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Instant symposium

Entomological Studies in Chernobyl and Fukushima

T. A. Mousseau and A. P. Møller

Radioactive emissions can occur as a consequence of natural deposition in rocks, as a consequence of human release of radioactive material such as during nuclear testing and the operations of nuclear power plants (NAS 2012), and from nuclear accidents such as those at the Three Mile Island, Chernobyl, and Fukushima Daiichi power plants. In some parts of the world (e.g. Ramsar, Iran), natural levels of radiation can be high, exceeding "normal" low levels by several hundred-fold (Ghiassi-Nejad et al. 2002), sometimes resulting in significant rates of disease and associated mortality in humans (e.g. Lubin and Boice 1997; Hendry et al. 2009) and, by inference, in other organisms. Much higher levels of radiation occur as a consequence of nuclear accidents that have produced levels that can exceed normal background levels by a factor of 10,000 or more.

Radiation can have both short- and long-term effects on living organisms. Short-term physiological effects may include oxidative stress (e.g. Ben-Amotz et al. 1998; Møller et al. 2005b; Bonisoli-Alquati et al. 2010a), increased damage to DNA (e.g. Sakharov et al. 1996; Bonisoli-Alquati et al. 2010b), immunosuppression (e.g. Camplani et al. 1999; Yablokov et al. 2009), and many other possible effects. Direct physiological effects can result in reproductive failure and even death. Reproductive failure associated with radiation often occurs as a consequence of embryo mortality (Møller et al. 2005, 2008; Yablokov et al. 2009). Reproductive failure has also been reported for birds such as barn swallows (*Hirundo rustica*), in which more than 25% of females living in contaminated areas may forego reproduction altogether (Møller et al. 2005), and similarly reduced fecundity has been reported for humans (Yablokov et al. 2009). Males living in contaminated areas have shown a high degree of infertility, often producing few or mainly unviable sperm (Yablokov et al. 2009). Short-term physiological effects of radiation may have negative consequences for adult survival, especially in the sex that invests the most in reproduction (Møller et al. 2005; Yablokov et al. 2009).

Radioactive contaminants have long been known to cause mutations (Nadson and Philippov 1925), although these are more difficult to study due to their long-term nature that can extend across generations (Møller and Mousseau 2011a). Mutations arise from DNA damage that is not repaired, thereby causing a reduction in fitness if the mutation occurs in a coding region and it affects gene expression (Eyre-Walker and Keightley 2007). Extensive studies of a diverse array of plants, animals, and other organisms have shown increased levels of mutations by a factor of two to 20 around Chernobyl (review in Møller and Mousseau 2006).

Impacts on Wildlife in Chernobyl

We have been studying the impacts of nuclear accidents on wildlife for more than 12 years (APM since 1991; TAM since 2000). Initially, our studies were descriptive and aimed primarily at documenting whether or not there were measurable impacts on the morphology and life histories of organisms (mostly birds) living in the contaminated areas of Chernobyl (Møller and Mousseau 2001, 2003). Our efforts expanded to include Fukushima in July 2011 (Møller et al 2012, 2013). Largely in response to some untested assertions published in the 2005 Chernobyl Forum reports that suggested that plants and animals were thriving inside the exclusion zone, our efforts expanded to include detailed analyses of mutation rates, developmental abnormalities (e.g. visible mutations, tumors), fertility and reproductive capacity, longevity, population abundances, and biodiversity, as well as measures of ecosystem functioning in birds, insects, spiders, plants, and microbes (Møller and Mousseau 2006, 2007a, 2007b, 2007c, 2008, 2009, 2011a, 2011b; Møller et al. 2005a, 2005b, 2006, 2008). Here, we briefly summarize a few of our more interesting findings related to insects.

Our first efforts to study insects in Chernobyl focused on *Drosophila melanogaster*. Initially, in 2004, these studies were largely unsuccessful as it proved unexpectedly difficult to find *Drosophila*, even in the abandoned villages where fruit trees were abundant. Anecdotally, it appeared that fruit set was very low, possibly as a result of low pollinator numbers in the areas of high contamination. However, at the time, we noted that fruit trees in the town of Chernobyl itself were overladen with fruit, despite moderate radiation levels, and *Drosophila* were correspondingly abundant, thus calling into question our pollinator abundance hypothesis. We subsequently learned that several experimental beehives had been brought to Chernobyl, likely accounting for the high fruit set and large numbers of *Drosophila*

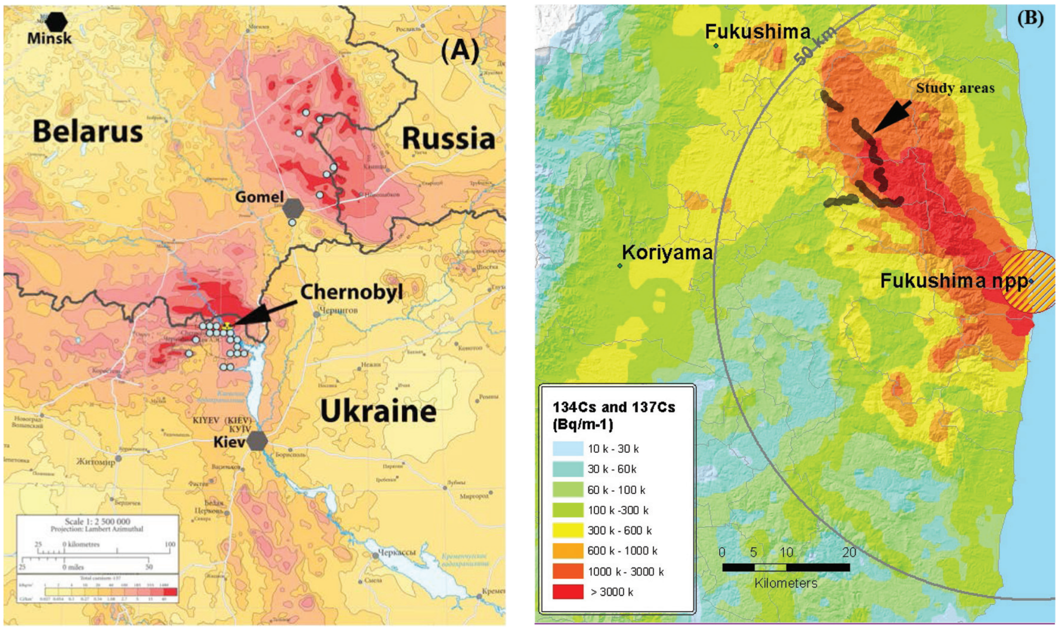

Fig.1. Location of census areas around (A) Chernobyl (Ukraine and Belarus) and (B) Fukushima Prefecture (Japan).

in this area, despite significant radiation levels. As a consequence of these insights and discoveries, we initiated a series of ecological censuses during 2006-2009 inside and out of the Chernobyl Exclusion Zone of Ukraine, as well as in several regions of southeastern Belarus, where contamination levels also varied considerably. Insect and spider censuses were performed at a total of 254 points in 2006, 235 points in 2007, 237 points in 2008, and 159 points in 2009 and were located at ≈100 m intervals within forested areas (excluding successional stages of secondary forest due to abandoned farming, which are still almost exclusively open grassland). We conduced similar censuses at a total of 300 sampling points in forested areas west of the exclusion zone around the Fukushima Daiichi power plants in 2011 (Møller et al. 2012a, 2013).

Our statistical analyses of abundance included many potentially confounding variables in addition to background radiation levels and animal abundance. These other factors included ground coverage with farmland, deciduous and coniferous forest, grass, bush, and trees; temperature, cloud cover, and wind; time of day, and time of day squared. We also included radiation level squared to account for non-linear relationships between species richness and abundance, respectively, and radiation. We developed statistical models to assess the relationship between abundance (response variables) and radiation, assuming a Poisson distribution of abundance, after inclusion of the potentially confounding variables, as implemented in the statistical software JMP (SAS Institute 2000). Further details concerning locations, methods, statistical analyses and results can be found in Møller and Mousseau (2007a, 2009, 2011b).

Results and Discussion

Radioactive contamination may affect the abundance of animals through direct effects on physiology or through indirect effects of mutations that can have deleterious consequences for reproduction and viability. Previous studies of animals at Chernobyl have shown negative effects of radiation on immunity, antioxidant status, reproductive failure by females, and sperm production. Likewise, mutation rates at Chernobyl have increased by up to a factor of twenty relative to the normal background mutation rates (Møller and Mousseau 2006).

In Chernobyl, the abundance of all investigated taxa decreased with the level of background radiation (Mousseau and Møller 2011) (Table 1). The mean of the slopes describing the relationship between abundance and level of background radiation for different taxa was statistically significant (mean (SE) = -0.059 (0.015), N = 10, P = 0.0041), and the significance of this relationship remained strong even after adjusting for potentially confounding environmental variables (F = 33.98, d.f. = 1, 6, r^2 = 0.85, P = 0.0011, slope (SE) = 1.668 (0.286)).

Analyses of invertebrate abundances at Fukushima revealed a different pattern of variation (Møller et al. 2013). Butterflies and cicadas showed a drop in abundances with increasing contamination levels, while there was no pattern of change for bumblebees, dragonflies, or grasshoppers. Spiders, on the other hand, showed a statistically significant increase at the most contaminated sites, possibly reflecting the decreased abundance of birds found in these areas (Møller et al. 2013). Another possible explanation for the differences observed between Chernobyl and Fukushima could relate to the importance of mutation accumulation over multiple generations that we have previously suggested as an important factor impacting on

Table 1: Abundance of different animal taxa in Fukushima and Chernobyl in relation to radiation level. See Møller et al. 2012 and 2013 for further details.

	Sum of squares	d.f.	F	P	Estimate (SE)
Fukushima					
No. bumblebees	0.001	1, 298	0.16	0.69	
No. butterflies	4.553	1, 298	37.18	<0.0001	−0.254 (0.042)
No. cicadas	0.208	1, 298	19.24	<0.0001	−0.054 (0.012)
No. dragonflies	0.127	1, 298	0.87	0.35	
No. grasshoppers	0.004	1, 298	0.22	0.64	
No. spiders	0.636	1, 298	14.12	0.0002	0.095 (0.025)
Chernobyl					
No. bumblebees	1.595	1, 896	55.71	<0.0001	−0.037 (0.005)
No. butterflies	2.153	1, 896	57.63	<0.0001	−0.043 (0.006)
No. dragonflies	1.195	1, 402	34.58	<0.0001	−0.049 (0.008)
No. grasshoppers	0.891	1, 372	13.58	0.0003	−0.071 (0.019)
No. spiders	5.738	1, 896	81.94	<0.0001	−0.071 (0.008)

populations in the Chernobyl region where radioactive contaminants have shaped populations for 25 generations for most insect species (Møller and Mousseau 2011a). Alternatively, differences could relate to the many contrasts between Fukushima and Chernobyl events, especially with regard to the composition of contaminants that were dispersed. In Fukushima, cesium-134 and cesium-137 predominate, while in Chernobyl, cesium-137, strontium-90, plutonium-239 and americium-241 are found at significant levels across the landscape, and differential sensitivity to these mixtures could perhaps account for some of the differences between locales. Clearly, significant research effort should be directed towards a clear understanding of the mechanisms underlying differences and similarities of the impacts resulting from these two catastrophes.

Acknowledgments

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What is it? answer:

This is a leafhopper (Cicadellidae: Deltocephalinae) abdomen with an adult female strepsipteran (Halictophagidae) head protruding from the side. The strepsipteran's body is filled with first instar larvae. The leafhopper, *Alocoelidia fulva* Evans, was collected in Madagascar.

This photo was submitted by James N. Zahniser, Illinois Natural History Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign, 1816 S. Oak St., Champaign, IL 61820, zahniser@illinois.edu.

If you have a color photograph of an insect, insect part, or entomological apparatus that you would like to submit for the "What is it?" feature, please e-mail a 300-dpi TIFF and a description of the image to the editor at cdarwin@aol.com.