The effects of low-dose radiation

Soviet science, the nuclear industry – and independence?

Chernobyl and Fukushima have led to worldwide interest in the effects of so-called low-dose radiation. But research so far has been a puzzling mix of Soviet science and research supported by the nuclear industry, with some independent scientists contributing. **Anders Pape Møller** and **Timothy A. Mousseau** navigate between these diverse efforts to investigate the effects of low-dose radiation on animals, plants and people.

Visiting Chernobyl or Fukushima is a special experience because radiation is everywhere but it cannot be seen, smelt or felt. However, a careful observer will quickly become aware of the gnarly distortions of tree growth, and numerous abnormalities in insects, birds and other animals. These are caused by genetic mutations induced by exposure to the radiation in the region. We have visited both regions regularly. Further scientific scrutiny by our research programme has since 1991 produced a long list of responses by all kinds of species, that vary with the dose of radiation in their area. Although the technical definition of low-dose radiation is set by international policy-making panels (e.g. the International Council for Radiation Protection) and as such is to a large extent arbitrary, it is generally characterised as the dose below which it is not possible to detect adverse health effects. No figure for this dosage has ever been calculated; the so-called "threshold theory" assumes that there is a dosage of low-level radiation below which no damage occurs. It is a comforting theory, but it has never been shown to be true, nor has any safe "threshold" been established.

Abandoned corridor in Pripyat School, 2012. © iStockphoto.com/Oliver Sved

Given that radiation causes damage to DNA molecules (leading to mutations if not repaired) and that humans cannot sense it but require a dosimeter or a Geiger counter for its detection, it is not surprising that the general public has a particular interest in – but

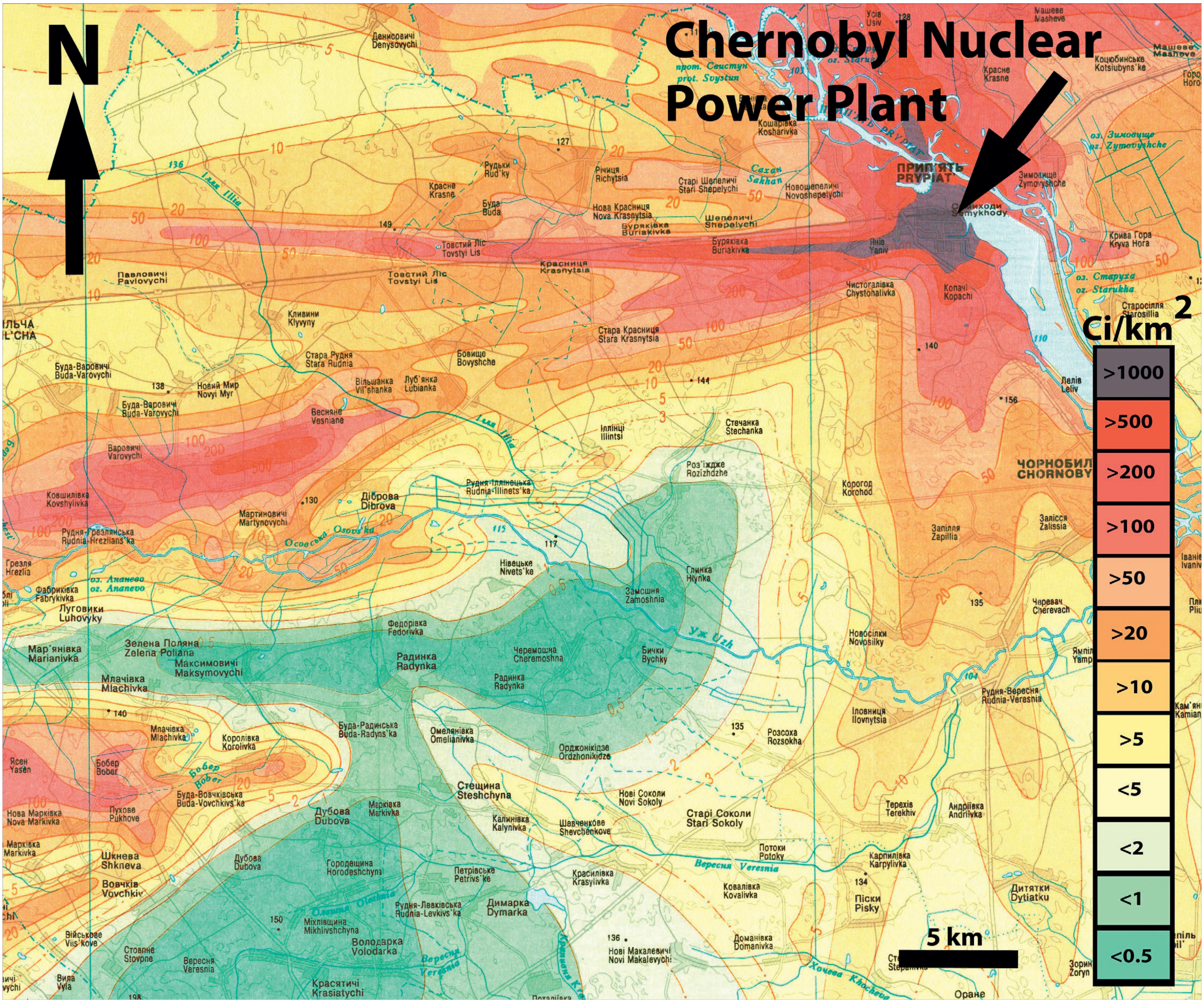

Figure 1. The patchwork of background radiation (Ci/km^2) around Chernobyl, showing clear heterogeneity in radiation that facilitates research of the effects of low-dose radiation. Adapted from Shestopalov[10]

also a particular fear of – this topic. This public interest has been heightened by the delay or suppression of information on Chernobyl and Fukushima by governments and government agencies in countries as diverse as the Soviet Union, France and Japan.

Shortly after the Chernobyl disaster on 26 April 1986 the Kremlin issued a decree stating that medical or veterinary doctors and others were not allowed without prior permission to publish data related to the disaster. Several scientists ended up in house arrest or worse (Yuri Bandazhevsky was one, sentenced to 8 years in jail, a sentence believed by Amnesty International to be related to his scientific research into Chernobyl). Obviously this approach did not promote independent assessment of the consequences of the disaster. Official Soviet scientists conducted preliminary research in the late 1980s and early 1990s. The resulting literature was characterised by a lack of replication (typically one low-dose site was compared to one high-dose site), an absence of information on variances for the obtained estimates and a general lack of statistical evaluation. Furthermore, much of the literature from the Soviet Union was not readily accessible to Western scientists, although Yablokov *et al.*[1] recently provided a comprehensive if not exhaustive review of this literature.

Soviet era obstructionism might have been expected; but the lack of interest of the nuclear industry in providing reliable information on the consequences of Chernobyl and Fukushima cannot be left unmentioned. This is an industry that deals with investments of many hundred billions of dollars, so there are large business interests. Of course, there are national and local oversight agencies that monitor the industry, although, as was demonstrated at both Chernobyl and Fukushima, the same persons tend to move between these different positions on a regular basis, thereby blurring the boundaries between the interests of the industry and those of the average citizen of a country. As recently as December

2012 it was revealed by the *Washington Post* that the Japanese nuclear industry has for years paid the travel expenses of scientists to attend overseas meetings on radiation safety, raising doubts about the impartiality of the scientists involved. Nowhere else than in the nuclear industry are scientists so partial with respect to research questions regarding public health or ecological effects of low-dose radiation. One is reminded of the 1950s when medical doctors employed by the tobacco industry acted as witnesses in court cases about the role of tobacco as a cause of lung cancer. History repeats itself.

What to do when $N = 1$?

We have known for more than 80 years that low-dose radiation has cytotoxic effects and that it causes mutations. Luckily there is only one Chernobyl, just as there is only one Fukushima. Given that replication is the trademark of scientific research, this could raise a problem. However, sample size is not really one, not even in Chernobyl! There were several major nuclear accidents in the former Soviet Union, accidents that have left areas that today have high levels of radiation. In Chernobyl and Fukushima there is a patchwork of radiation, with nearby locations separated by only a few hundred metres differing in radiation level by more than four orders of magnitude (Figure 1). The situation is akin to radionuclides having been dispersed from above in a haphazard fashion, with heavy particles like plutonium being deposited close to the Chernobyl reactor. Therefore, there is ample opportunity to investigate the effects of radiation on living beings by simply sampling nearby plots differing in level of contamination. There are at least four statistical approaches that allow evaluation of the hypothesis that low-dose radiation has negative fitness consequences for humans and other living beings: (1) analyses of the same phenomenon in contaminated areas and in naturally irradiated areas; (2) analyses of the relationship between abundance, diversity or phenotype of individuals in nearby areas that differ in level of background radiation; (3) repeated patterns in multiple tests on different species; and (4) repeated patterns in Chernobyl, Fukushima and other accident sites.

Repeated patterns in areas with natural and unnatural radiation

Radiation is a major cause of excess mortality in areas with high background levels of radiation caused by radon, thorium and other elements emanating from the local geology. The number of cases of excess mortality due to lung cancer alone caused by radon in the US is close to 20 000. There are numerous cases of high natural background radiation across the world with such deposits occurring in China, India, Iran, France, Brazil and many other countries. If it were possible to show that there are negative effects of such natural low-dose radiation, then we could conclude that similar or higher levels of radiation due to nuclear accidents are equally likely to have detrimental effects. Although there has been scientific interest in this topic for decades, this literature has until recently never been compiled or assessed[2]. We carried out a meta-analysis: we looked at 373 effect sizes from 46 different studies. The studies were of animals such as barn owls, rats and humans, and plants such as spiderwort and onion. Together they showed a statistically significant negative effect of radiation on organisms. This applied to negative effects on mutation, physiology, immunology and disease, and, as one would expect, effects were stronger on plants, which are stuck in one place, than on animals, which can move around. High natural levels of radiation also imply environmental conditions that impose selection on living beings, with the end result of adaptation to such conditions. Indeed, there is evidence of genetic variation in the ability to cope with low-dose radiation in organisms as diverse as bacteria, fungi, nematodes, rotifers, tardigrades, fruitflies, silk moths and house mice. These findings are consistent with radiation having been a potent force of selection over evolutionary time: over generations, living creatures adapt to withstand radiation. Current negative effects of low-dose radiation on plants and animals, including humans, suggest that this is an ongoing process, with migration from uncontaminated to contaminated areas disrupting such adaptation.

> Studies of barn owls, rats, humans, spiderwort plants and onions all showed significant negative effects of radiation

Abundance and diversity of animals in areas differing in level of background radiation

Both Chernobyl and Fukushima constitute a patchwork of sites with high and low levels of radiation, varying 35 000-fold in Chernobyl. This heterogeneity provides a useful tool for conducting research. All scientists assessing the abundance and distribution of organisms and their characteristics must consider alternative explanations for their findings such as habitat, soil quality and weather; but the overwhelming variations in dosages at Chernobyl make it difficult to imagine alternative explanations for relationships between low-dose radiation and biological variables such as abundance, species richness and phenotypic characteristics of individuals such as abnormality, cell damage, sperm quality, brain size, cataracts and many others. We are the first scientists in both Chernobyl and Fukushima to perform extensive and long-term studies of the communities of birds, mammals, reptiles, amphibians, insects and spiders, using standard procedures, which we did during 2006–2012. We can show that our findings are repeatable between countries such as Ukraine and Belarus and between years, and that the strength of the relationship between biological variables and low-dose radiation is only weakly affected by the confounding effects of habitat, soil and weather[3,4]. These findings are not surprising given the haphazard distribution of radiation in the study sites, but they are still well worth reporting because after all we are only studying correlations.

Repeated patterns in multiple tests

It is a hallmark of science that findings can be replicated. As an example of this approach let us briefly look at the association between radiation and irregular patterns of development in plants and animals. Embryos are particularly susceptible to environmental perturbations, including low-dose radiation. For example, the horns of stag beetles (*Lucanus cervus*) are large structures used for fighting over access to and mating with females. Males in Chernobyl have much more irregular and asymmetric horns than males in control populations, and such aberrant males are less successful in acquiring mates[5]. There are 15 such published tests of the hypothesis that low-dose radiation disrupts development. They are of organisms in Chernobyl ranging from plants through insects to birds and mammals, and all 15 studies show a higher degree of asymmetry in the more contaminated plots. This differs strongly from the random null expectation in a sign test ($p < 0.001$).

A sign test across 15 studies assessing whether the degree of asymmetry is greater in the most or the least contaminated area is a very conservative test because it does not quantify the magnitude of the effect, nor does it take sampling effort or quality of studies into account. Since the paper cited above was published three other papers have appeared, all going in the same direction (i.e. 0 versus 18 observed studies as compared to the randomly expected 9 versus 9 studies). With our colleague S. Randic we have carried out a meta-analysis on this topic too, taking sampling effort and data quality into account. We assembled effect sizes from all published studies of mutation rates from Chernobyl, in total 151 estimates of mutations in 45 studies of 33 species ranging from bacteria and plants to insects, birds and mammals including humans, and found a large mean effect size. Measured in terms of Pearson's product-moment correlation the coefficient was 0.665 (95% confidence interval from 0.585 to 0.733). This is significantly larger than the mean effect size reported in all meta-analyses in the biological sciences[6]. The conclusion from this meta-analysis was independent of the number of populations sampled, or whether the study was conducted during a single year or multiple years. Hence, our findings are robust, showing a strong overall mean effect size.

Repeated patterns in Chernobyl and Fukushima

A different research approach is to compare patterns observed in Chernobyl with patterns in Fukushima. Both sites are affected by low-dose radiation, albeit by different cocktails of radioactive isotopes. Coincidentally, the two sites are located in the same zoogeographic region, with the result that numerous animal and plant species are common to both. We can therefore perform statistical tests in the two sites of the same hypothesis. This paired design is particularly powerful because populations of the same species in different areas will share almost their entire evolutionary past. Indeed, we found evidence of population declines for birds and other organisms at higher levels of background radiation in both Chernobyl and Fukushima[7]. For 14 species of birds that occurred at both sites there was a negative relationship between abundance and radiation, although this relationship was more steeply negative at Fukushima than at Chernobyl. Therefore, low-dose radiation at a given level had a stronger negative effect on abundance of birds in Fukushima than in Chernobyl (Figure 2). Indeed, this relationship was unaffected by ecology or common evolutionary descent, which were the same for the pairs of populations in the two sites. Thus the difference between sites must be attributed to a longer history of selection due to radiation at Chernobyl compared to Fukushima. Chernobyl's populations have had longer time to adapt to low-dose radiation, but they have also had more generations for accumulation of mutations across generations.

There is a bias in sex ratio of birds at high levels of contamination in Chernobyl due to reproducing females being differentially susceptible to the negative effects of radiation, resulting in a greater female mortality rate and a greater number of unmated males. These males sing to attract a mate, and the proportion of singing males is consistently higher in more contaminated areas in Chernobyl. Such high frequency of birdsong may leave the false impression that nature is flourishing. A similar pattern was found in Fukushima, suggesting that similar mechanisms are at work in the two sites. In addition, birds in Chernobyl have reduced reproductive success and higher adult mortality in more contaminated areas. Again, we have found a similar pattern in Fukushima, with the frequency of juvenile birds being smaller in more contaminated areas. Such consistency in research findings between radioactively contaminated sites that are separated by more than 5000 km is surprising to say the least, but also provides strong evidence for convergent effects of low-dose radiation.

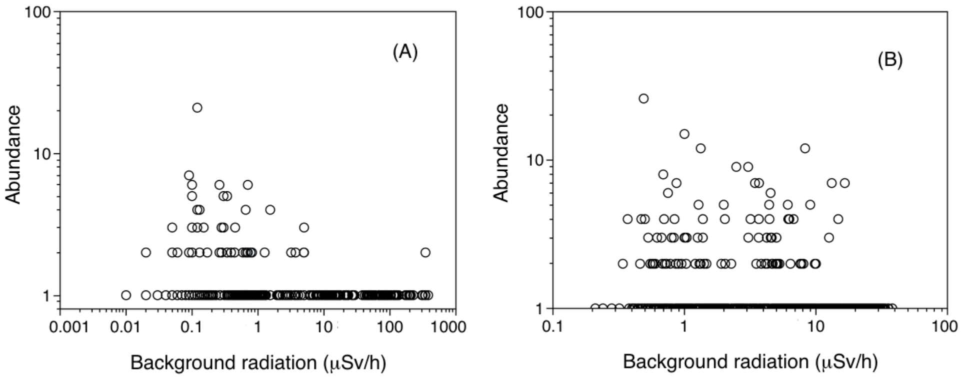

Figure 2. Abundance of barn swallows during the breeding season in relation to background radiation levels (μSv/h) in (A) Chernobyl and (B) Fukushima. Abundance is the number of individuals observed at census points

Human casualties of low-dose radiation

A primary question that all humans ask is how many people have died because of radiation from Chernobyl (and now Fukushima). The answer ranges from 9 to more than a million, depending on assumptions. Unfortunately, the chaotic events in Chernobyl in 1986, with the evacuation of thousands of inhabitants, were not used for selecting a random cohort that would have allowed quantitative assessment of public health effects. Today close to 1 million Ukrainians collect pensions linked to the effects of Chernobyl contamination. Again, Soviet science had a significant and long-lasting negative impact on the ability to assess the largest environmental disaster ever. In the official reports by the International Atomic Energy Agency (IAEA), United Nations and several other organisations released on the 20th anniversary of the accident in 2006, the total number of excess deaths was estimated to be very low. An additional conclusion in these reports was that negative health effects were likely to be due to psychological stress associated with worrying about the effects of low-dose radiation rather than being directly caused by biological effects. Interestingly, we can show strong negative effects on birds and other animals, and it is certain that neither birds nor free-living animals are known to worry about the negative effects of low-dose radiation. The official reports were restricted to effects recorded in highly contaminated regions of Ukraine, thereby excluding vast contaminated areas in Russia and Belarus. Several official representatives from these

Figure 3. Birds with aberrations (arrows) from contaminated areas in Chernobyl. (a) A barn swallow with normal plumage. (b)–(h) Various bird species with albinistic feathers. (i)–(x) Various bird species with solid tumours

countries refused to sign the final documents. Subsequent research in Ukraine has shown extensive negative effects of low-dose radiation on many different medical conditions[8]. Humans have generation times on the order of 30 years, so we are still only dealing with the first generation after Chernobyl. Mutations accumulate with time and across generations, so we may only be seeing the first stages of the negative consequences. A better perspective on the effects of low-dose radiation is perhaps achieved by investigating organisms with short lifespan such as birds, rodents or even insects, many of which now are now in their 25th or greater generation. Unfortunately, the negative effects of low-dose radiation from Chernobyl documented for these organisms are much worse than what is reported for humans. Most likely, we will never know the true impact of Chernobyl.

There is little evidence of a lower threshold to the negative effects of low-dose radiation on living things

One reason why the IAEA-sponsored Chernobyl Forum restricted its cancer rate projections to areas of high contamination is the dramatically larger estimates of risks to human health that come from inclusion of the much larger populations inhabiting regions of central and western Europe that were subjected to fallout from the Chernobyl disaster. In effect, the Chernobyl Forum took the position that if risks could not be *measured* because of relatively low frequencies, then they should not be *estimated* either. However, if it is assumed that the probability of a health consequence (e.g. cancer) is directly proportional to the radiation dose received with no threshold below which effects are not expected, as has been repeatedly suggested by independent analyses[11], then the population level risks are equal to the probability of the effect times the consequences of the exposure. In other words, even if the probability of a negative health outcome for an individual is small, if a large population is exposed, then a correspondingly large number of individuals are likely to be affected. This is the underlying driver behind the heated discussions of thresholds and linear effects. If one accepts that there is no threshold below which radiation exposure has no effect, then one is forced to accept that there will be significant health consequences given the regional and near-continental scale of contamination related to the Chernobyl disaster. It also follows that the shape of the response to low-dose exposures will similarly influence overall population risks, particularly if effects at the lowest levels of exposure are supra-linear, as has been suggested by some[12]. Even a very small increase in the hazards related to low-dose exposures would generate very large increases in risks to populations when exposed population sizes are large, as is the case for Chernobyl. The consensus among independent scientific groups and implications from all of our studies do not support a threshold model and at present seem most consistent with something approaching a linear response model, although the exact shape of the observed dose response is of secondary interest to us, given the large diversity of responses observed for different traits and different species.

Waiting for the next nuclear accident

Since the dawn of commercial nuclear energy production in the late 1950s, there have been three major nuclear accidents (Three Mile Island, Chernobyl, and Fukushima). With 435 active commercial nuclear reactors running (and 62 in production), many of these dating from a previous era, it is only a question of when and not whether another accident will happen. Many reactors are not fulfilling the requirements for stringent stress tests such as the ability to sustain an earthquake, tsunami or loss of cooling water. Most nuclear reactors are located near densely populated parts of the world where energy demand is the highest. Indeed, it has been estimated that the next accident may expose as many as 30 million people to radioactive contamination[9]. There is every reason to study the effects of low-dose radiation and synthesise available information in order to develop the highest level of preparedness for future events. That is especially the case since there is little evidence of a lower threshold to the negative effects of low-dose radiation on living beings.

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