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Investigating the Effects of Low-Dose Radiation from Chernobyl to Fukushima: History Repeats Itself

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The disasters at Chernobyl and Fukushima released large amounts of radioactive material, equivalent to many hundreds of nuclear bombs the size of those at Hiroshima and Nagasaki. Currently, there is worldwide interest in the effects of so-called low-dose radiation on public health and on biological systems from molecules to ecosystems. Research efforts to quantify these effects constitute a curious mixture of Soviet science, research by independent scientists, and research supported by the nuclear industry. The article explains how navigating between these diverse efforts can be reconciled to synthesize available information to the benefit of the general public and the policymaking community. *KEYWORDS: Fukushima nuclear disaster, Chernobyl nuclear disaster, nuclear industry, Soviet science.*

VISITING CHERNOBYL OR FUKUSHIMA IS AN UNUSUAL EXPERIENCE because although radiation is everywhere, it cannot be seen, smelled, or felt. However, a careful observer will quickly become aware of the peculiar distortions of tree growth (Mousseau et al. 2013), numerous abnormalities in insects, and tumors and cataracts in birds (Møller et al. 2013b; Mousseau and Møller 2013), all caused by genetic mutations induced by exposure to the radiation in the region. We have visited both regions regularly, and scientific scrutiny by our research program since 1991 has 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 policymaking panels (e.g., the International Council for Radiation Protection, ICRP) and as such is to a large extent arbitrary, it is generally characterized as the dose below which it is not possible to detect adverse health effects. No figure for this dosage has ever been calculated, and the so-called threshold theory assumes that there is dosage of low-level radiation below which no damage occurs. The theory is comforting, but it has never been shown to be true, nor has any safe "threshold" been established.

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

Shortly after the Chernobyl disaster on April 26, 1986, the Kremlin issued a decree stating that medical or veterinary doctors and other researchers were not allowed without prior permission to publish data related to the disaster. Several scientists were put under house arrest or exiled, such as Yuri Bandazhevsky. 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 characterized by a lack of replication (typically one low-dose site and 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, Nesterenko, and Nesterenko (2009) recently provided a comprehensive even if somewhat telegraphic review of this literature.

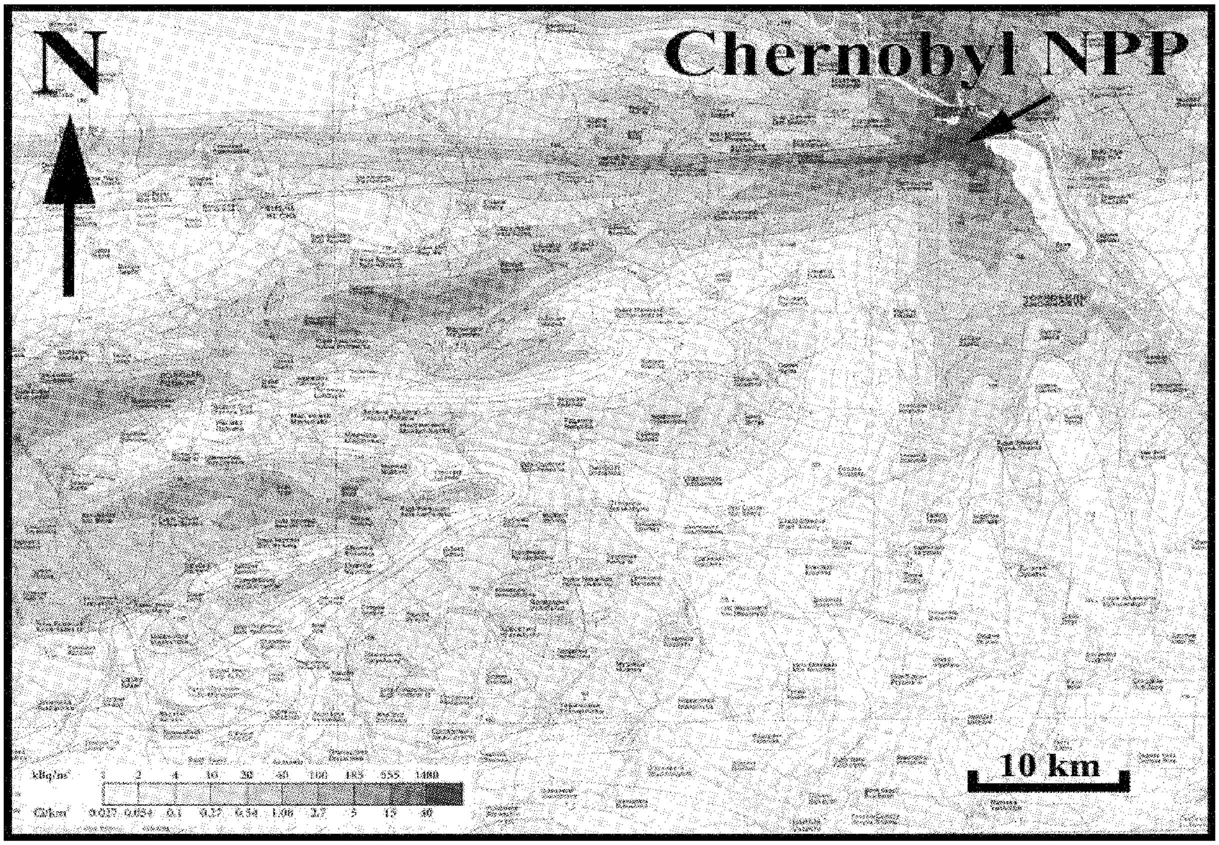
The lack of interest by the nuclear industry in providing reliable information on the consequences of Chernobyl and Fukushima should not be ignored. This industry deals with investments of many hundred of billions of dollars, so business interests loom large. Of course, national and local oversight agencies monitor the industry, although as was demonstrated at both Chernobyl and Fukushima the same individuals 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. For example, on December 6, 2012, the *Washington Post* revealed that the Japanese nuclear industry has for many years paid the travel expenses of regulatory agency 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 the 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. Perhaps history repeats itself?

What to Do When Events Are Singular?

We have known for more than eighty years that low-dose radiation has cytotoxic effects and 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 be problematic. However, sample size is not really one, not even in Chernobyl. There have been several major nuclear accidents in the former Soviet Union that have generated regions of high radiation. Also, Chernobyl and Fukushima contain a patchwork of radiation, with nearby locations separated by only a few hundred meters differing in radiation level by more than four orders of magnitude (see Figures 1 and 2). The situation is akin to radionuclides having been dispersed from above in a haphazard fashion, with heavy particles like plutonium being deposited closer to the Chernobyl reactor.

Thus, considerable opportunity exists to investigate the effects of radiation on living beings by simply sampling nearby plots differing in level of contamination. At least four statistical approaches 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 (i.e., shape, size, color) of individuals in nearby areas that differ in level of background radiation; (3) repeated patterns in multiple

Figure 1 The Patchwork of Background Radiation (Ci/km2) Around Chernobyl Showing Clear Heterogeneity in Radiation that Facilitates Research of the Effects of Low-Dose Radiation



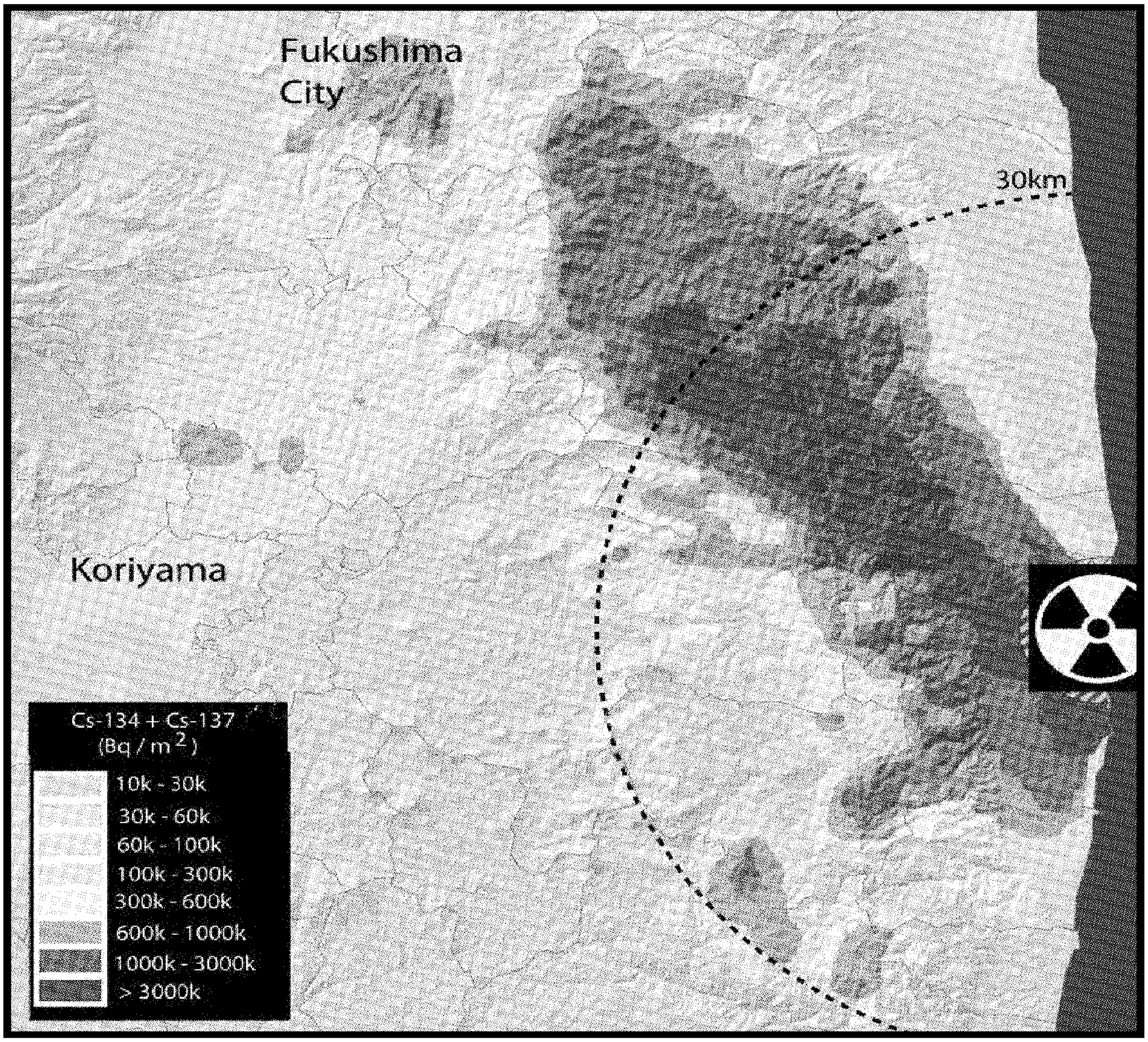
Source: Adapted from Shestopalov (1996).

tests on different species; and (4) repeated patterns in Chernobyl, Fukushima, and other accident sites.

Convergent 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. In the United States, the annual mortality due to lung cancer alone caused by radon is close to 20,000 (Lubin and

Figure 2 The Distribution of Radioactive Contaminants Around the Fukushima Daiichi Nuclear Power Plant



Source: Adapted from Mousseau and Møller (2012).

Boice 1997). 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 the negative effects of such natural low-dose radiation, we could conclude that similar or higher levels of radiation due to nuclear accidents are equally likely to have detrimental effects.

Although scientific interest in this topic has existed for decades, the literature has until recently never been compiled or assessed (Møller and Mousseau 2013). We carried out a meta-analysis: we looked at 373 effect sizes from forty-six 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. As one would expect, effects were stronger on plants, which are stuck in one place, than on animals that 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 deal with low-dose radiation in organisms as diverse as bacteria, fungi, nematodes, rotifers, tardigrades, fruit flies, silk moths, and house mice. These findings are consistent with radiation having been a potent force of natural selection over evolutionary time. Over generations, some living creatures adapt to withstand radiation while others do not. 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.

Impact on Animals in Areas of Differing Background Radiation

Research on Low-Dose Radiation at Chernobyl

Both Chernobyl and Fukushima constitute a patchwork of sites with high and low levels of radiation, varying up to 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 variation in dosages at Chernobyl makes 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 morphological abnormalities, cellular damage, sperm quantity and quality, brain size, and cataracts.

As the first scientists in both Chernobyl and Fukushima, we have performed extensive long-term studies of the communities of birds, mammals, reptiles, amphibians, insects, and spiders during 2006–2012, using standard ecological procedures. Our findings are repeatable between countries such as Ukraine and Belarus and between years, and 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 (Møller and Mousseau 2011; Møller et al. 2013a). These findings are not surprising given the haphazard distribution of radiation in the study sites.

Repeated Patterns Using Multiple Tests

An important characteristic of science is 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 (Møller 2002). There are fifteen such published tests, of organisms ranging from plants and insects to birds and mammals in Chernobyl, that support the hypothesis that low-dose radiation disrupts development, and all fifteen 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 fifteen 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 or take sampling effort or quality of studies into account. Since 2002 when the Møller paper cited above was published, three other papers have appeared, all showing the same effect (i.e., zero vs. eighteen observed studies as compared to the randomly expected nine vs. nine studies). Research questions in the medical and social sciences, but also recently in the biological sciences, are often evaluated using a meta-analysis of the entire literature, a quantitative assessment of research findings that takes sampling effort and data quality into account. With our colleague S. Randic we have assembled effect sizes from all published studies of mutation rates from Chernobyl, in total 151 estimates of mutations in forty-five studies of thirty-three species ranging from bacteria and plants to insects, birds, and mammals, including humans, and we have found a large mean effect size. Measured in terms of Pearson's product-moment correlation, the coefficient was 0.665 (95 percent confidence intervals of 0.585 to 0.733). This contrasts with a mean effect size reported in all meta-analyses in the biological sciences of 0.205; 95 percent confidence intervals 0.158–0.251 (Møller and Jennions 2002). The effect that we found was therefore significantly larger.

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. In other words, our findings are robust in showing a general, strong overall mean effect size of radiation on mutation rates.

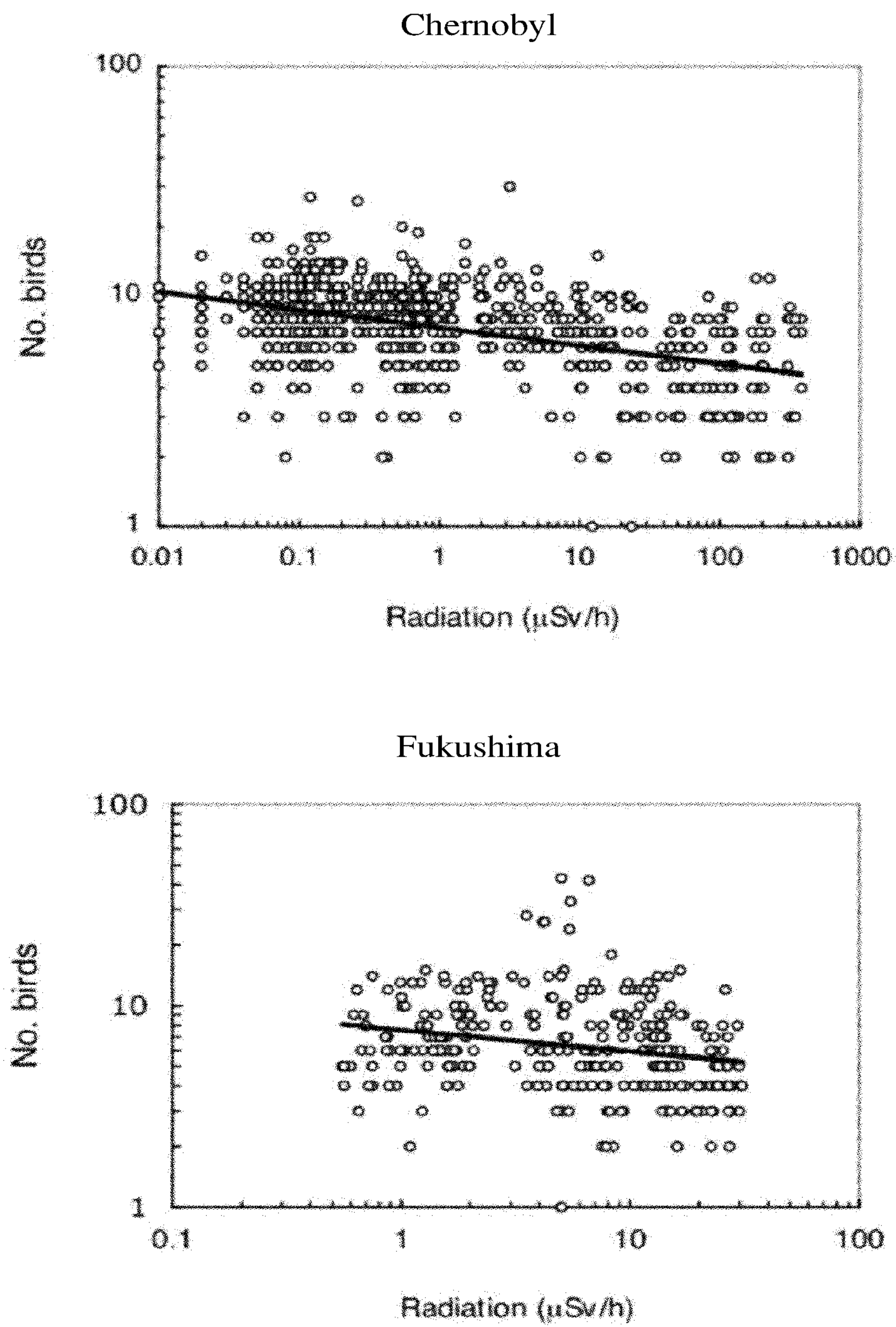
Repeated Patterns in Chernobyl and Fukushima

An alternative research approach is to compare patterns observed in Chernobyl with patterns in Fukushima. Both regions are affected by low-dose radiation, albeit by a different cocktail of radioactive isotopes. Coincidentally, the two sites are located in the same zoogeographic region, with the result that numerous animal species (but also plants) are common to both, allowing us to perform statistical tests in the two sites using the same hypothesis. This paired design is especially powerful because populations of the same species in different areas will share most of their evolutionary past.

Indeed, we found evidence of population declines for birds and other organisms at higher levels of background radiation at both Chernobyl and Fukushima (Møller et al. 2012a). For fourteen 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 the abundance of birds in Fukushima than in Chernobyl (see Figure 3). Indeed this relationship was unaffected by ecology or common phylogenetic (evolutionary) descent, which were the same for the pairs of populations in the two sites. Thus, the difference between sites can only be attributed to a longer history of selection due to radiation at Chernobyl compared to Fukushima. Chernobyl's populations have had a 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 the sex ratio of birds at high levels of contamination in Chernobyl due to reproducing females being particularly susceptible to the negative effects of radiation. The result is 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 (Møller et al. 2012b). Such high frequency of birdsong may leave the false impression that nature is flourishing. (A similar pattern has been found in Fukushima, suggesting that similar mechanisms are at work in the two sites.) In addition, birds in Chernobyl have lower reproductive success and higher adult mortality in more contaminated areas (Møller et al. 2005; 2012b). 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 8,000 kilometers is surprising to say the least, but also provides strong evidence for the convergent effects of low-dose radiation.

Figure 3 Abundance of Birds During the Breeding Season in Relation to Background Radiation Levels in Chernobyl and Fukushima



Note: Abundance is the number of individuals observed at census points.

Human Casualties of Low-Dose Radiation

How many people have died because of radiation from Chernobyl (and now Fukushima)? The answer to this frequently asked question ranges from nine 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 one 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 of the International Atomic Energy Agency, the United Nations, and several other organizations released at the twentieth anniversary of the accident in 2006, the total number of excess deaths was estimated as very low (Chernobyl Forum 2005a; 2005b). An additional conclusion in these reports was that negative health effects were likely due to the psychological stress associated with worrying about low-dose radiation and factors related to relocation rather than to direct biological consequences. Importantly, however, we can now show strong negative effects on birds and other animals, and we know that neither birds nor free-living animals worry about the negative effects of low-dose radiation or anything else for that matter.

Moreover, the official reports were restricted to effects recorded in highly contaminated regions of Ukraine, thereby excluding vast contaminated areas in Russia and Belarus, not to mention other parts of Europe. Several official representatives from these 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 (Serdiuk et al. 2011). Humans have generation times on the order of thirty 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 public health consequences.

A better perspective on the effects of low-dose radiation is perhaps achieved by investigating organisms with short life spans such as birds, rodents, or even insects, many of which now experience their twenty-fifth 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 impacts on humans of the Chernobyl disaster.

One reason that 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 per capita 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 such as the BEIR VII report of the US National Academy of Sciences (National Research Council 2006) and by the National Council on Radiation Protection and Measurements (NCRP 2002), then the population level risks are equal to the probability of effect times the consequences of the exposure. In other words, even if the probability of a negative health outcome to an individual is small, if a large population is exposed, then a correspondingly large number of individuals is 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 some have suggested (e.g., Sawant et al. 2001). 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 the 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. 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, three major nuclear accidents have occurred: Three Mile Island, Chernobyl, and Fukushima. With around 435 active commercial nuclear reactors running worldwide, many of these dating from a previous era, and sixty-two more under construction, it is only a question of when and not whether another accident will happen. Many utility companies are not fulfilling the requirements from stringent stress tests, such as the ability to sustain an earthquake, a tsunami, or the loss of cooling systems. 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 (Lelieveld, Kunkel, and Lawrence 2012).

There is every reason to study the effects of low-dose radiation and synthesize available information in order to develop the highest level of preparedness for future events—especially because little evidence exists for a threshold to the negative effects of low-dose radiation on living beings.

Notes

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