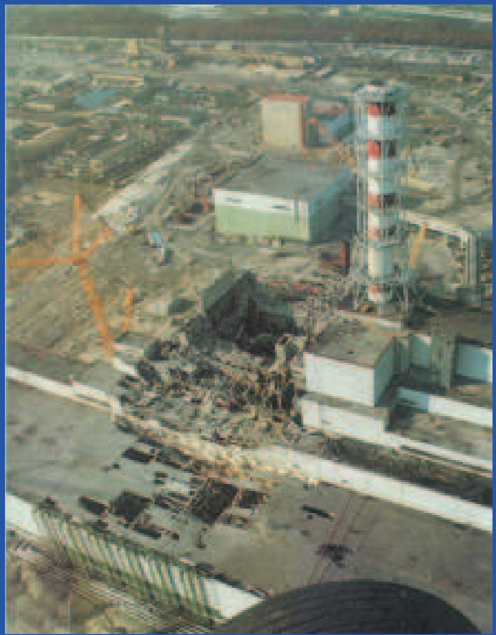
Biological Consequences of Chernobyl and Fukushima



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

Directors, Chernobyl + Fukushima Research Initiative

[1] University of South Carolina

[2] CNRS, France

Sponsored by:

The Samuel Freeman Charitable Trust,
USC College of Arts & Sciences,
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G. Milinevsky, A. Bonisoli-Alquati, B. Coull, H. Smith, J. Palms, M. Fitzpatrick, P. Nagarkartti, and K. Kawai

A Brief History of Nuclear Power Plants:

- There have been more than 600 commercial Nuclear Power Plants
- Currently, there are 439 Nuclear Power Plants in 31 countries
- There have been three major nuclear accidents:

  1) Three Mile Island (1979)

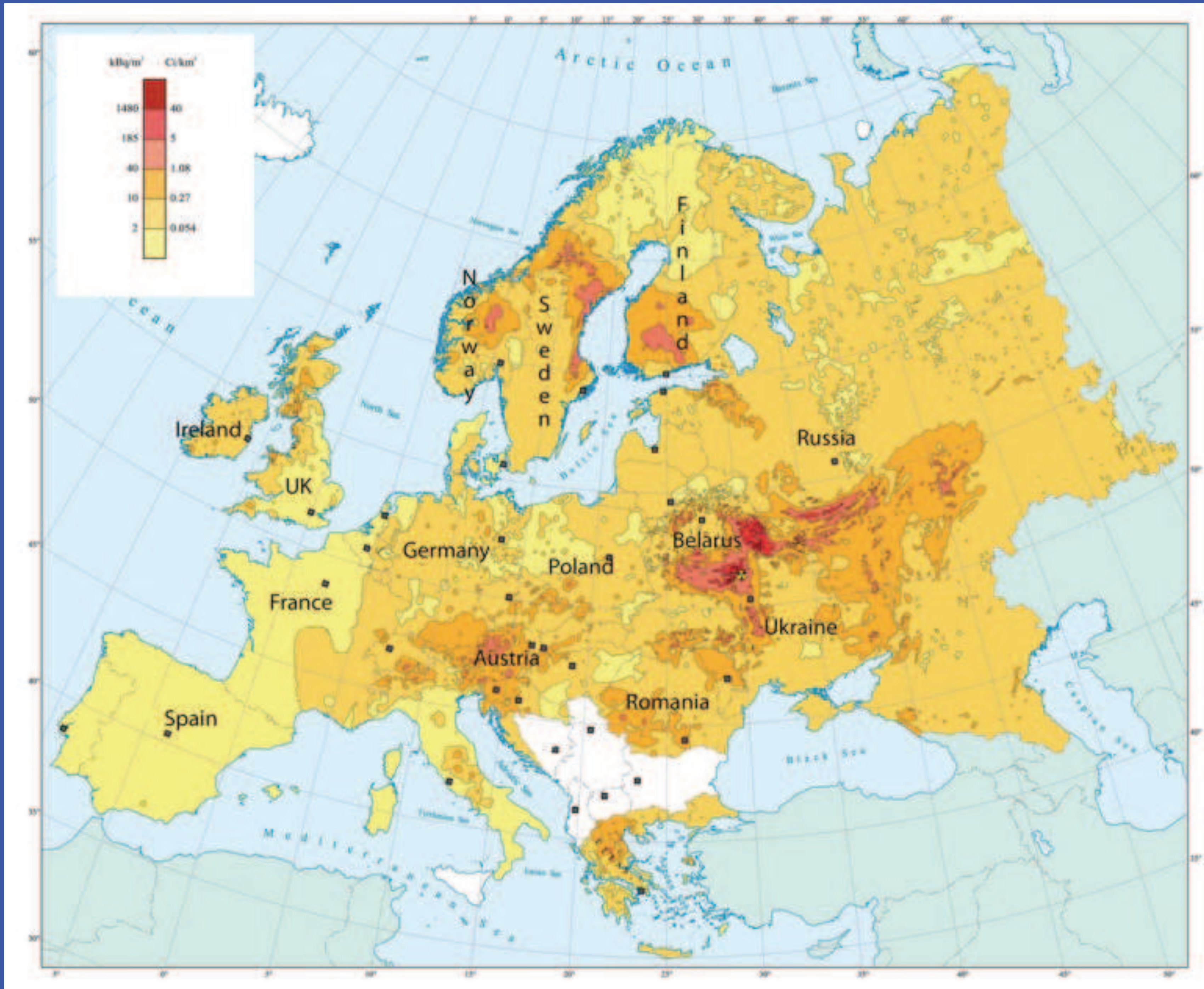
  2) Chernobyl (1986)

  3) Fukushima (2011)

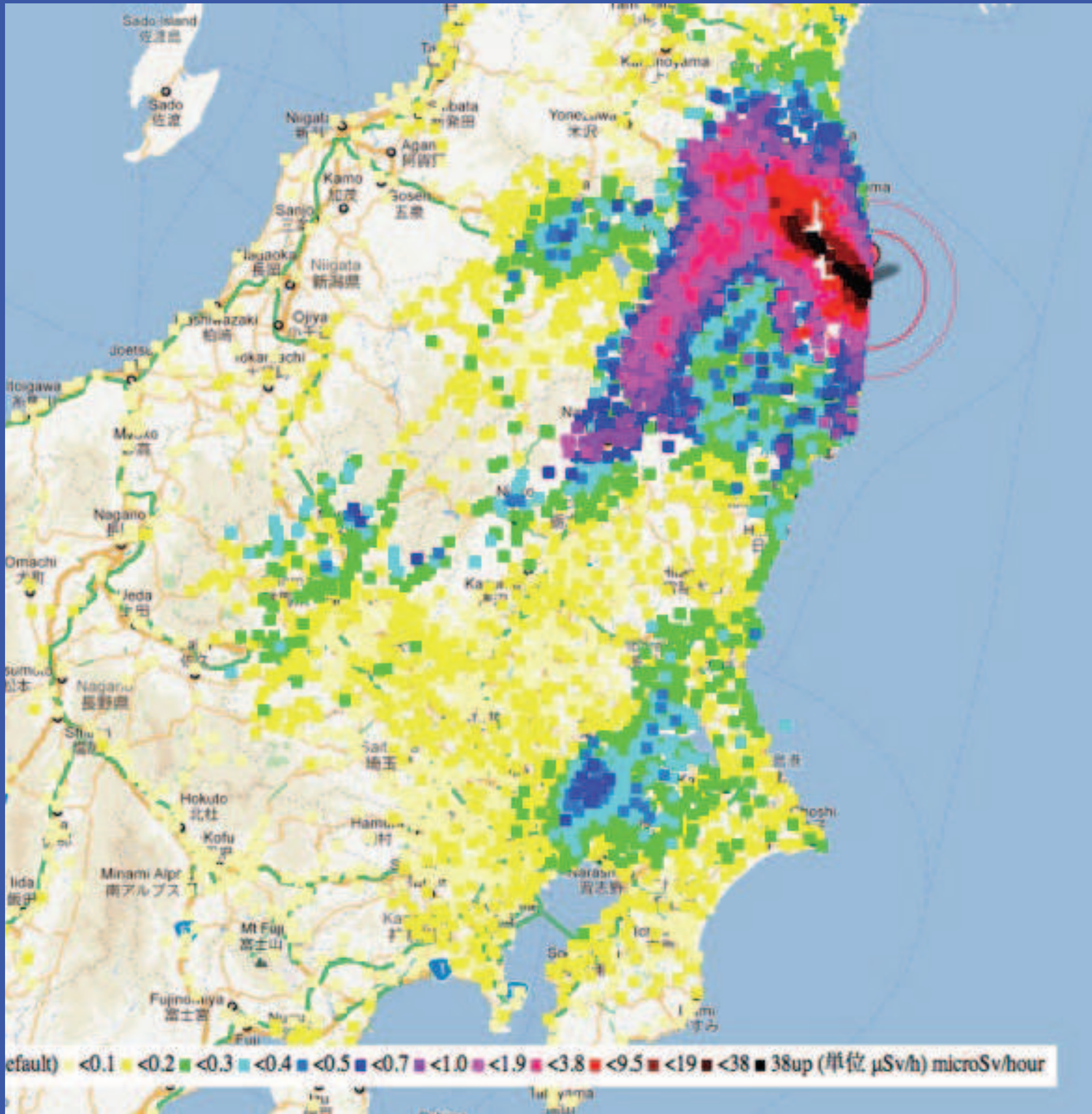
- There have been 33 serious incidents or accidents at Nuclear Power Plants since 1952
- Yet, we still do not adequately understand the impacts of nuclear accidents on human health or the environment.

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

- More than 200,000 km^2 significantly contaminated land or abut half the land area of Japan



Fukushima Disaster – March 11, 2011 – more than 10,000km^2 land are significantly contaminated, unknown impacts on the marine system.



Chernobyl Research Initiative

Chernobyl + Fukushima Research Initiative

- **Began in 2000 by T.A. Mousseau (South Carolina) and A.P.** Møller (France).
- **Research in Fukushima beginning July 2011**
- **Studies of natural populations of birds, insects, microbes, mammals, and plants.**
- **Studies of the Children of the Narodichesky region of Ukraine.**
- **More than 30 research expeditions to Chernobyl, and 10 expeditions to Fukushima.**
- **More than 50 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.**

The UN Chernobyl Forum Report (IAEA, 2006: p137):

“. . . the populations of many plants and animals have expanded, and the present environmental conditions have had a positive impact on the biota in the Chernobyl Exclusion Zone.”

Human morbidities primarily the result of psychological stress….

But:

No quantitative data in support of this position and it avoids the primary question of whether or not there are injuries to individuals, populations and the ecosystem as a result of radioactive contaminants.

Animal Models – Provide Clues to Human Populations

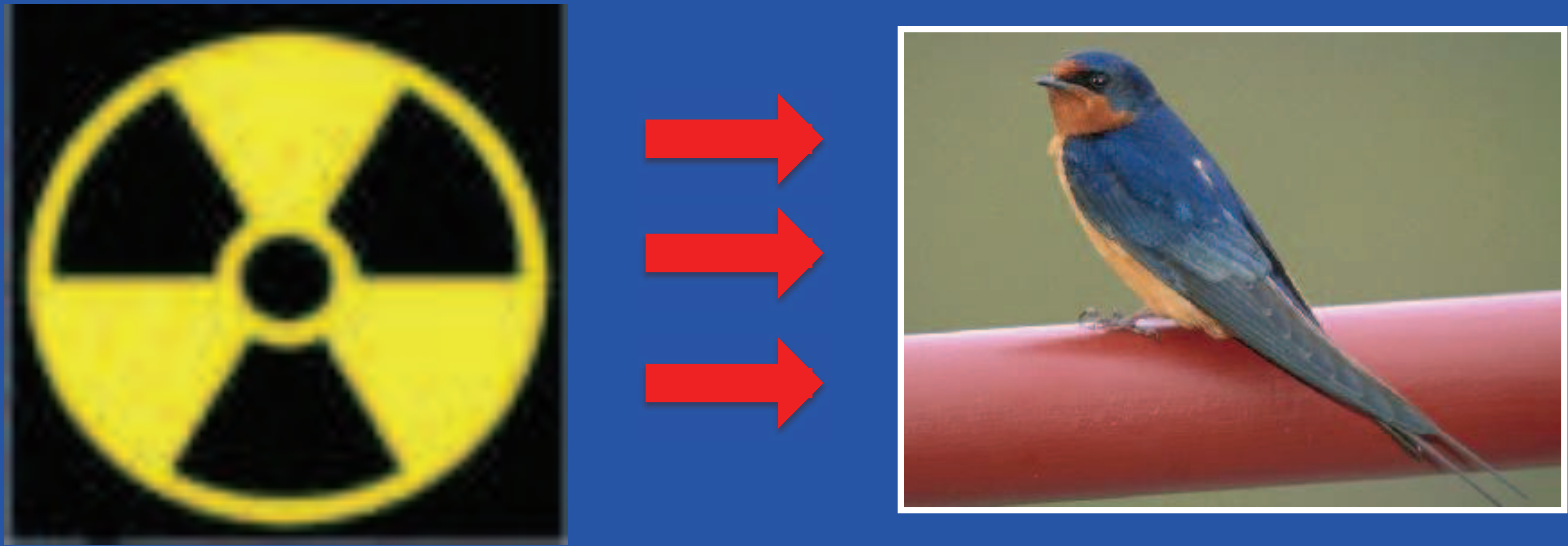
Animals don't usually drink, smoke or get depressed!

Animals live in the most contaminated areas where people have left

The Barn Swallow, *Hirundo rustica*

Hot Fukushima Cattle! This area is 50 to 300 microseiverts per hour!

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



In Chernobyl:

- 0.5 km of mist nets, rotated daily, >2000 birds captured since 2010 (and released).
- 492 birds outfitted with TLD’s in May, 2012

“TLD” dosimeters to measure external radiation dose received by bird is attached to bird leg band.

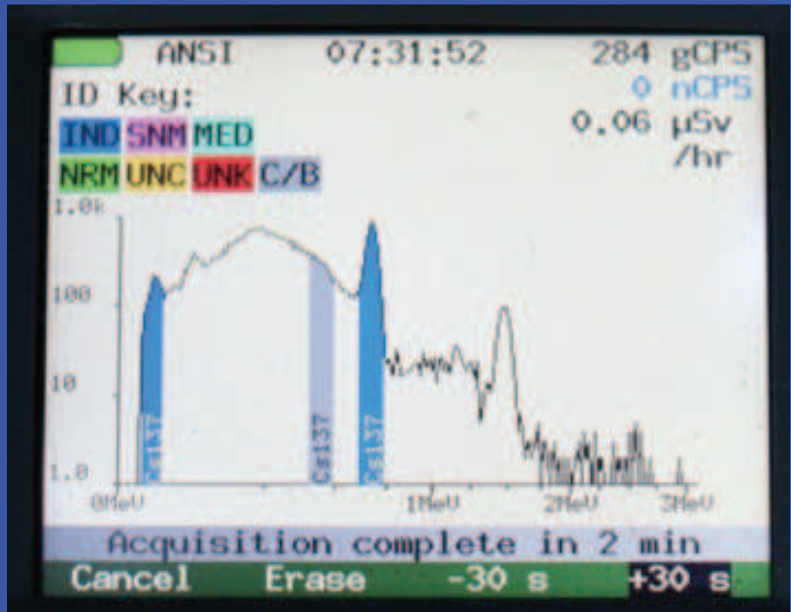
Mouse collars with TLD dosimeters

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


TLD
dosimeter
7659


TLD
dosimeter
16
JP 1 3352
7659 7

Gamma Spectrometry on blood sample

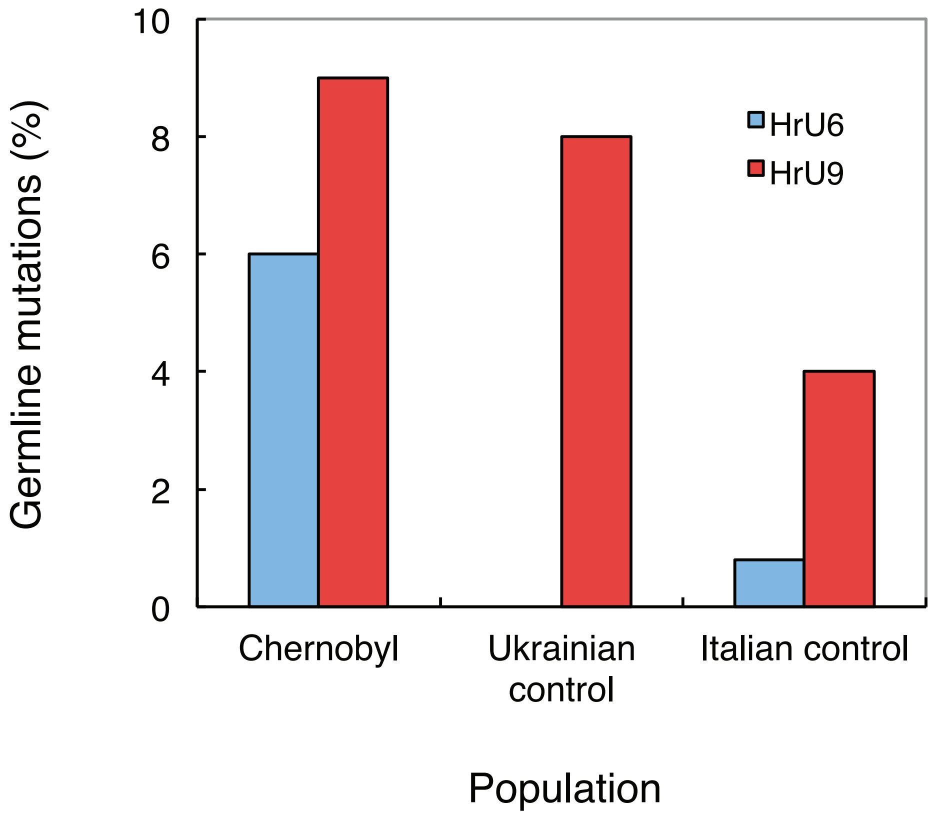


Estimating Mutation Rates

- Microsatellite DNA markers
- Comet assays for single and double strand break rates
- Micronuclei frequency
- Sperm morphological damage as a proxy for mutation rates
- Future: - Gene expression profiles
  - Whole genome scans for de novo mutation rate estimates.

Microsatellite mutations in barn swallows

DNA of parents and offspring are compared to find mutations



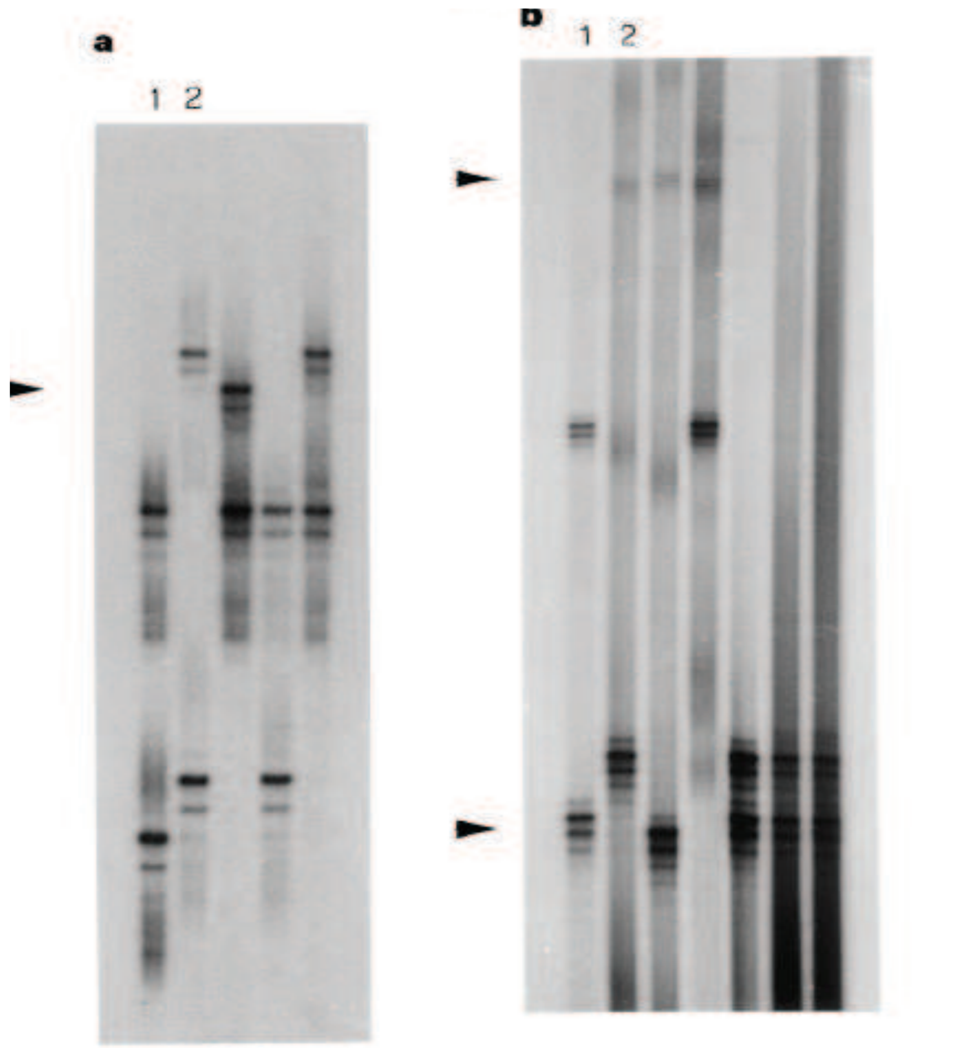
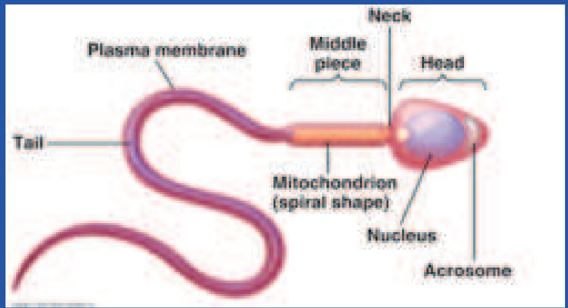


Figure 1 Examples of microsatellite germline mutations for barn swallow loci in the Chernobyl population. **a**, *HrU6*; **b**, *HrU9*. Lane 1, the father; lane 2, the mother; other lanes show offspring. Mutant alleles are arrowed. Note that the offspring to the left in **b** is mutant for both its father's and mother's allele.

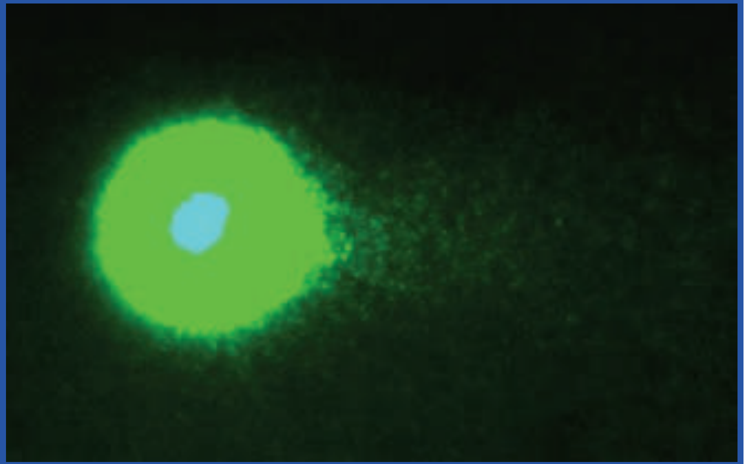
(Ellegren et al., Nature 389:593-596, 1997)

Barn Swallow Sperm (Chernobyl)

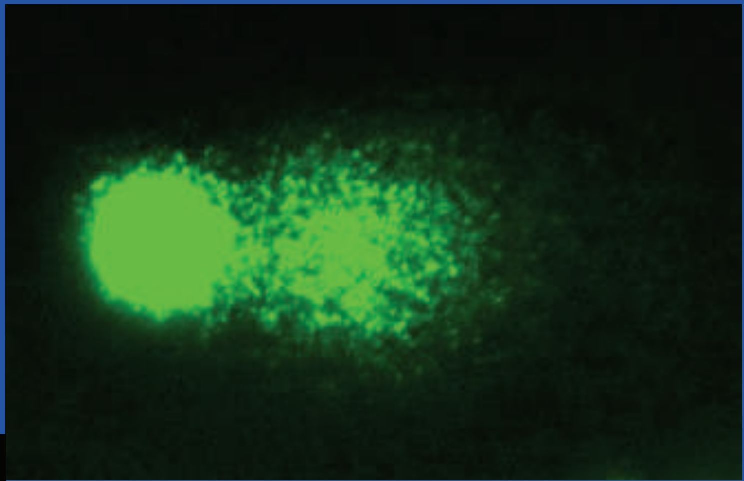
- The DNA (chromosomes) in single cells (red blood cells or sperm) is examined for damage



DNA is intact and in nucleus of cell

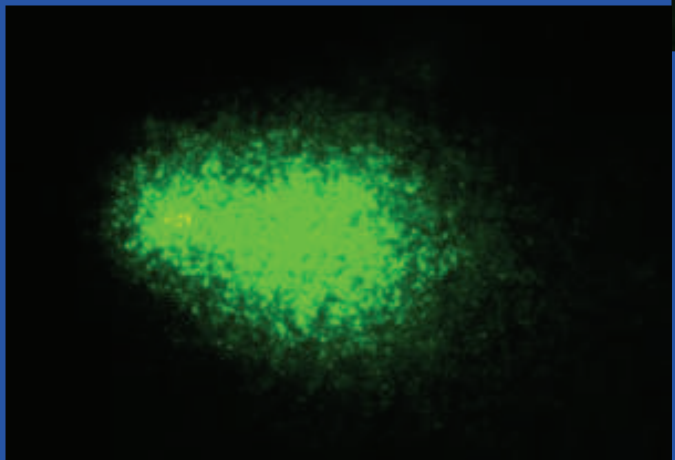


Low Damage



Medium Damage

DNA is broken into pieces by radiation exposure

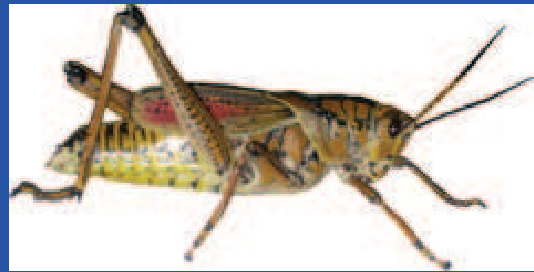


High Damage

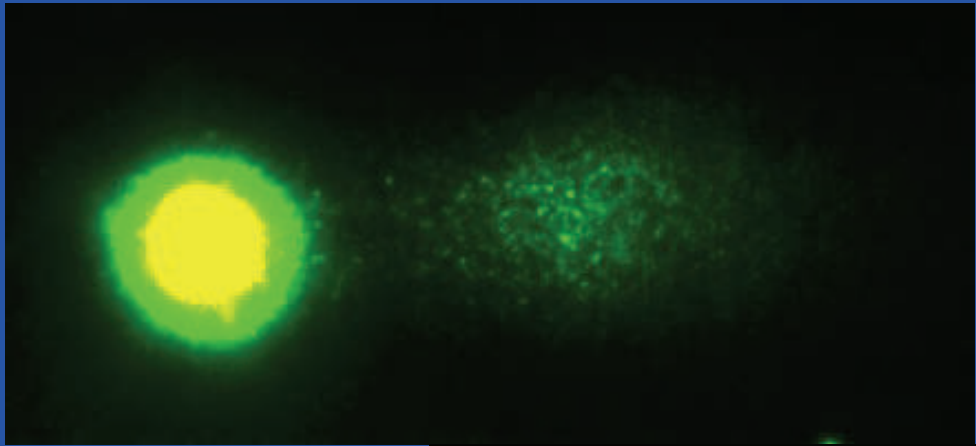
Bonisoli-Alquati, A., , **A. Voris,** T. A. Mousseau, A. P. Møller, N. Saino, and M. Wyatt. 2010. DNA damage in barn swallows (*Hirundo rustica*) from the Chernobyl region detected by the use of the Comet assay. **Comparative Biochemistry and Physiology C- Toxicology & Pharmacology** 151: 271-277.

Comet assays of genetic damage to RBCs and sperm

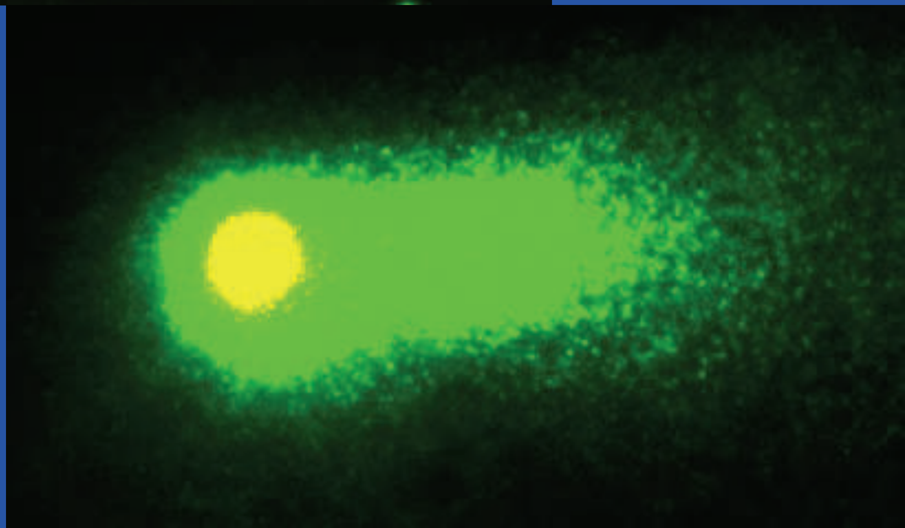
Grasshopper Hemolymph



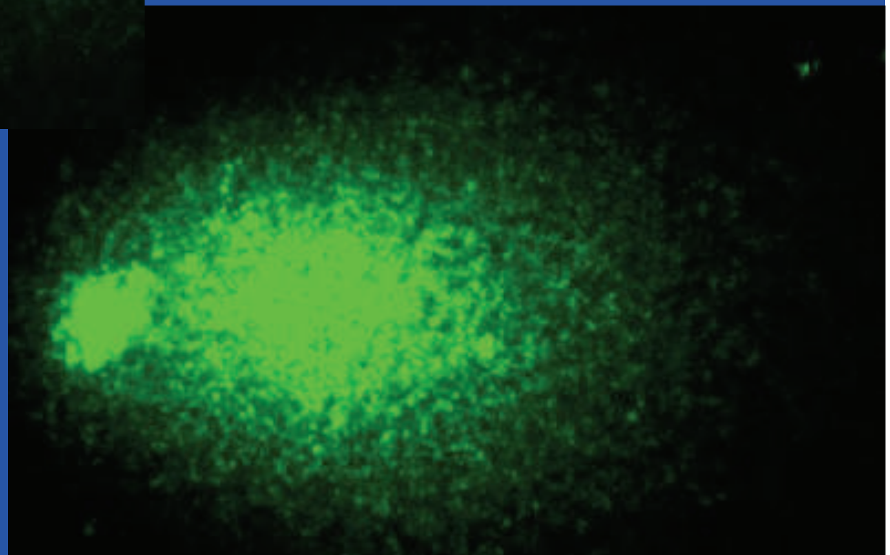
(Chernobyl)



Low Damage

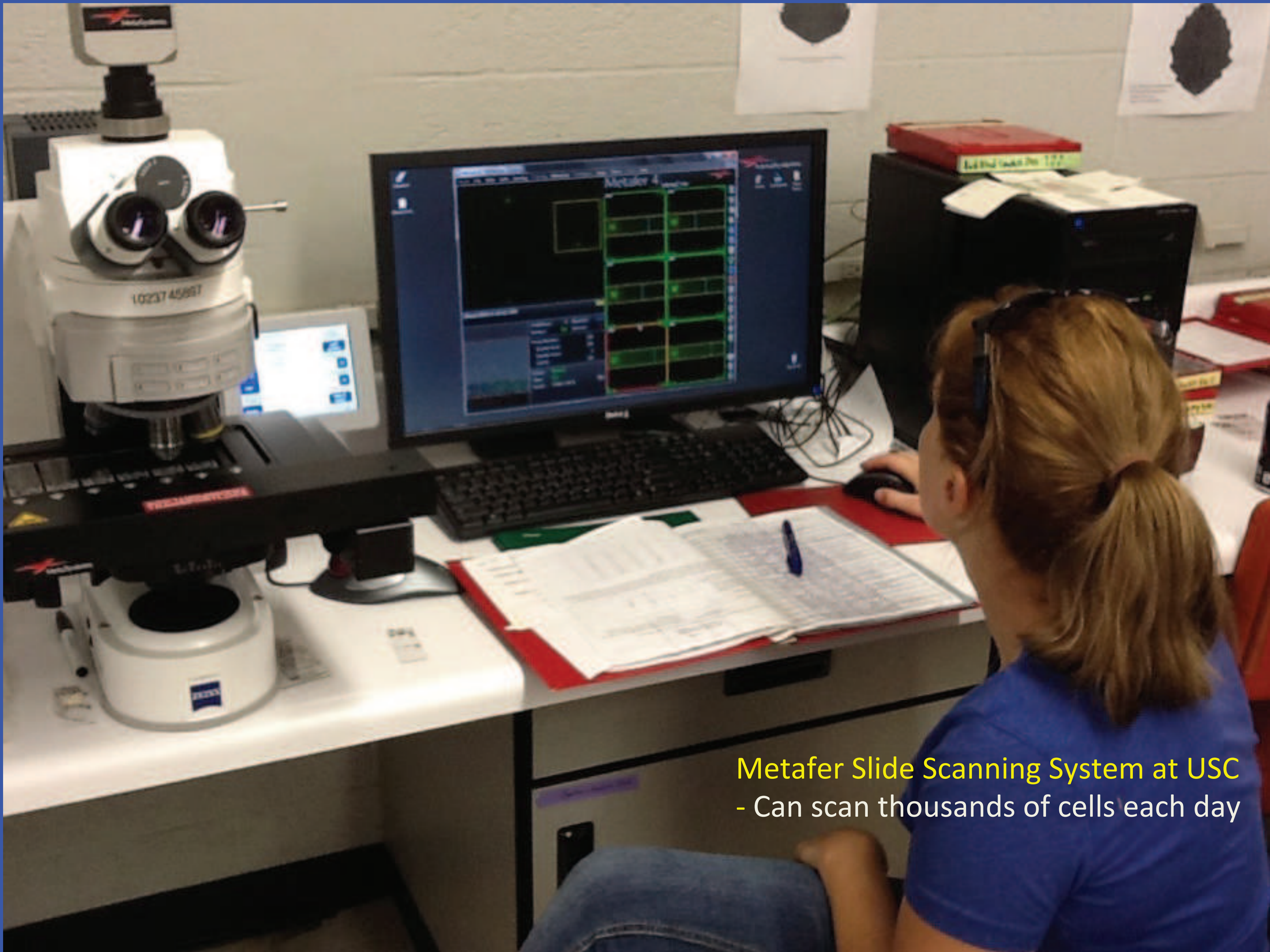


Medium Damage



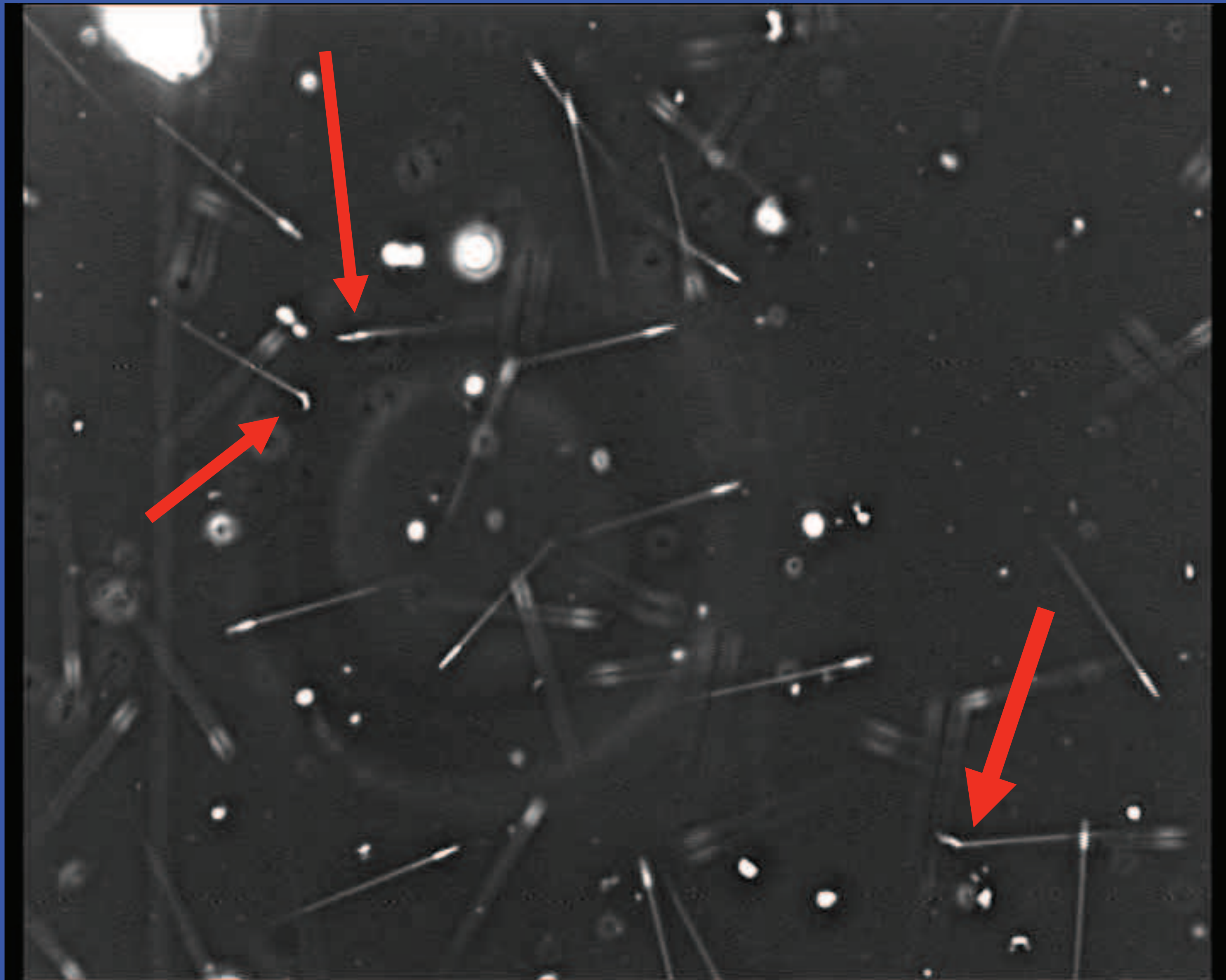
High Damage

Beasley, D.A.E., A. Bonisoli-Alquati, S.M. Welch, A. P. Møller, T.A. Mousseau. Effects of parental radiation exposure on developmental instability in grasshoppers (Chorthippus albomarginatus). **Journal of Evolutionary Biology**, in press.

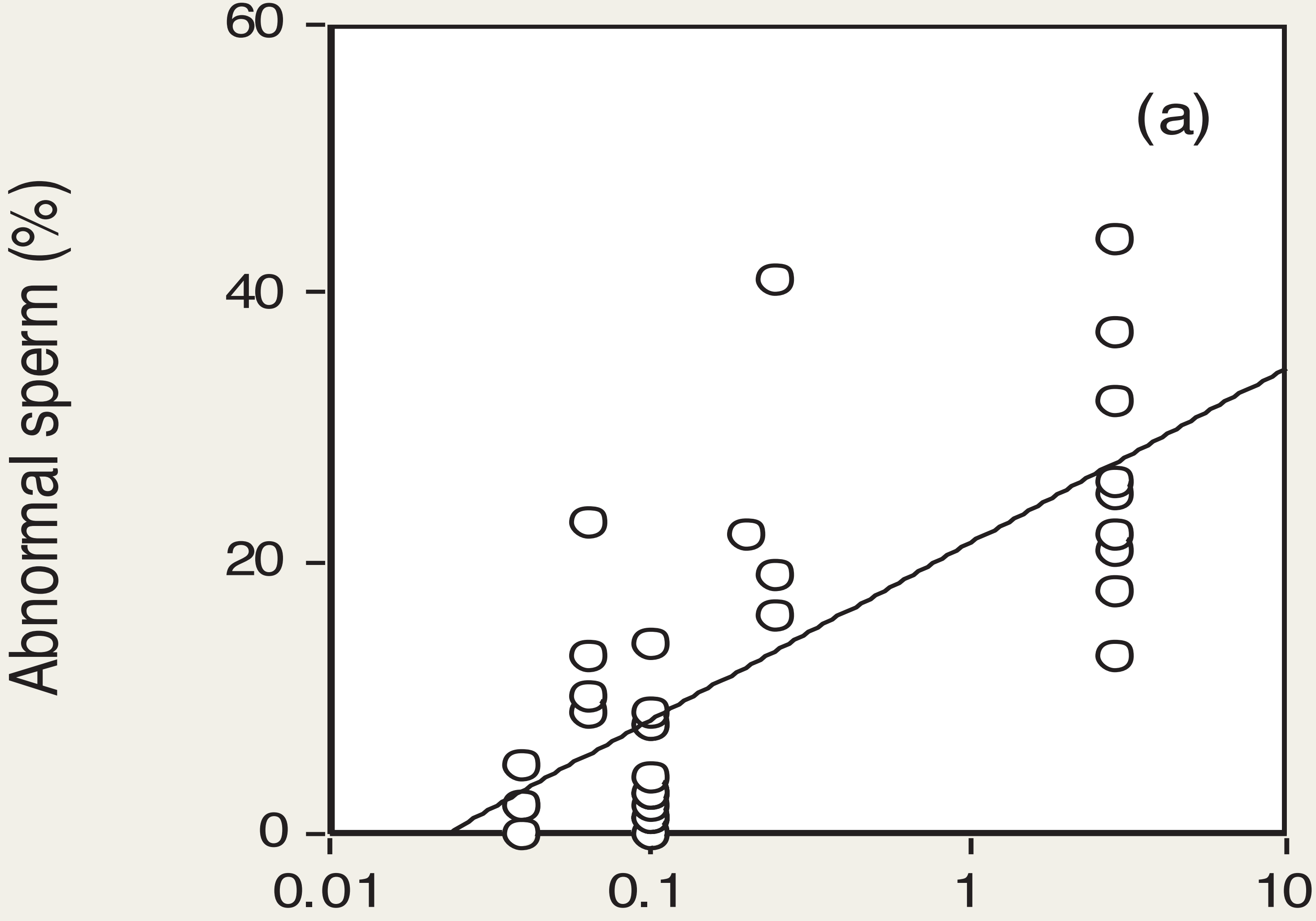

Metafer Slide Scanning System at USC
- Can scan thousands of cells each day

Sperm from Chernobyl Barn Swallow

- many deformed sperm in high radiation areas



Frequency of abnormal sperm in Chernobyl barn swallows is directly related to background radiation levels.



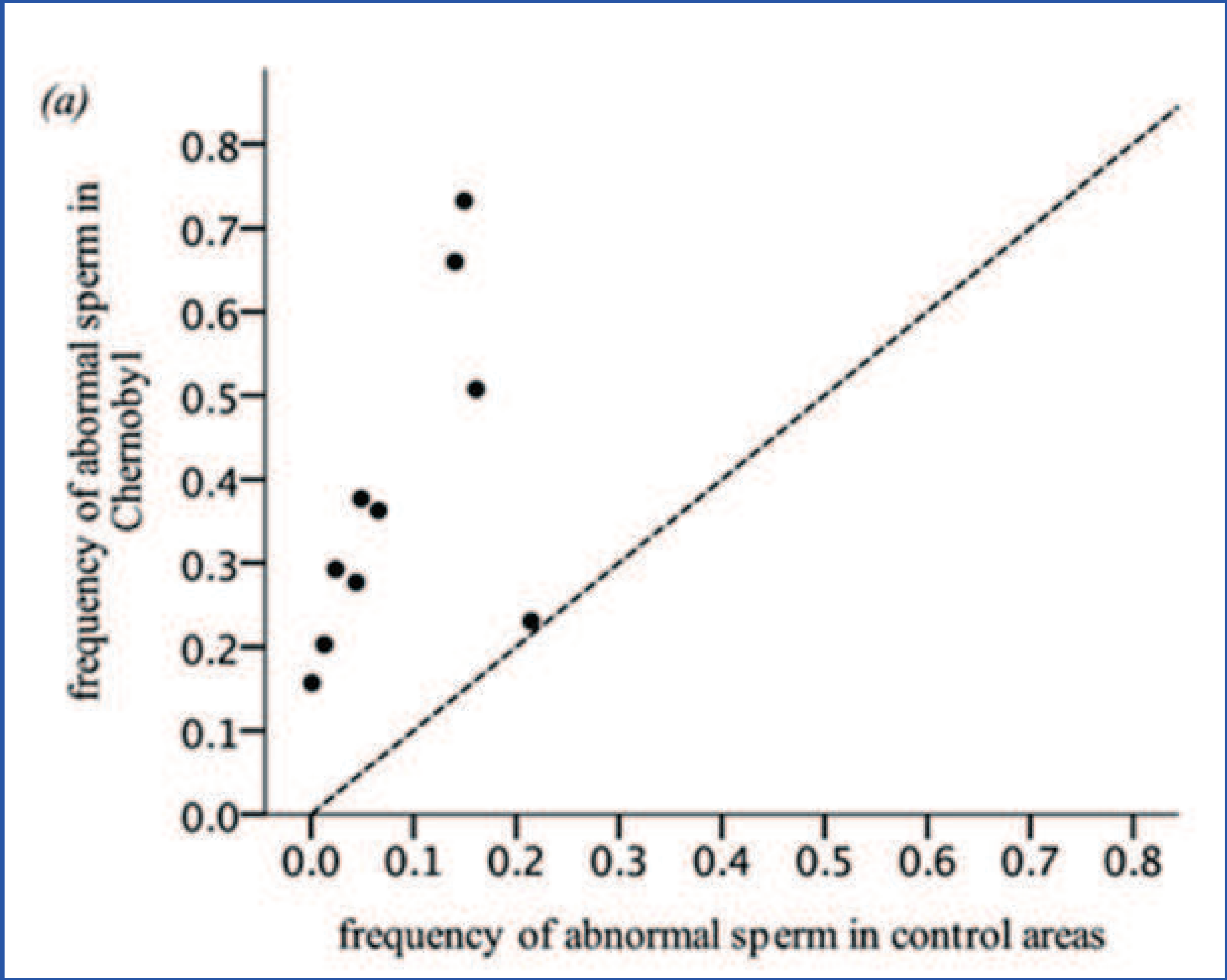
uGy per hour

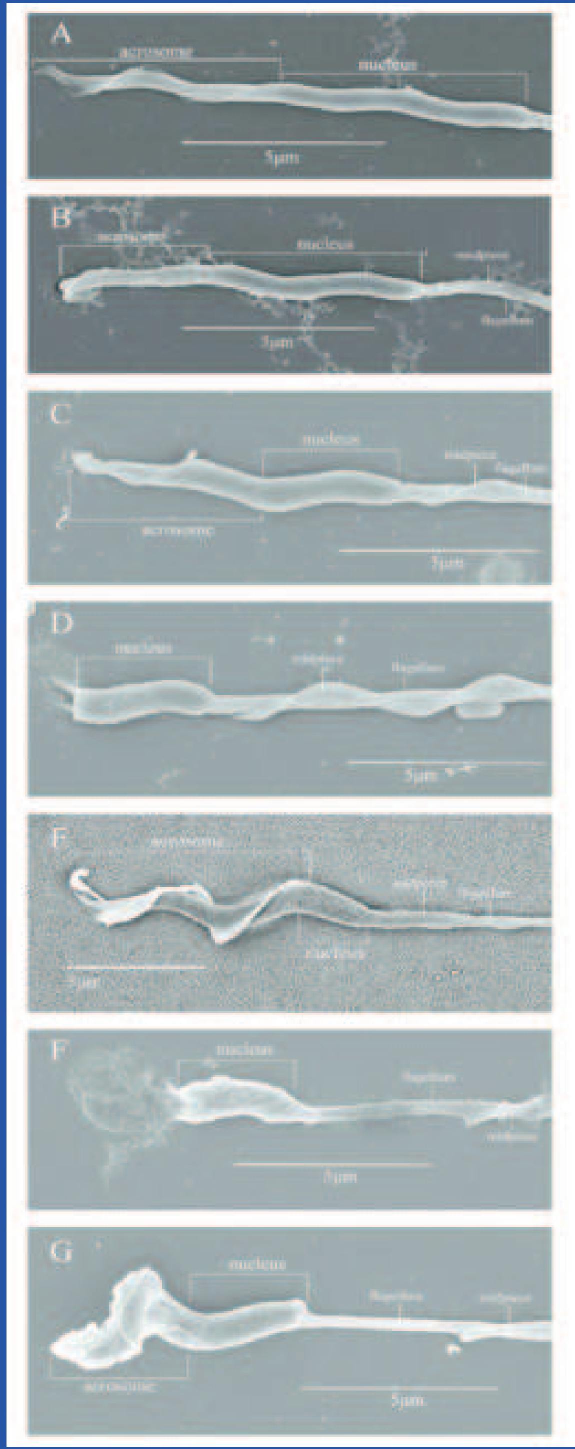
(multiply by 8.8 for mGy/y)

Moller, Mousseau & Surai. 2005. Proc. Roy. Soc. Lond. B.

Frequency of abnormal sperm in 10 Chernobyl bird species.

- 9 out of 10 species have much higher rates of abnormalities in Chernobyl





Hermosell, Laskemoen, Rowe, Møller, Mousseau, Albrecht & Lifjeld. 2013. Biology Letters.

Bird Sperm swimming performance is impaired in radioactive areas of Chernobyl.

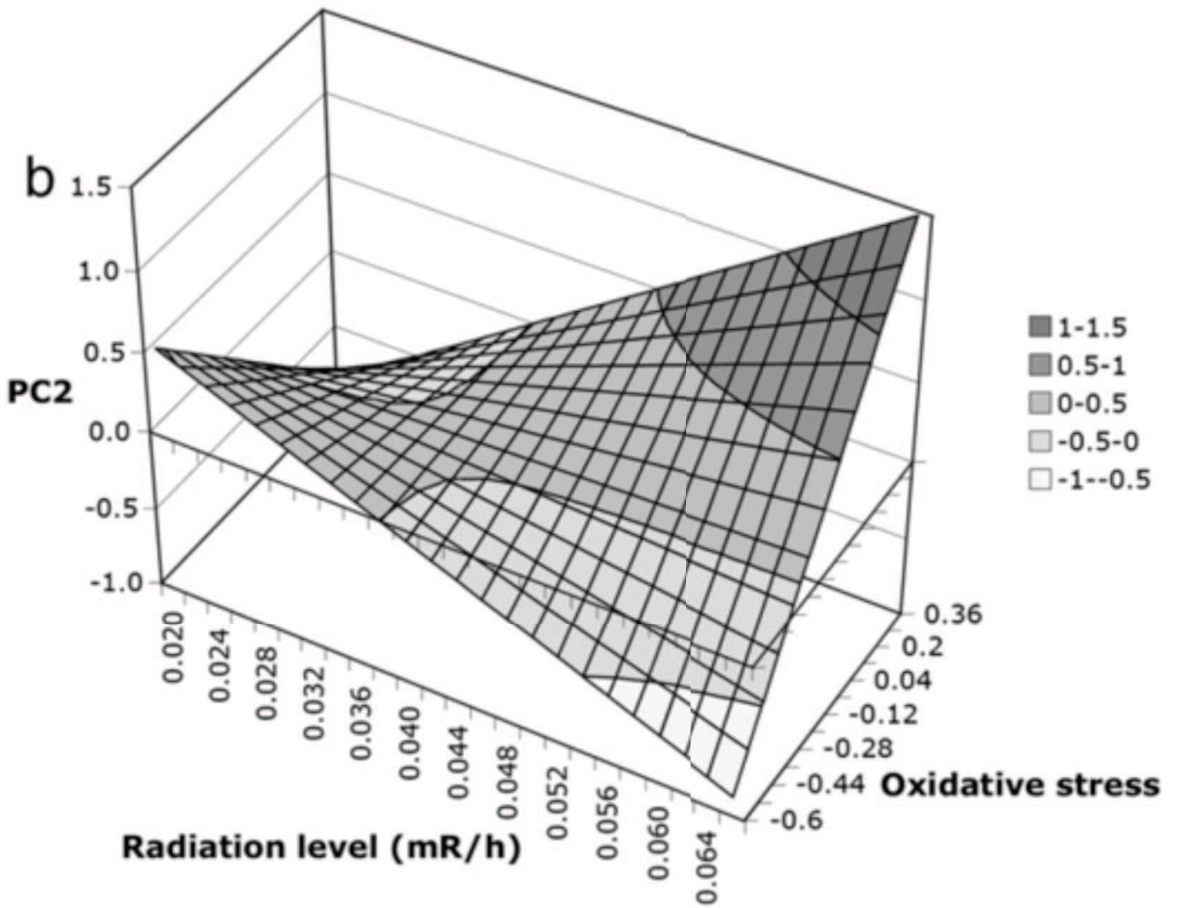
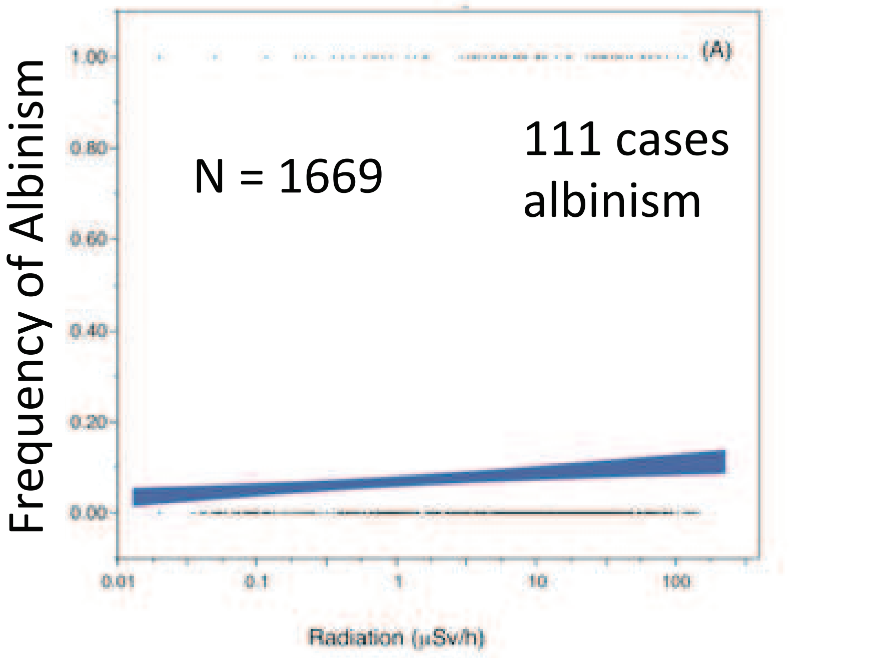
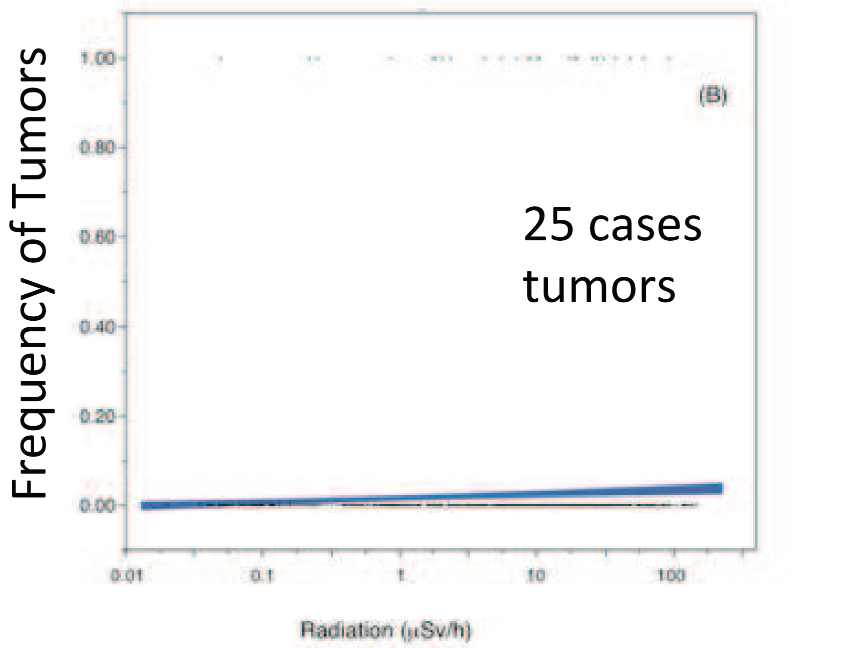


Fig. 3. Relationship between the PC2 scores, background radiation level and oxidative stress in the plasma. In panel (a), individual values of those individuals for which we could determine both TAC and ROMs levels are shown (n = 65). In panel (b), a surface was interpolated based on the coefficients for the effects of background radiation level, oxidative stress levels and the interaction between the two in the best-fit model. The

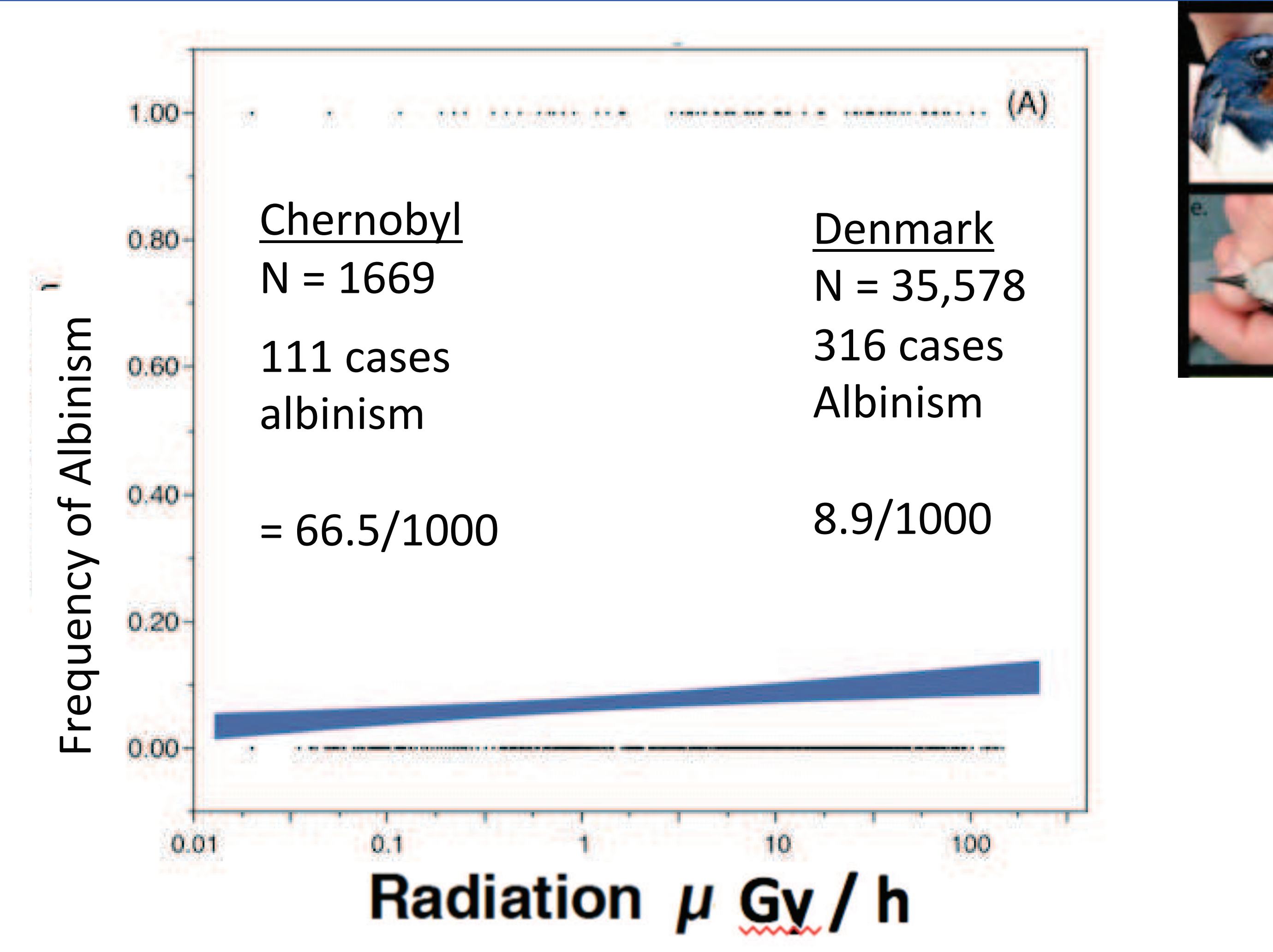
Bonisoli-Alquati, A., A.P. Møller., G. Rudolfsen, N. Saino, M. Caprioli, S. Ostermiller, T.A. Mousseau. 2011. The effects of radiation on sperm swimming behavior depend on plasma oxidative status in the barn swallow (Hirundo rustica). Comparative Biochemistry and Physiology – Part A – Molecular & Integrative Physiology, 159(2): 105-112. DOI: 10.1016/j.cbpa.2011.01.018





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 Show High Levels of Partial Albinism (“White Spots”)

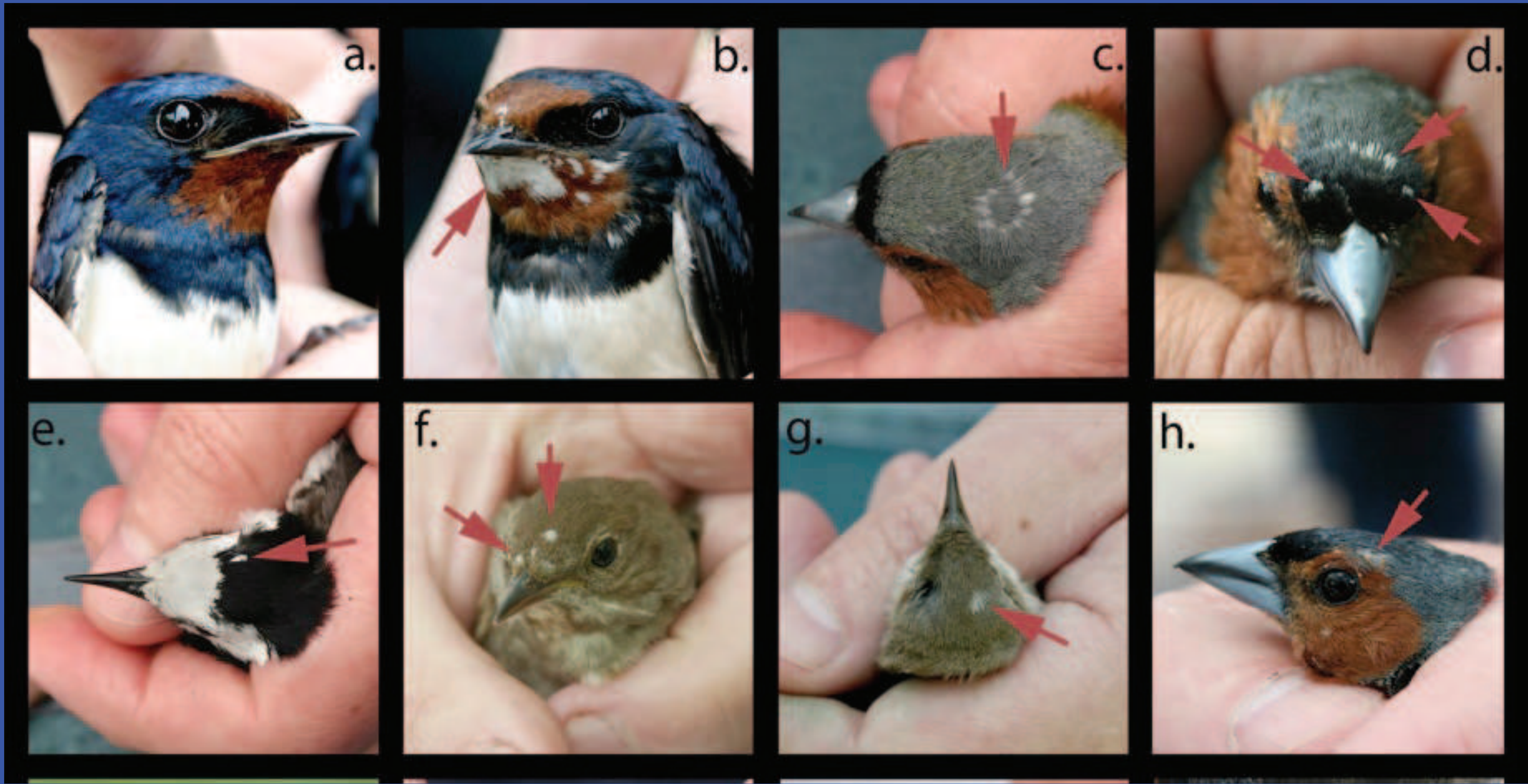


Møller, A.P., A. Bonisoli-Alquati, and T.A. Mousseau. 2013. High frequencies of albinism and tumors in free-living birds at Chernobyl. **Mutation Research**.

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
Albinism						
Species	146.97	61	<0.0001			
Radiation	33.82	1	<0.0001	0.660 (0.120)	0.309	0.162, 0.577
Tumours						
Radiation	15.06	1	0.0001	0.722 (0.210)	0.061	0.011, 0.271

Partial albinos



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**.

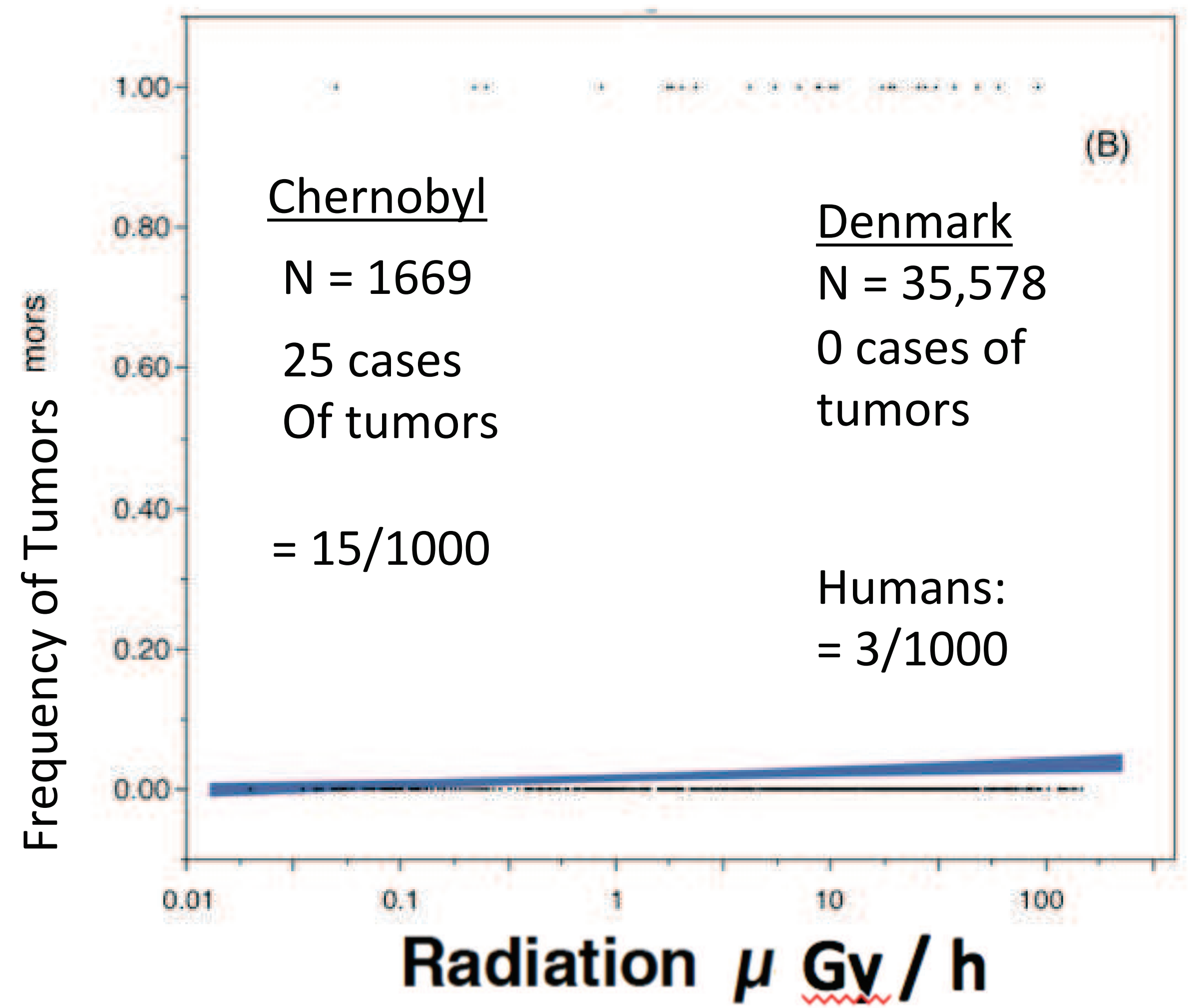

Barn swallow from Fukushima
Albinistic feathers


Fukushima barn swallow
Albinistic feathers
白化した羽

15 cases of partial albinos reported from Fukushima region by the Wild Bird Society of Japan in 2012-13

White spots on Fukushima cow

Chernobyl Birds Have Significantly Higher Rates of Tumors



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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**.

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ごり、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。

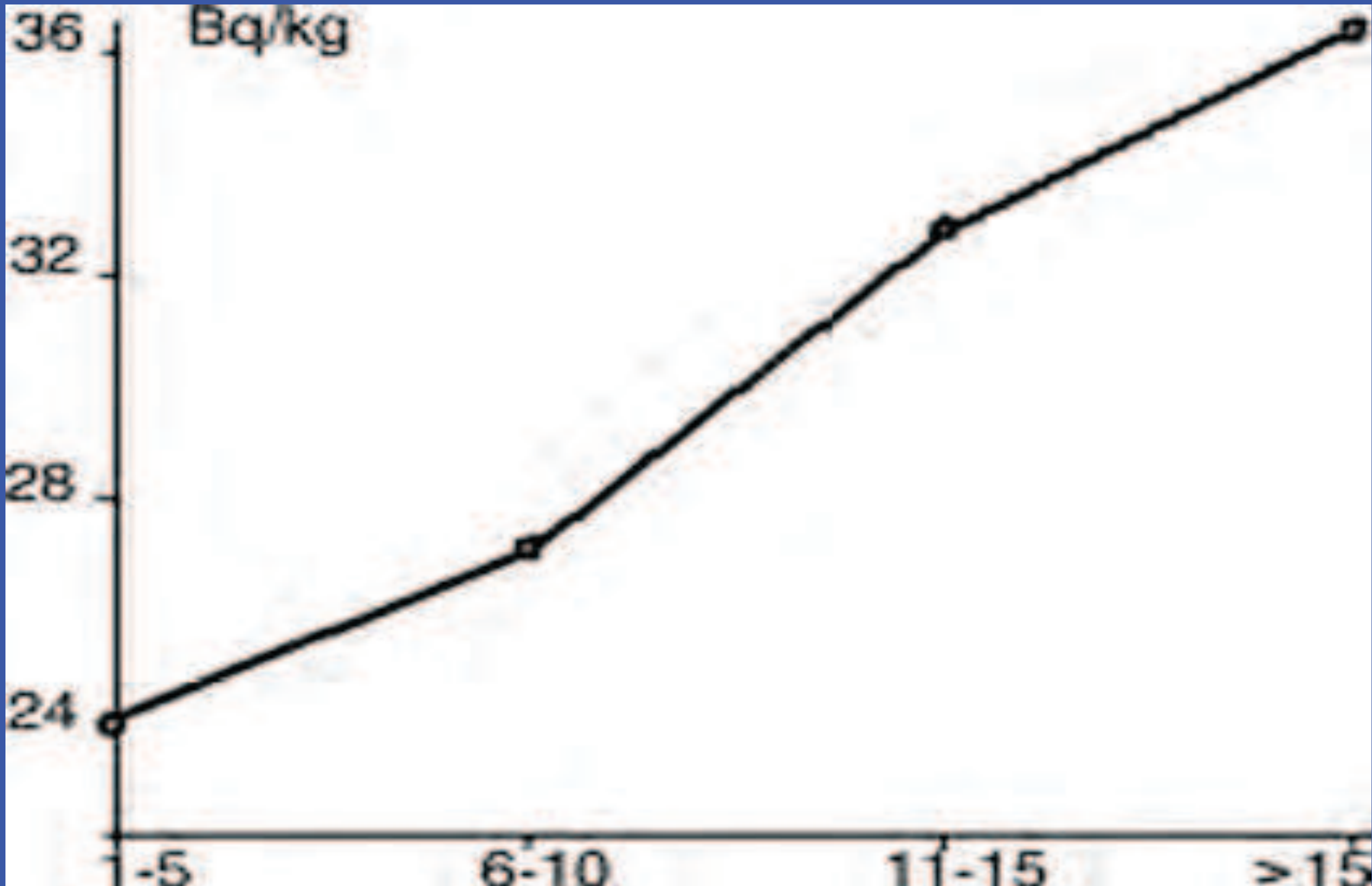
The eye of an A-bomb cataract patient

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.

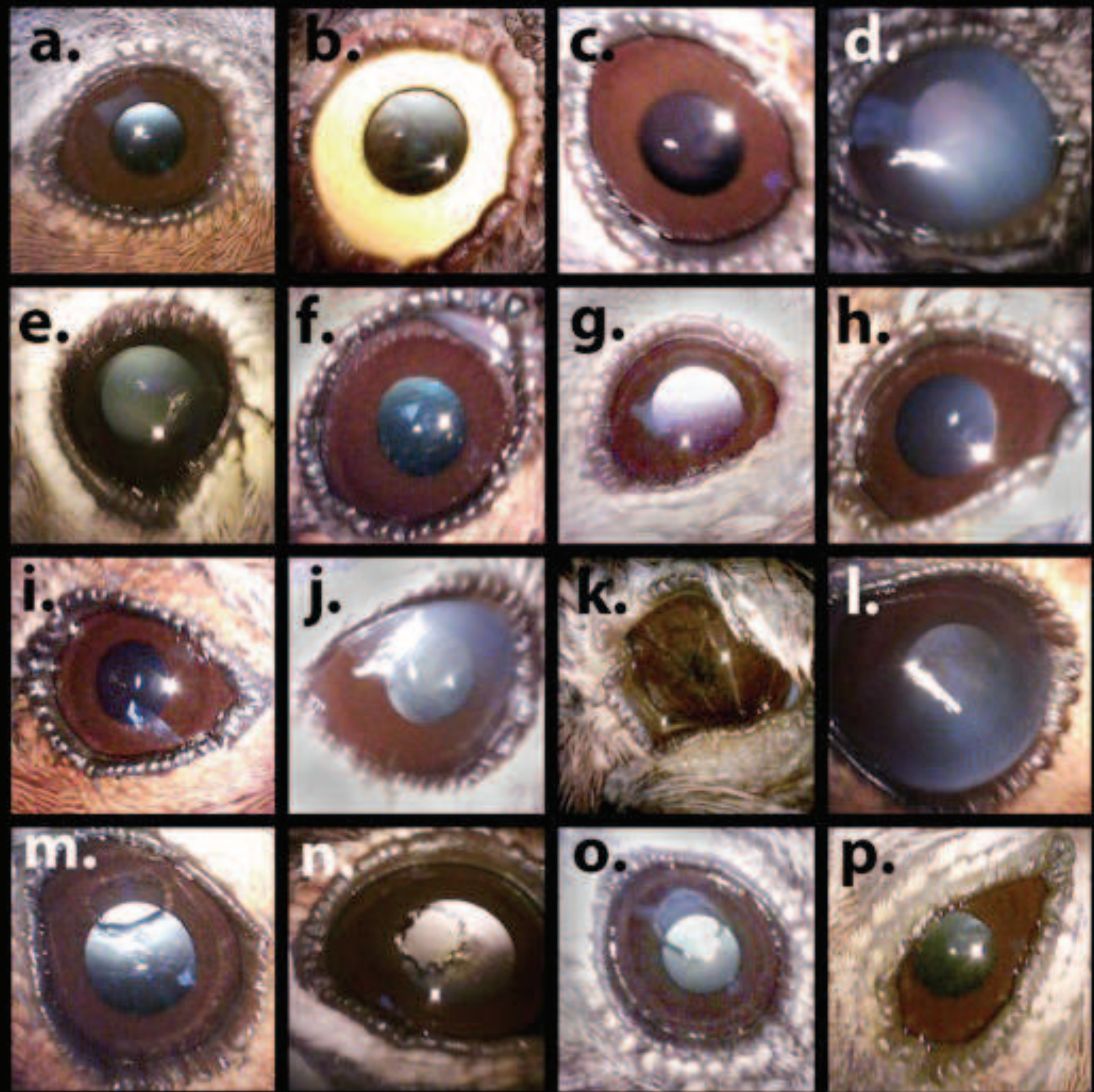
Number of bilateral lens opacities and level of incorporated Cs-137 in Belarussian children (Arynchyn and Ospennikova, 1999)



Yablokov, 2013

Cataracts & Deformities

Bird Eyes of Chernobyl



(a.) Black cap, (*Sylvia atricapilla*), normal. (b.) Barred warbler, (*Sylvia nisoria*), normal. (c.) Black cap, (*Syvia 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 fly catcher, (*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 pipet (*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 (*Saxicola rubetra*), tear on cornea. (o.) Spotted flycatcher (*Muscicapa striata*), tear on cornea (p.) Chiffchaff (*Phylloscopus collybita*), deformed eye lids, haze on cornea.

All photos captured using an EyeQuick Digital Ophthalmoscope Camera.

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

Chernobyl Birds

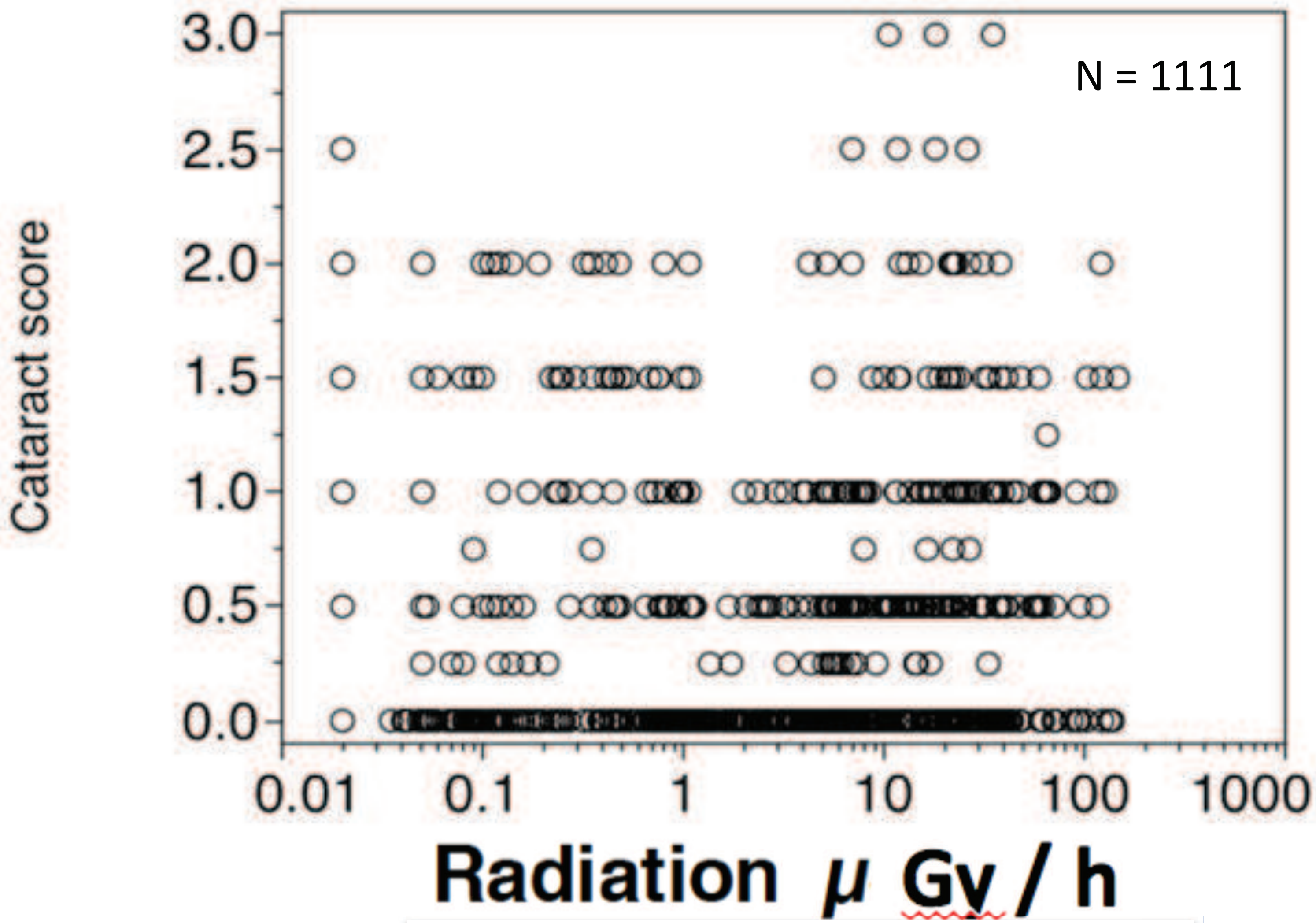


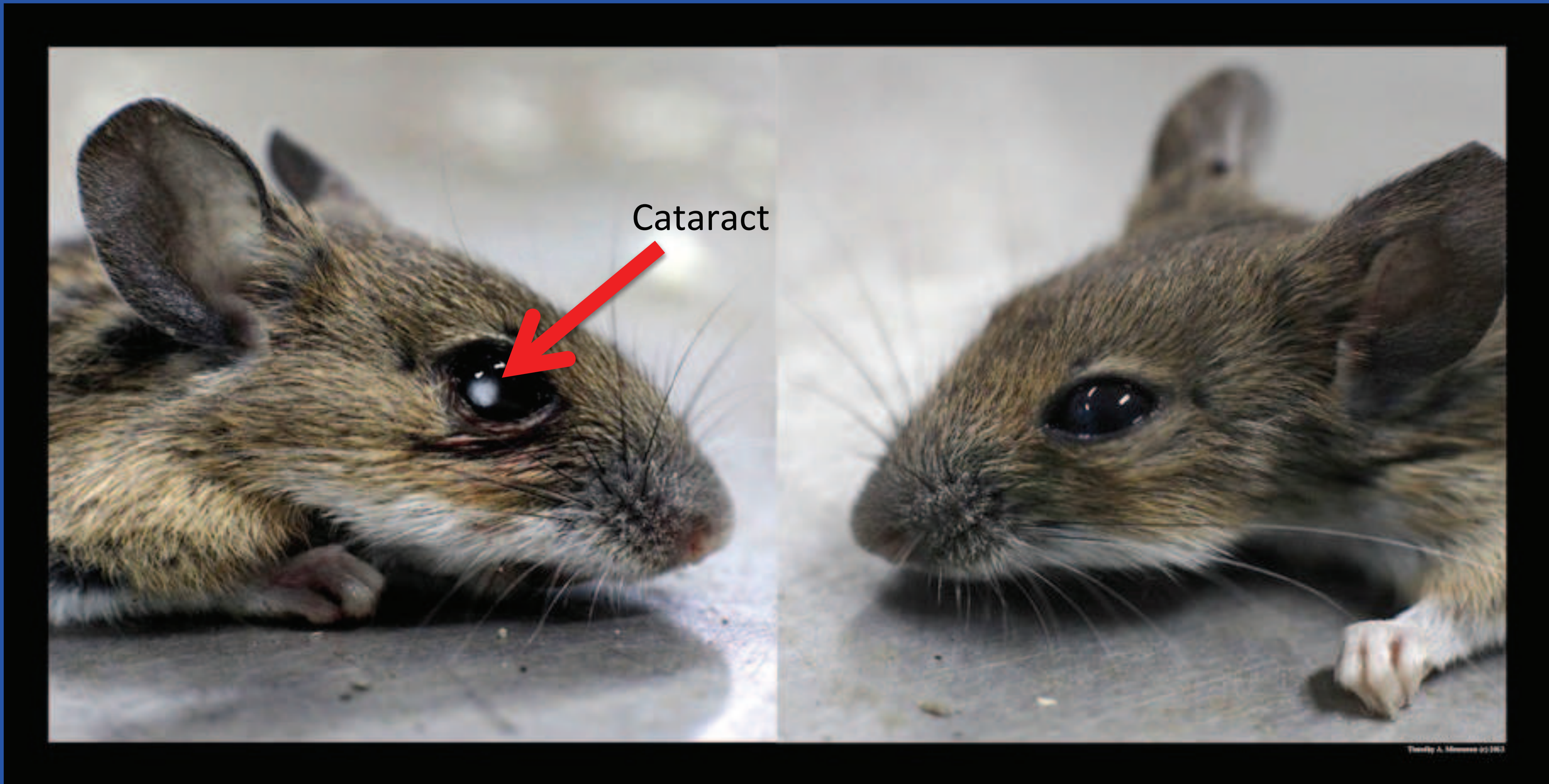
Table 1. Mixed model of cataracts in relation to species (random factor) and radiation. The random species effect accounted for a variance ratio of 0.0955 and 8.71% of the total variance.

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)

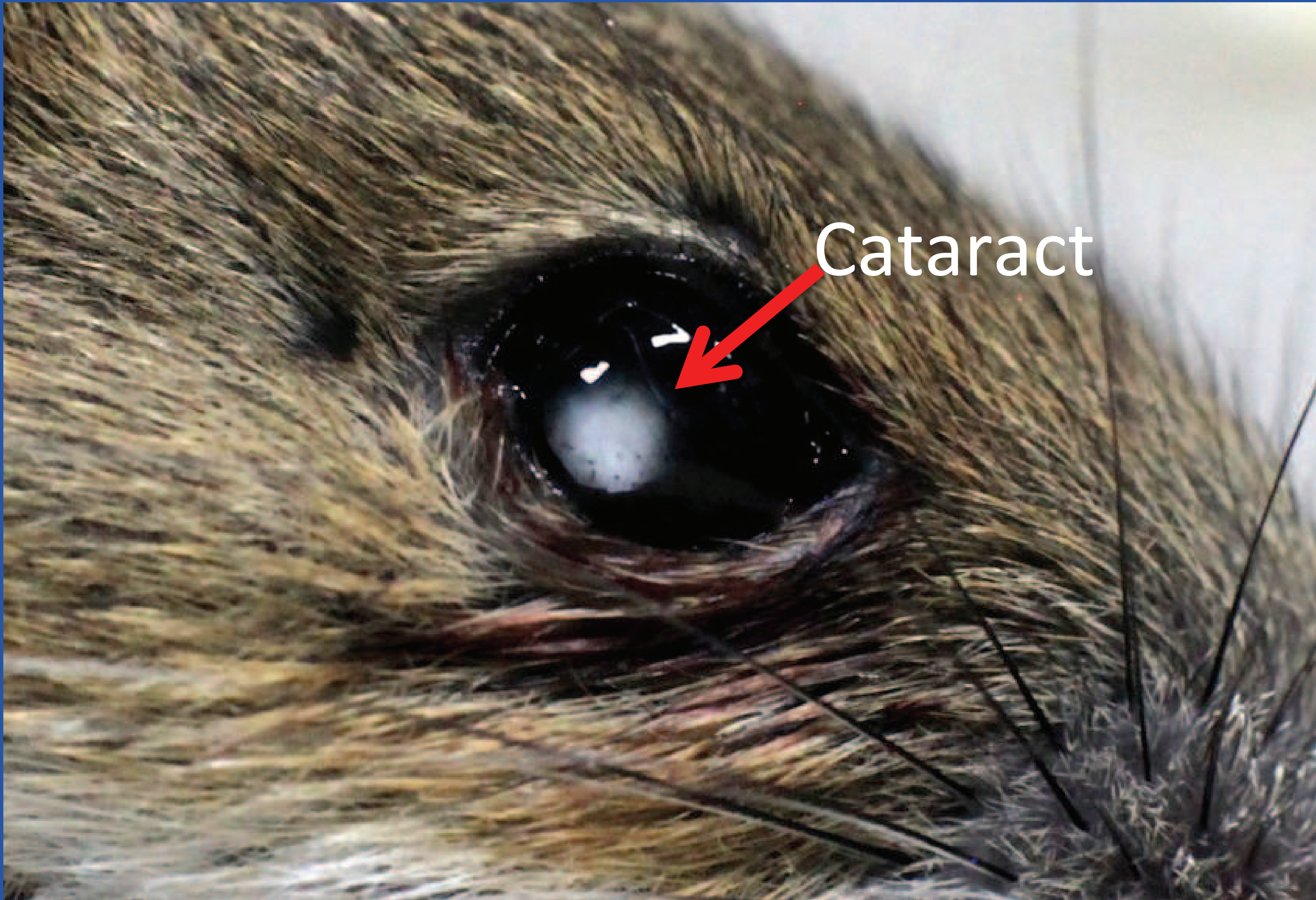
Mousseau, T.A., and A.P. Møller. 2013. Elevated frequencies of cataracts in birds from Chernobyl. **PLoS ONE**.

PLOS ONE

Cataract in Chernobyl mouse



Mousseau, Mappes, Boratynsji, and Moller. 2013. unpublished data.


Cataract

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Page last updated at 09:05 GMT, Saturday, 5 February 2011

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Chernobyl birds are small brained

By Matt Walker
Editor, Earth News

Marsh warblers are one of the species affected

Birds living around the site of the Chernobyl nuclear accident have 5% smaller brains, an effect directly linked to lingering background radiation.

Smaller brained birds die younger and appear to have lower “IQs”.

Moller, Mousseau, et al. 2011. PLoS One

Birds from "hot" regions of Chernobyl have significantly smaller brains.

	Sum of squares	df	F	P	Slope (SE)
Species	1.008	32	13.93	<0.0001	
Radiation [Species]	0.146	33	1.96	0.0015	
Body mass	0.011	1	4.94	0.027	0.140 (0.063)
Keel length	0.008	1	3.59	0.059	0.177 (0.094
Error	1.013	448			

The model had the statistics $F_{67,448} = 171.15$, $r^2 = 0.96$, $P < 0.0001$.
doi:10.1371/journal.pone.0016862.t001

Møller AP, Bonisoli-Alquati A, Rudolfsen G, Mousseau TA (2011) Chernobyl Birds Have Smaller Brains. PLoS ONE 6(2): e16862. doi:10.1371/journal.pone.0016862
http://www.plosone.org/article/info:doi/10.1371/journal.pone.0016862

Mouse collars with TLD dosimeters

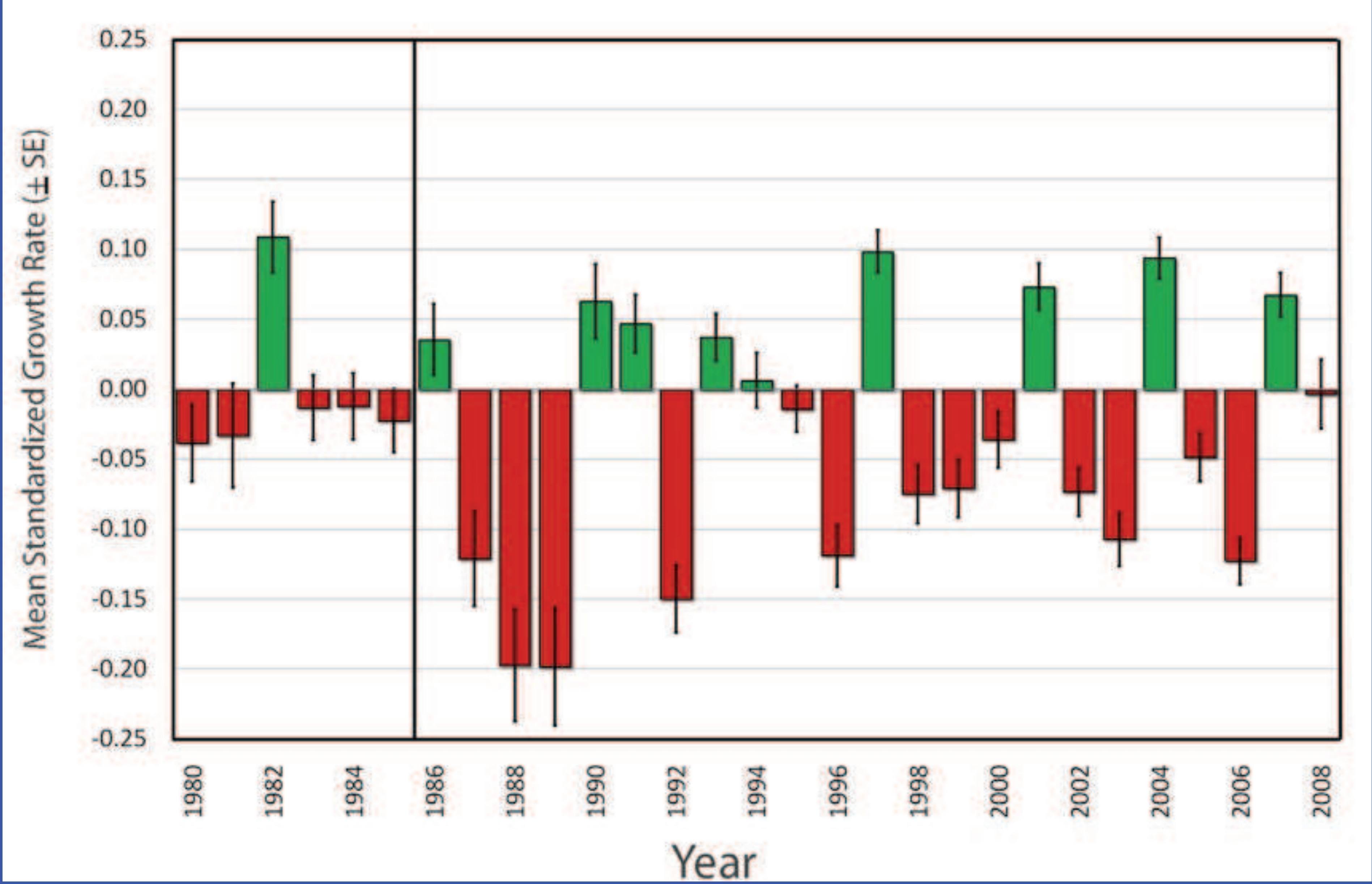
Mutant Firebugs from Chernobyl

Abnormal pine trees (*Pinus sylvestris*) from Chernobyl.

Mousseau, T.A., S.M. Welch, I. Chizhevsky, O. Bondarenko, G. Milinevsky, D. Tedeschi, A. Bonisoli-Alquati, and Møller, A.P., 2013. Tree rings reveal extent of exposure to radiation in Scots pine, Pinus sylvestris. **Trees – Structure and Function**, DOI 10.1007/s00468-013-0891-z

Radiation and tree growth

Standardized tree growth rate



Mousseau et al. 2013. TREES.

How is Animal Abundance and Biodiversity Affected by Radiation?

The UN Chernobyl Forum Report (IAEA, 2006: p137):

". . . the populations of many plants and animals have expanded, and the present environmental conditions have had a positive impact on the biota in the Chernobyl Exclusion Zone."

Human morbidities primarily the result of psychological stress….

But:

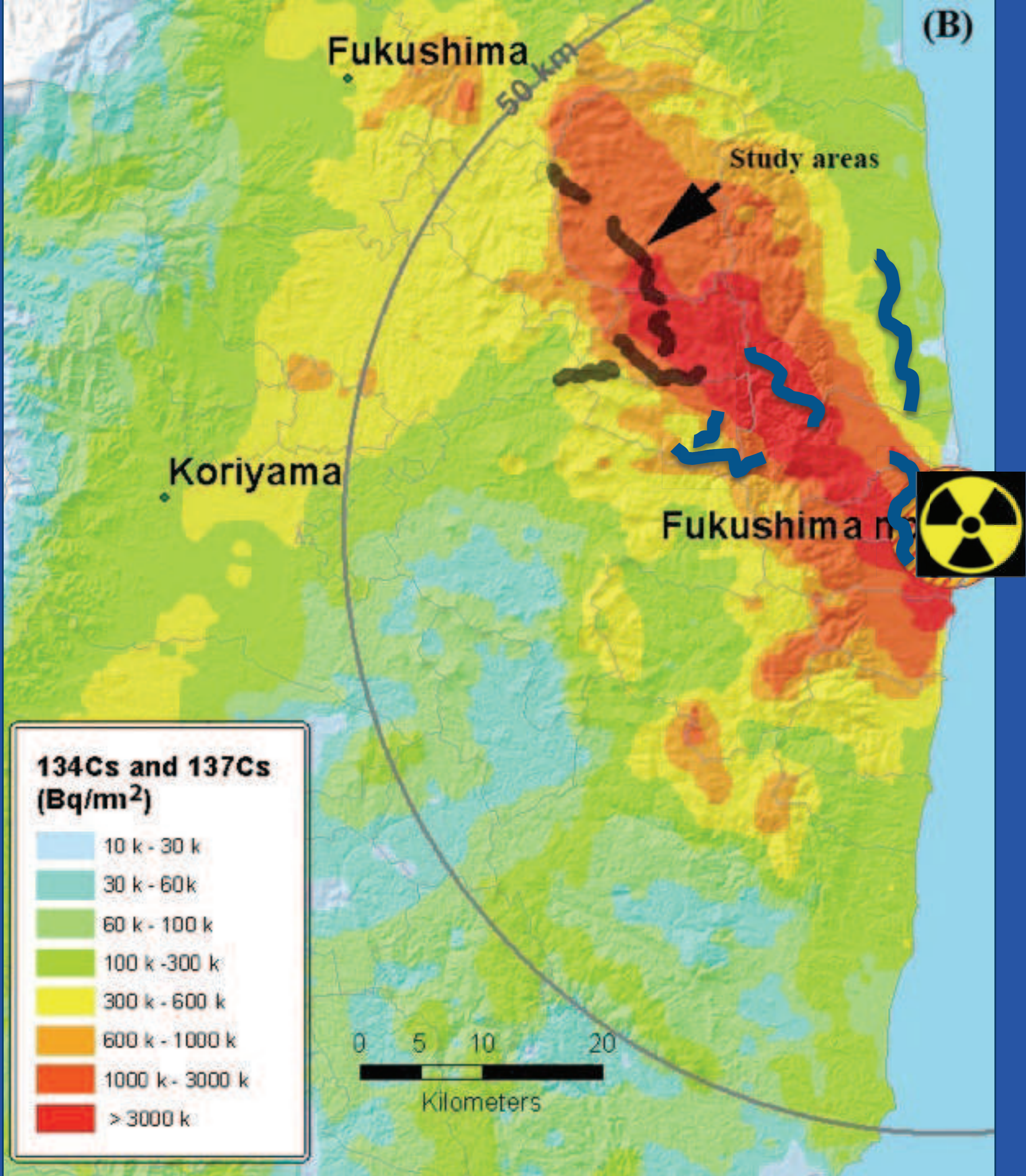
No quantitative data in support of this position and it avoids the primary question of whether or not there are injuries to individuals, populations and the ecosystem as a result of radioactive contaminants.

調査地域は、ほとんどが、最も高濃度の汚染地域

ウクライナと
ベラルースで
鳥と昆虫の調査を
896回

コントロール個体群:

- イタリア (ミラノ)
- スペイン (バダホス)
- デンマーク (オールボー)
- ウクライナ (ボリスポリ)



400地点で調査した鳥類と昆虫は、現在までに合計700 => 1,100インベントリー

Massively Replicated Biotic Inventories
(700 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

+

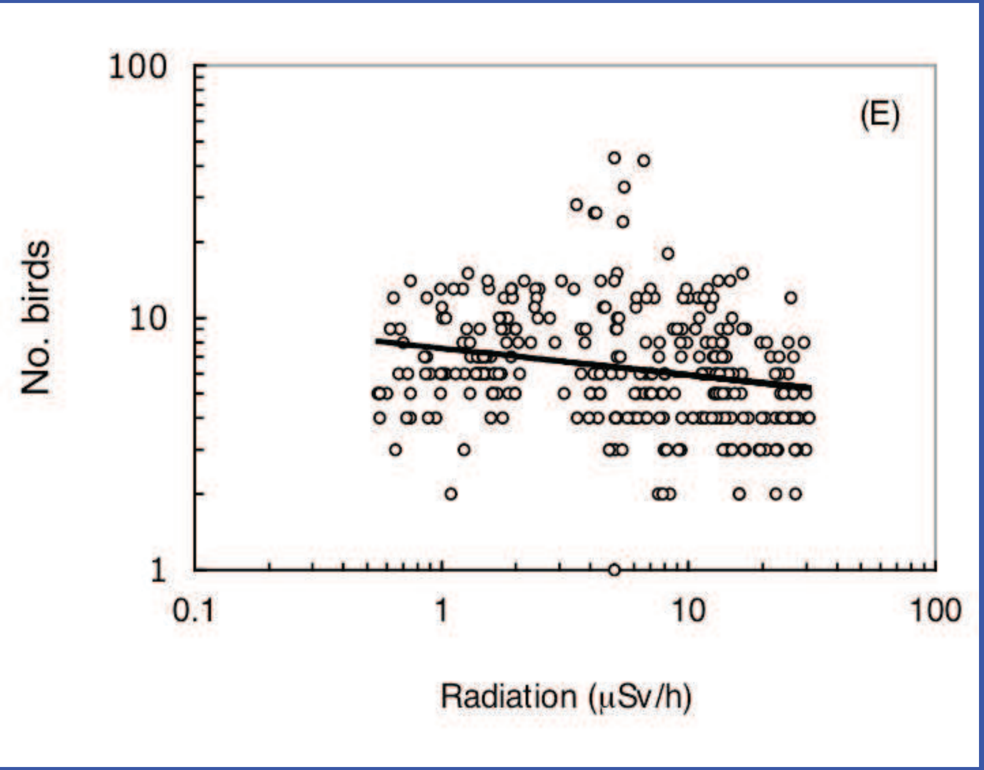
Multivariate Statistics

=

Predictive Models of Radiation Effects on Populations

Birds in Fukushima show larger effects of Radiation than in Chernobyl

Fukushima 2011



Chernobyl 2006-09

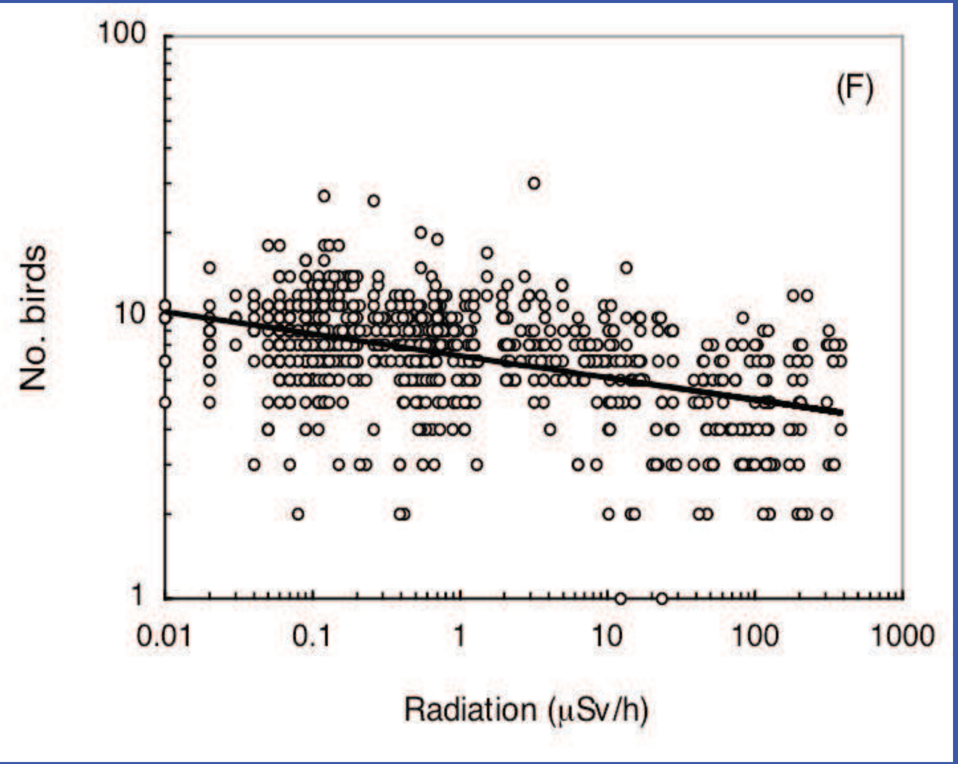


Table 1. Bird abundance in Fukushima and Chernobyl in relation to radiation level.

	SS	d.f.	*F*	*P*	Estimate (SE)
Fukushima:					
No. bird individuals	0.775	1, 298	14.89	0.0001	-0.105 (0.027)
Chernobyl:					
No. bird individuals	6.973	1, 896	256.89	< 0.0001	-0.078 (0.005)

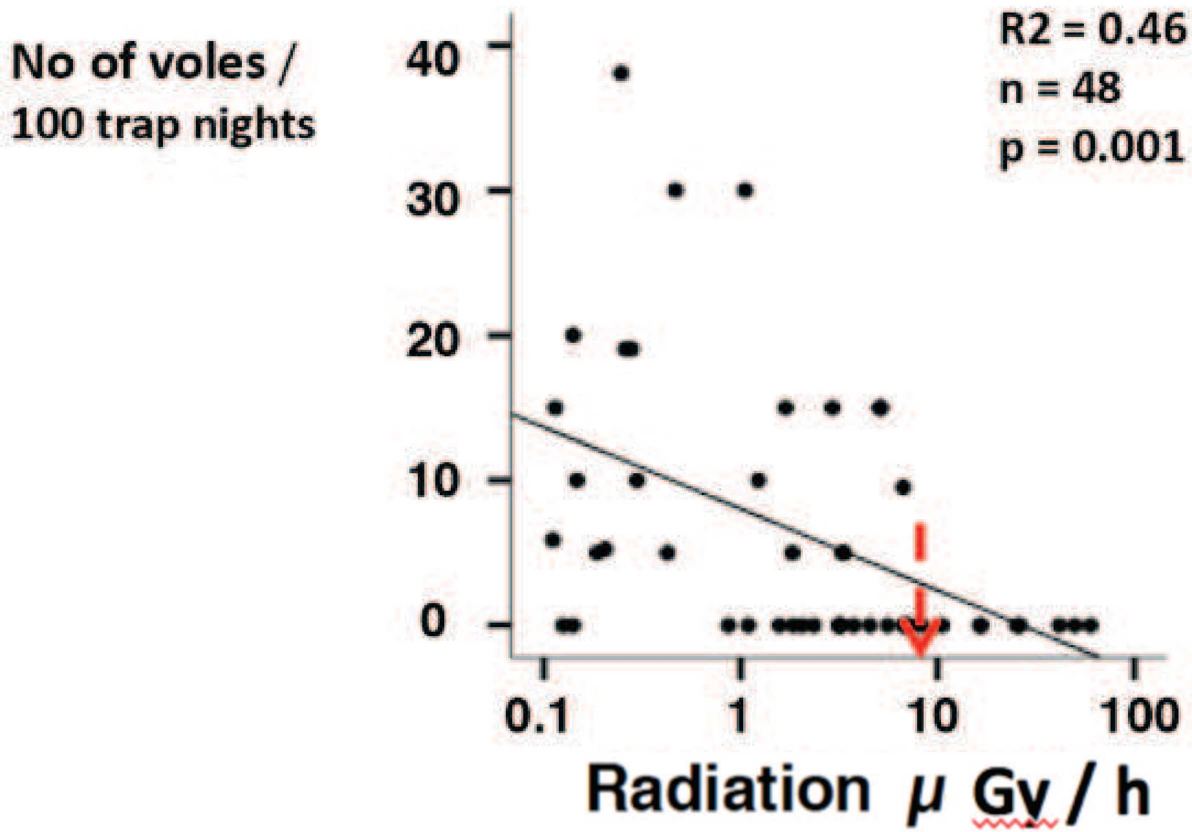
A.P. Møller, A. Hagiwara, S. Kasahara, S. Matsui, I. Nishiumi, H. Suzuki, K. Ueda and T. A. Mousseau. 2012. Environmental Pollution.

Impacts on Abundance in Chernobyl and Fukushima

	Chernobyl	**Fukushima**
Birds	--	--
Butterflies	--	--
Cicadas	--	--
Grasshoppers	--	NE
Bees	--	NE
Dragonflies	--	NE
Spiders	--	+

A.P. Møller, A. Hagiwara, S. Kasahara, S. Matsui, I. Nishiumi, H. Suzuki, K. Ueda and T. A. Mousseau. 2012. Environmental Pollution.

Radiation effects on populations



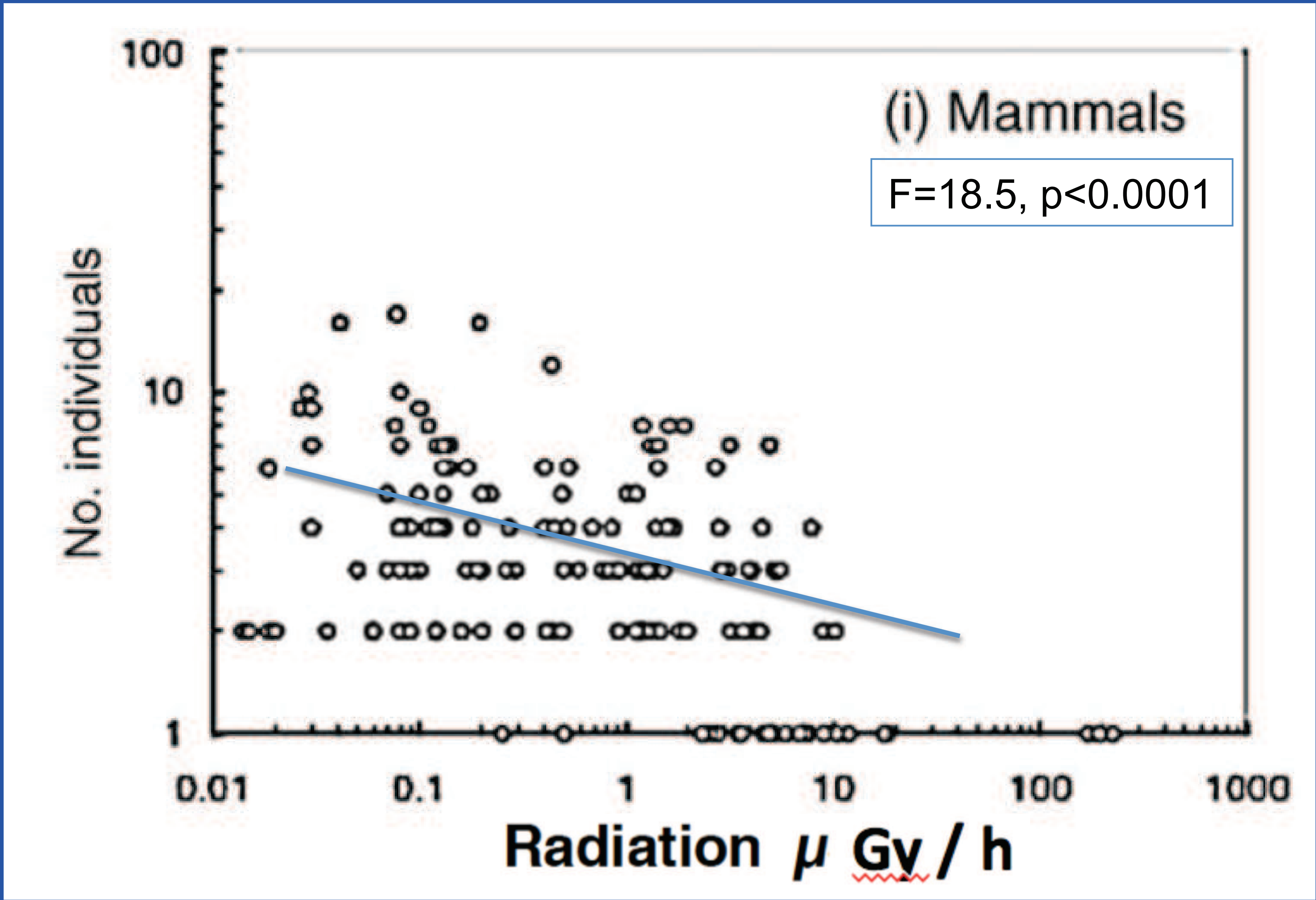
Radiation decrease the densities of voles

- no voles in higher than 10 μSv / h

- 48 trapping areas / 20 traps in each
- early breeding season
- density estimates only 2011

Wolf footprint in snow

Most mammals show significant declines in areas of high contamination.



Moller and Mousseau. 2010. Ecological Indicators.
Mousseau and Moller. 2011. Bulletin of the Atomic Scientists.

Major Findings from studies of Wildlife in Chernobyl:

1) Most organisms studied show significantly increased rates of genetic damage in direct proportion to the level of exposure to radioactive contaminants
2) Many organisms show increased rates of deformities and developmental abnormalities in direct proportion to contamination levels
3) Many organisms show reduced fertility rates…..
4) Many organisms show reduced life spans……
5) Many organisms show reduced population sizes…..
6) Biodiversity is significantly decreased…… many species locally extinct.

More speculative, but potentially larger impact:

7) Mutations are passed from one generation to the next, and show signs of accumulating over time.
8) Mutations are migrating out of affected areas into populations that are not exposed (i.e. population bystander effects).

Priorities for the Future

- We must continue monitoring birds, insects, mammals and plants into the future.
- We must develop methods for accurate measurement of genetic damage and genetic changes in populations.
- We must assess if there is any evidence for adaptation to radiation in plants and animals.
- This will require development of collaborations among scientists and significant investment of money for research that is not available currently.

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Radiation and evolution

Surviving fallout

Birds can evolve to cope with the lingering effects of nuclear incidents

Mar 3rd 2012 | from the print edition

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And the raven, never flitting, still is sitting

THE disaster last year at the Fukushima Dai-ichi nuclear power plant, caused by an earthquake and tsunami, scored seven on the International Nuclear and Radiological Event Scale (INES). No worse rating exists. Radiation is harmful to living things, yet the long-term effects of persistently high levels of background radiation on ecosystems are poorly understood. With this in mind, a team led by Timothy Mousseau of the University of South Carolina and Anders Moller of the University of Paris-Sud set out to compare bird species dwelling near the Fukushima plant with those living at the site of another nuclear incident that scored a seven on the INES: the Ukrainian town of Chernobyl, where disaster struck in 1986. Remarkably, they found that some species seem to develop a tolerance for radioactivity over time.

Have Chernobyl birds adapted to radiation?

Can organisms evolve adaptations to cope with nuclear fallout?

Highlights from research published by the Chernobyl Research Initiative include the following:

- Population sizes and numbers of species (i.e. biodiversity) of birds, mammals, insects, and spiders are significantly lower in areas of high contamination in Chernobyl.

- For many birds and small mammals, life spans are shorter and fertility is depressed, in areas of high contamination.

- In Fukushima, only birds, butterflies, and cicadas showed significant declines during the first summer following the accident. Other groups were not negatively affected.

- Many species show evidence of genetic damage stemming from acute exposures and the differences observed between Fukushima and Chernobyl suggests some species may show the consequences of mutation accumulation over multiple generations.

- The bird species that are most likely to show declines in numbers in response to radiation are those that historically have shown increased mutation rates for other reasons possibly related to DNA repair ability or reduced defenses against oxidative stress.

- Deleterious effects of radiation exposure seen in natural populations in Chernobyl include increased rates of cataracts, tumors, growth abnormalities, deformed sperm, and albinism.
-
- Neurological development is impacted as evidenced by depressed brain size in both birds and rodents and consequent effects on cognitive ability and survival have been demonstrated in birds.

- In Fukushima, the first signs of developmental abnormalities have been observed in birds in 2013, although significant genetic damage has not yet been documented.

- There is considerable variability among species in their sensitivity to radionuclides. Many species are not affected, and a few species even appear to increase in numbers in areas of high contamination in both Chernobyl and Fukushima, presumably in response to competitive release (i.e. more available food and shelter) and fewer predators.

- Some individuals and species show no evidence of genetic damage in relation to radiation exposure and some even show evidence of evolutionary adaptation to the effects of radiation through increased antioxidant activity, which may provide protection against ionizing radiation.