Biological Consequences of Chernobyl and Fukushima

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¹ University of South Carolina
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National Science Foundation, National Geographic Society, CRDF, NATO

A Special Thank you to:
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 km² significantly contaminated land or about half the land area of Japan
Fukushima Disaster – March 11, 2011 – more than 10,000km² land are significantly contaminated, unknown impacts on the marine system.
Chernobyl 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.
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.
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

DNA is broken into pieces by radiation exposure

Low Damage

Medium Damage

High Damage

Comet assays of genetic damage to RBCs and sperm

Grasshopper Hemolymph

Low Damage

Medium Damage

High Damage

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.

(multiply by 8.8 for mGy/y)

Frequency of abnormal sperm in 10 Chernobyl bird species.

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

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

Cronobyl Birds Show High Levels of Partial Albinism ("White Spots")

- Chernobyl
  - N = 1669
  - 111 cases albinism
  - 66.5/1000

- Denmark
  - N = 35,578
  - 316 cases Albinism
  - 8.9/1000


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**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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Chi-square</th>
<th>d.f.</th>
<th>p</th>
<th>Estimate (SE)</th>
<th>Odds ratio</th>
<th>95% CI for odds ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Albinism</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>146.97</td>
<td>61</td>
<td>&lt;0.0001</td>
<td>0.660 (0.120)</td>
<td>0.309</td>
<td>0.162, 0.577</td>
</tr>
<tr>
<td>Radiation</td>
<td>33.82</td>
<td>1</td>
<td>&lt;0.0001</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Tumours</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
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<td>1</td>
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<td>0.722 (0.210)</td>
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</table>
Partial albinos

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

<table>
<thead>
<tr>
<th>Chernobyl</th>
<th>Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 1669</td>
<td>N = 35,578</td>
</tr>
<tr>
<td>25 cases</td>
<td>0 cases of</td>
</tr>
<tr>
<td>Of tumors</td>
<td>tumors</td>
</tr>
<tr>
<td>= 15/1000</td>
<td>Humans:</td>
</tr>
<tr>
<td></td>
<td>= 3/1000</td>
</tr>
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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.

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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.**
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.

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 (Arynychyn and Ospennikova, 1999)

Yablokov, 2013
Bird Eyes of Chernobyl

Cataracts & Deformities
Chternobyl 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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>d.f.</th>
<th>F</th>
<th>P</th>
<th>Estimate (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>48.66, 1074</td>
<td>&lt; 0.0001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>log Radiation</td>
<td>1, 1074</td>
<td>89.63</td>
<td>&lt; 0.0001</td>
<td>0.131 (0.014)</td>
</tr>
</tbody>
</table>

Cataract in Chernobyl mouse

Mousseau, Mappes, Boratynski, and Moller. 2013. unpublished data.
Smaller brained birds die younger and appear to have lower “IQs”.

Birds from “hot” regions of Chernobyl have significantly smaller brains.

<table>
<thead>
<tr>
<th></th>
<th>Sum of squares</th>
<th>df</th>
<th>F</th>
<th>P</th>
<th>Slope (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>1.008</td>
<td>32</td>
<td>13.93</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Radiation [Species]</td>
<td>0.146</td>
<td>33</td>
<td>1.96</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>Body mass</td>
<td>0.011</td>
<td>1</td>
<td>4.94</td>
<td>0.027</td>
<td>0.140 (0.063)</td>
</tr>
<tr>
<td>Keel length</td>
<td>0.008</td>
<td>1</td>
<td>3.59</td>
<td>0.059</td>
<td>0.177 (0.094)</td>
</tr>
<tr>
<td>Error</td>
<td>1.013</td>
<td>448</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Mouse collars with TLD dosimeters
Mutant Firebugs from Chernobyl
Abnormal pine trees (*Pinus sylvestris*) from Chernobyl.

Radiation and tree growth

“Chernobyl event”
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シ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posição)
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**

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

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>d.f.</th>
<th>$F$</th>
<th>$P$</th>
<th>Estimate (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fukushima:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. bird individuals</td>
<td>0.775</td>
<td>1,298</td>
<td>14.89</td>
<td>0.0001</td>
<td>-0.105 (0.027)</td>
</tr>
<tr>
<td><strong>Chernobyl:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. bird individuals</td>
<td>6.973</td>
<td>1,896</td>
<td>256.89</td>
<td>&lt; 0.0001</td>
<td>-0.078 (0.005)</td>
</tr>
</tbody>
</table>

## Impacts on Abundance in Chernobyl and Fukushima

<table>
<thead>
<tr>
<th></th>
<th>Chernobyl</th>
<th>Fukushima</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birds</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Butterflies</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cicadas</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Grasshoppers</td>
<td>--</td>
<td>NE</td>
</tr>
<tr>
<td>Bees</td>
<td>--</td>
<td>NE</td>
</tr>
<tr>
<td>Dragonflies</td>
<td>--</td>
<td>NE</td>
</tr>
<tr>
<td>Spiders</td>
<td>--</td>
<td>+</td>
</tr>
</tbody>
</table>

Radiation effects on populations

No of voles / 100 trap nights

Radiation $\mu$ Gy / h

R2 = 0.46
n = 48
p = 0.001

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

Radiation decrease the densities of voles

- no voles in higher than 10 $\mu$Sv / h
Wolf footprint in snow
Most mammals show significant declines in areas of high contamination.

F=18.5, p<0.0001

Moller and Mousseau. 2010. Ecological Indicators.
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.
Have Chernobyl birds adapted to radiation?

Can organisms evolve adaptations to cope with nuclear fallout?

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.
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.