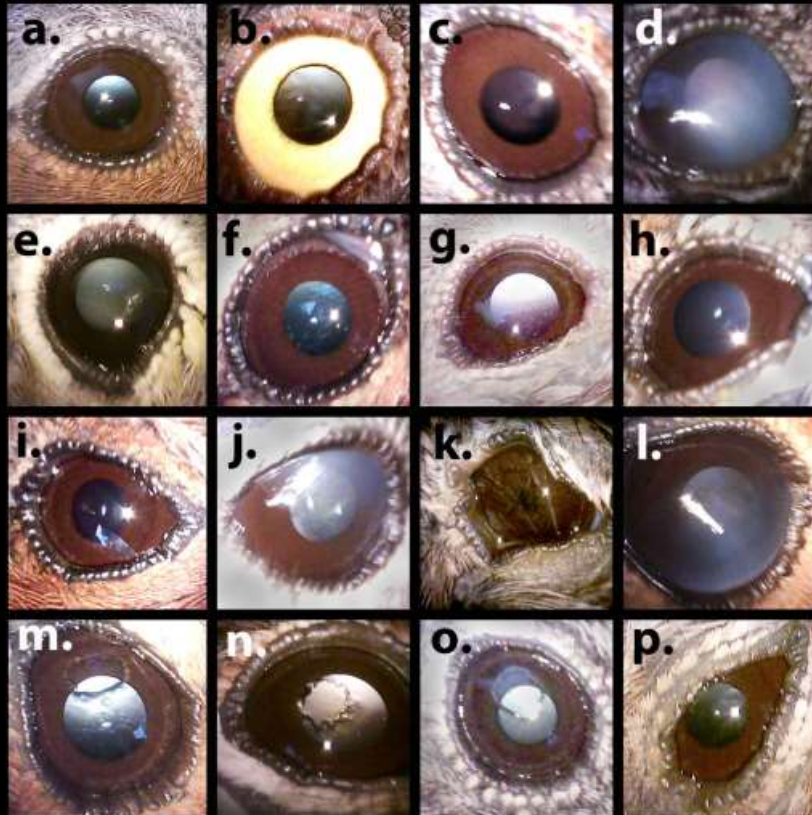
**Background:** Radiation cataracts develop as a consequence of the effects of ionizing radiation on the development of the lens of the eye with an opaque lens reducing or eliminating the ability to see. Therefore, we would expect cataracts to be associated with reduced fitness in free-living animals.

**Methodology/Principal Findings:** We investigated the incidence of lens opacities typical of cataracts in more than 1100 free-living birds in the Chernobyl region in relation to background radiation. The incidence of cataracts increased with level of background radiation both in analyses based on a dichotomous score and in analyses of continuous scores of intensity of cataracts. The odds ratio per unit change in the regressor was 0.722 (95% CI 0.648, 0.804), which was less than odds ratios from investigations of radiation cataracts in humans. The relatively small odds ratio may be due to increased mortality in birds with cataracts. We found a stronger negative relationship between bird abundance and background radiation when the frequency of cataracts was higher, but also a direct effect of radiation on abundance, suggesting that radiation indirectly affects abundance negatively through an increase in the frequency of cataracts in bird populations, but also through direct effects of radiation on other diseases, food abundance and interactions with other species. There was no increase in incidence of cataracts with increasing age, suggesting that yearlings and older individuals were similarly affected as is typical of radiation cataract.

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

# Cataracts & Deformities

## Bird Eyes of Chernobyl



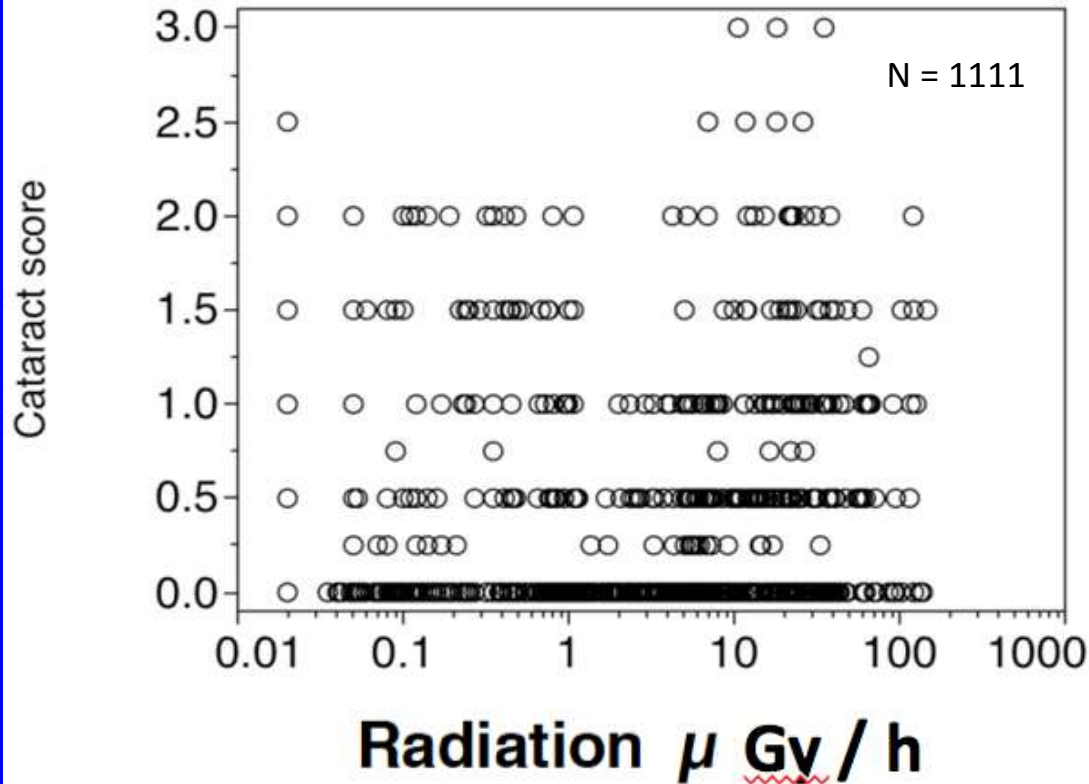
(a.) Black cap (*Sylvia atricapilla*), normal. (b.) Barred warbler (*Sylvia nisoria*), normal. (c.) Black cap (*Sylvia atricapilla*), very slight haze in cornea. (d.) Barn swallow (*Hirundo rustica*), significant haze on cornea. (e.) Chiffchaff (*Phylloscopus collybita*), slight haze on cornea. (f.) Chiffchaff (*Phylloscopus collybita*), significant haze on cornea. (g.) Spotted flycatcher (*Muscicapa striata*), partial haze on cornea. (h.) Chaffinch (*Fringilla coelebs*), slight haze on cornea. (i.) Chaffinch (*Fringilla coelebs*), clear eye but deformed eye lids. (j.) Tree pipit (*Anthus trivialis*), significant opacity of cornea. (k.) Barn swallow (*Hirundo rustica*), highly deformed eye lids and iris. (l.) Robin (*Erithacus rubecula*), significant haze on cornea. (m.) Robin (*Erithacus rubecula*), tear in cornea. (n.) Whinchat (*Saskola rubetra*), tear in cornea. (o.) Spotted flycatcher (*Muscicapa striata*), tear on cornea. (p.) Chiffchaff (*Phylloscopus collybita*), deformed eye lid, haze on cornea.

All photos captured using an EyeQuick Digital Ophthalmoscope Camera.

Further information can be found at <http://cricket.biol.sc.edu/chernobyl/>

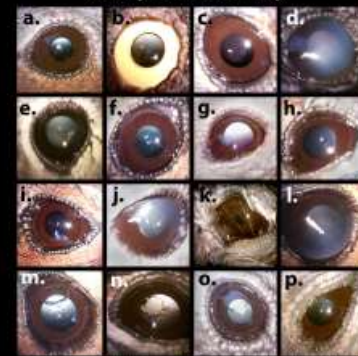
All photos (c) 2012 - T.A.Mousseau & A.P.Møller

# Chernobyl Birds



## Cataracts & Deformities

### Bird Eyes of Chernobyl



Mousseau, T.A., and A.P. Møller. 2013. Elevated frequencies of cataracts in birds from Chernobyl. **PLoS ONE**.

**Table 1.** Mixed model of cataracts in relation to species (random factor) and radiation. The random species effect accounted for a variance ratio of 0.0955 and 8.71% of the total variance.

Variable	d.f.	F	P	Estimate (SE)
Intercept	48.66, 1074		< 0.0001	
log Radiation	1, 1074	89.63	< 0.0001	0.131 (0.014)



# **Mental Retardation Following *In Utero* Exposure to the Atomic Bombs of Hiroshima and Nagasaki<sup>1</sup>**

**William J. Blot, Ph.D., and Robert W. Miller, M.D.**

**ABSTRACT**—The prevalence of mental retardation in children tested at 17 years of age who had been exposed *in utero* to the atomic bombs of Hiroshima and Nagasaki was studied in relation to the most recent estimate of radiation dose received. Significant increases at doses greater than 50 rads in Hiroshima and 200 in Nagasaki were found, with the risk of mental retardation generally rising directly with increasing dose. The lower dose-effect in Hiroshima may have been due to irradiation by neutrons which were virtually absent in Nagasaki.

**INDEX TERMS:** Mental Deficiency • Radiations, Injurious Effects, embryonal, fetal

**Radiology 106:617-619, March 1973**



# Chernobyl Birds Have Smaller Brains

Anders Pape Møller<sup>1\*</sup>, Andea Bonisoli-Alquati<sup>2</sup>, Geir Rudolfson<sup>3</sup>, Timothy A. Mousseau<sup>2</sup>

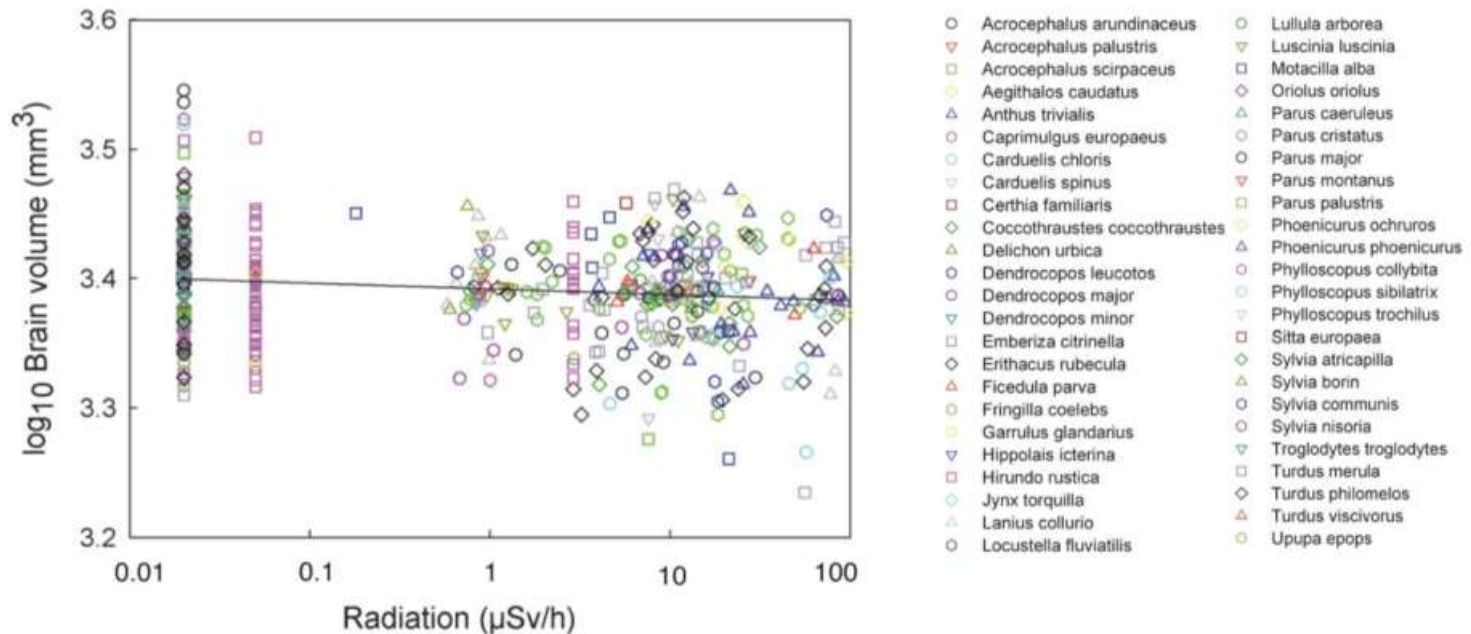
**1** Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Orsay, France, **2** Department of Biological Sciences, University of South Carolina, Columbia, South Carolina, United States of America, **3** Norwegian Radiation Protection Authority (NRPA), Department of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

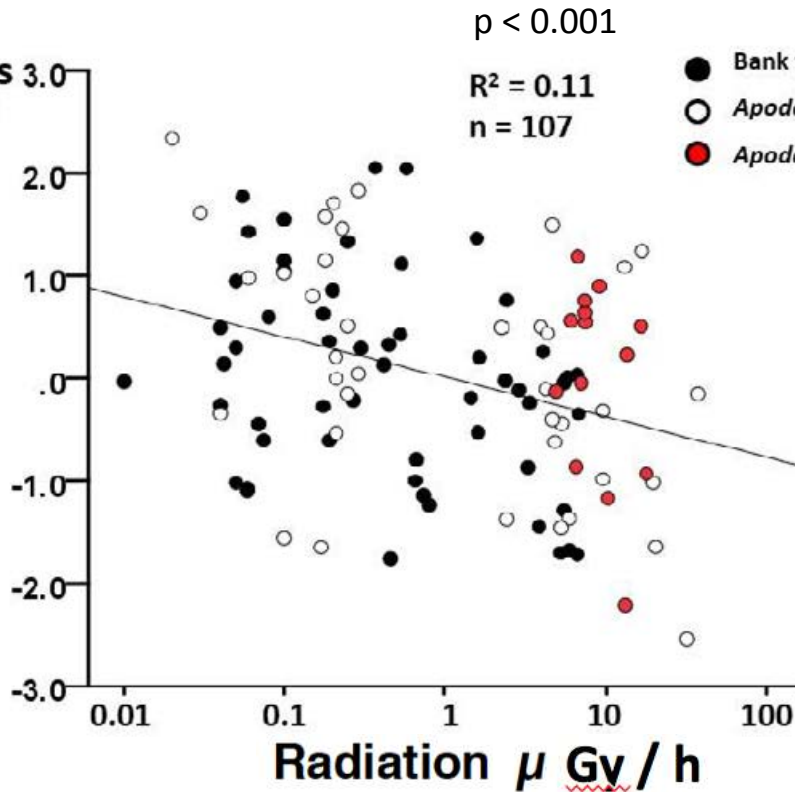
**Conclusions/Significance:** Low dose radiation can have significant effects on normal brain development as reflected by brain size and therefore potentially cognitive ability. The fact that brain size was smaller in yearlings than in older individuals implies that there was significant directional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



**Figure 2. Head volume of birds ( $\text{mm}^3$ ) in relation to level of background radiation ( $\mu\text{Sv/h}$ ), after controlling for species and body mass.** The line is the linear regression line with the equation  $\log_{10}(\text{Head volume}) = 3.3918 - 0.0045 \log_{10}(\text{Background radiation})$ . Residuals from a model that included species as a predictor were added mean  $\log_{10}$ -transformed head volume 3.3934 to facilitate interpretation.  
doi:10.1371/journal.pone.0016862.g002

## Rodents from Chernobyl and Fukushima show smaller brains in radioactive areas

**Brain mass 3.0**  
(corrected by  
body mass)



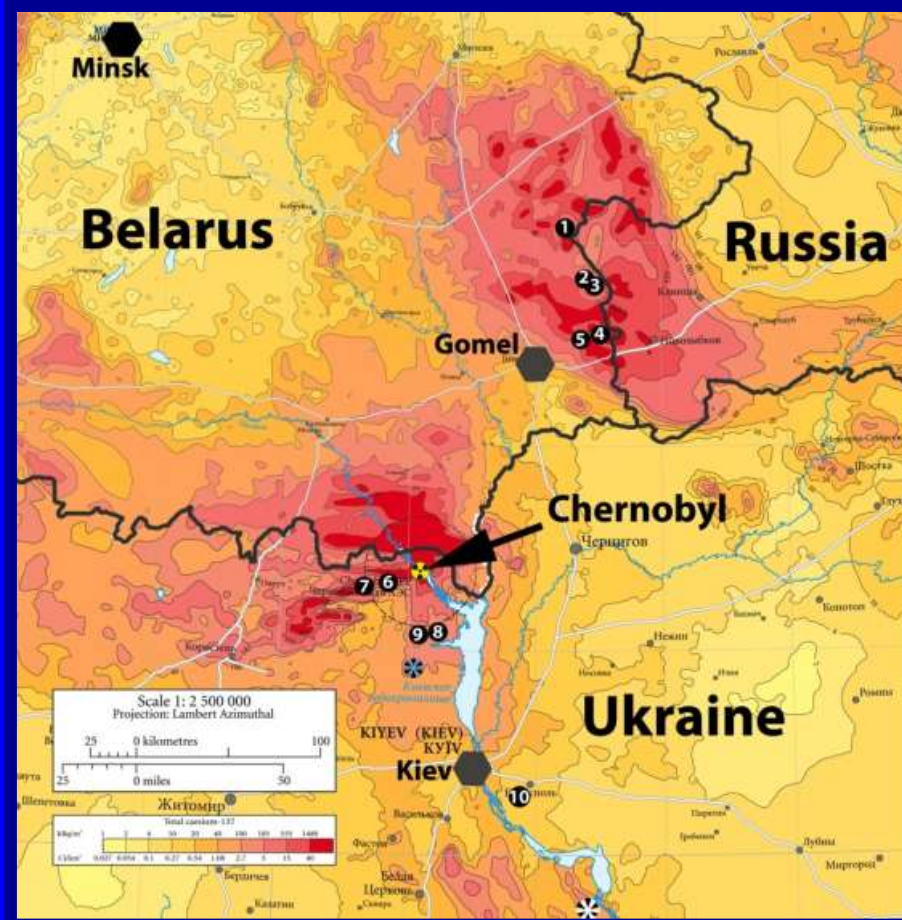


# Population and Ecosystem Consequences of Injuries to Individuals





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.



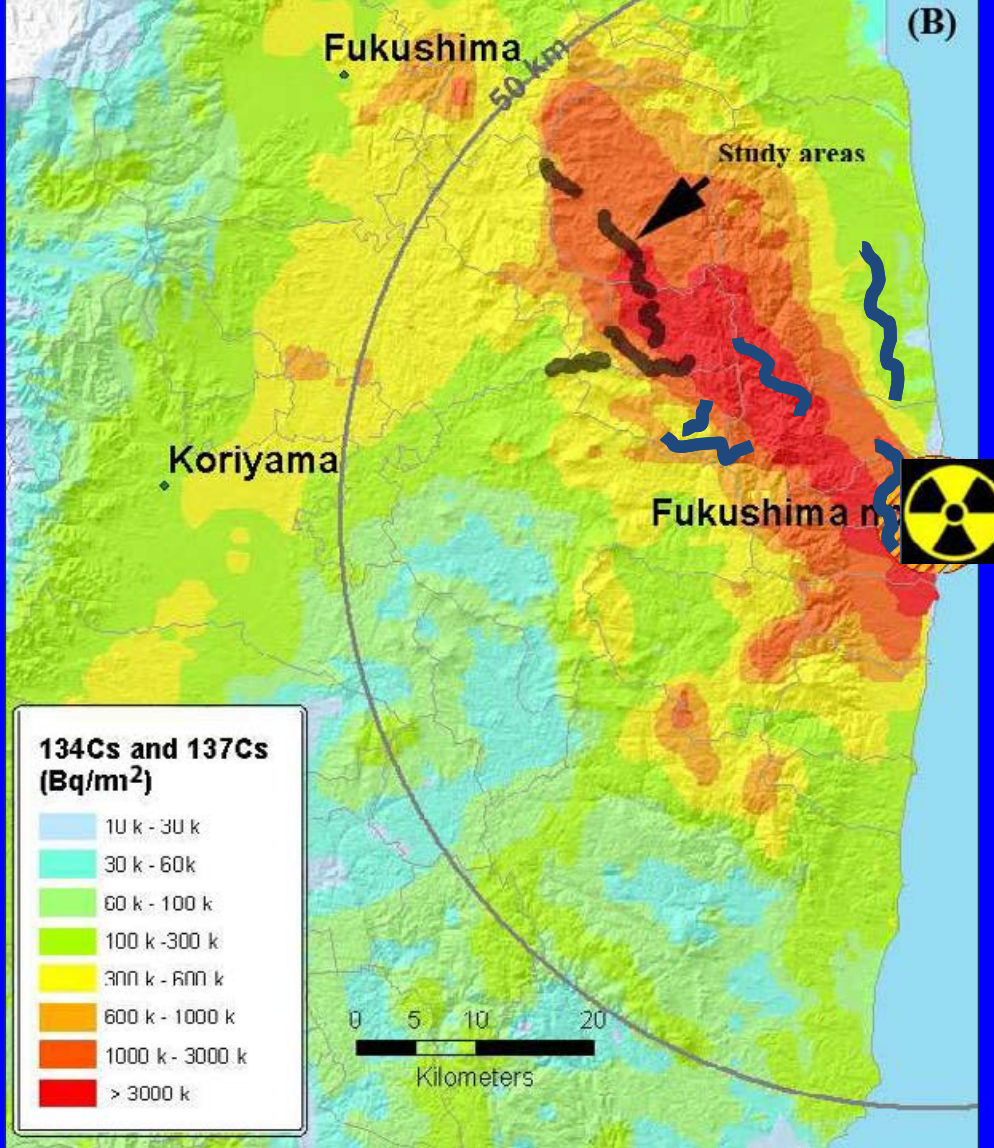
- 896 bird and insect surveys at about 300 locations in Ukraine and Belarus

Additional Control Populations:

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

(B)

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**