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 performing better than at typical background radiation in uncontaminated areas.

Chernobyl, Fukushima, and Resistance to Ionizing Radiation

The year 2016 demarks the 5th and 30th anniversaries of the Fukushima and Chernobyl nuclear disasters, respectively, and there is growing public and scientific interest concerning the impacts of such accidents on natural systems, given the likelihood of additional accidents in the future [1]. In addition, there is considerable heterogeneity in natural levels of ionizing background radiation across the globe, with significant negative effects on numerous organisms, including humans [2]. Hence, it is not surprising that not only many microorganisms [3–5], but also eukaryotes, have evolved an ability to tolerate, resist, or even benefit from such radiation [2]. Furthermore, there is reason to believe that adaptation to other stressors, such as ultraviolet (UV) radiation, can facilitate the evolution of resistance to ionizing radiation. Thus, microorganisms that do well in Chernobyl are also those that do well on sunlight-exposed surfaces elsewhere ([6] S. Jenkinson et al., unpublished data, 2016). Therefore, adaptation to ionizing radiation can arise either from an increase in the frequency of alleles that were already present before the accident at Chernobyl, due to adaptation to other stressors, or *de novo* from mutations. There is every reason to expect evolution of resistance to radiation, even among organisms that have only been irradiated since recent nuclear accidents, such as that at Chernobyl in 1986, because the intervening period of 30 years is sufficient for changes in phenotype in standard selection experiments for all organisms apart from those with the longest generation times. Such effects of radiation will depend on exposure to radionuclides, as reflected by internal dose (Box 1). In the past, novel radioactive sources, such as those caused by asteroids and eruption of volcanoes, will have caused significant levels of deleterious mutations resulting in reduced viability and, thus, preventing large fractions of populations from evolving significant levels of resistance to radiation. There is also reason to believe that populations of animals were exposed to such a high level of radiation that it could have reduced their population size and imposed significant directional selection (Box 2).

Ionizing radiation directly increases the frequency of chromosome breakage, although it also has indirect effects via oxidative stress that causes DNA mutations (Box 3). Since mutations ultimately are the source of novel genetic variants, ionizing radiation could contribute to evolution

[1]Ecologie Systématique Evolution, CNRS, University Paris-Sud, AgroParisTech, Université Paris-Saclay, 91400 Orsay, France
[2]Laboratoire d'Ecologie, Systématique et Evolution, CNRS UMR 8079, Université Paris-Sud, Bâtiment 362, F-91405 Orsay Cedex, France
[3]Department of Biological Sciences, University of South Carolina, Columbia, SC 29208, USA

*Correspondence: anders.moller@u-psud.fr (A.P. Møller).

Box 1. Dose Rates and Populations

In the first study of its sort, Garnier-Laplace *et al*. [58] calculated dose rates for 57 species of birds (almost 7000 individuals) living in Fukushima following the nuclear disaster of 12 March, 2011. Doses were calculated based on radiological conditions at the point of observation and corrected for by including ecological and life-history attributes of a given species. Dose was used to predict the total number of birds, while statistically controlling for potentially confounding environmental variables (e.g., habitat type, elevation, presence of water bodies, ambient meteorological conditions, and time of day). Total dose was found to be a strong predictor of abundances ($P < 0.0001$), which showed a proportional decline with increasing doses with no indications of a threshold or intermediate optimum. Overall, the $ED_{50\%}$ (i.e., the total absorbed dose causing a 50% reduction in the total number of birds) was estimated to be 0.55 Gy. This value can be compared with a value of 0.05 Gy as background radiation in uncontaminated areas around Fukushima before the accident in 2011 [59] Figure I.

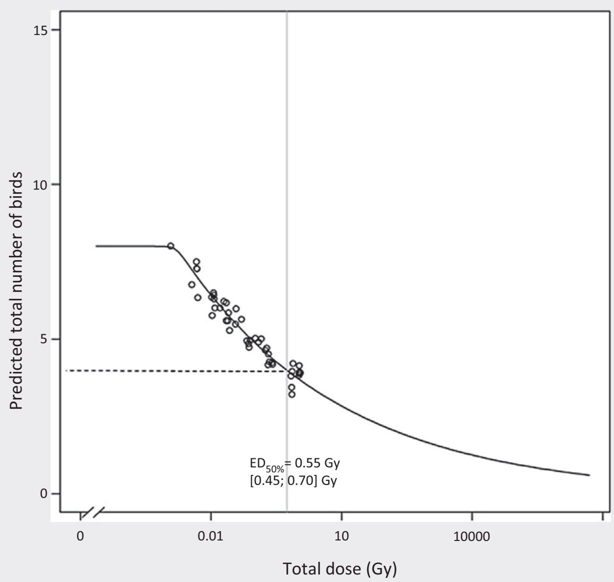

Figure I. Log Logistic Model Fitted to Randomly Predicted Total Number of Birds Derived from a Global General Linear Mixed model, and Its $ED_{50\%}$ Prediction and Associated 95% Confidence Interval $ED_{50\%}$ Is the Total Absorbed Dose Causing a 50% Reduction in the Total Number of Birds. Adapted from [58].

by speeding up evolutionary change. For example, radiation was used as early as 1925 to induce novel variants for plant breeding and agriculture [7,8], and the genes encoding such variants were subsequently selected in selection experiments. Some scientists have even speculated that adaptation to low-dose radiation *per se* could facilitate evolution. These hypothetical effects also relate to the notion of radiation hormesis, which suggests that low doses can have beneficial effects on organisms, for example via induced DNA repair [9–11]. Here, we not only review the literature on the evolution of resistance to ionizing radiation, but also address the potential underlying mechanisms and experimental designs used to assess the genetic and environmental effects on adaptation to radiation.

Adaptation to Radiation

Several studies have concluded that there is evidence of adaptation to low-dose radiation at Chernobyl (Table 1). These range from proteomic analyses of plants showing changes in the amounts of proteins produced [12,13] and studies of DNA methylation that affect whether a gene is expressed [17] to other physiological mechanisms [12,14]. There is also evidence consistent with adaptation through the intracellular antioxidant glutathione, showing that some species of birds that do best under conditions of ionizing radiation have evolved the highest levels of glutathione [15]. Perhaps the most clear-cut evidence for adaptations concerns resistance to radioactivity in generalist bacteria, which are widely distributed across Europe [16].