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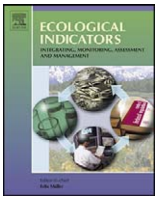

Original article

Efficiency of bio-indicators for low-level radiation under field conditions

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ABSTRACT

Relatively little is known about biological consequences of natural variation in background radiation, and variation in exposure due to nuclear accidents, or even the long term consequences to human health stemming from the over-use of nuclear medicine and imaging technologies (i.e. CAT scans). This realization emphasizes the need for assessment and quantification of biological effects of radiation on living organisms. Here we report the results of an environmental analysis based on extensive censuses of abundance of nine animal taxa (spiders, dragonflies, grasshoppers, bumblebees, butterflies, amphibians, reptiles, birds, mammals) around Chernobyl in Ukraine and Belarus during 2006–2009. Background levels of radiation explained 1.5–26.5% of the variance in abundance of these nine taxa, birds and mammals having the strongest effects, accounting for a difference of a factor 18 among taxa. These effects were retained in analyses that accounted for potentially confounding effects. Effect size estimated as the amount of variance in abundance explained by background level of radiation was highly consistent among years, with weaker effects in years with low density. Effect sizes were greater in taxa with longer natal dispersal distances and in taxa with higher population density. These results are consistent with the hypotheses that costs of dispersal (i.e. survival) were accentuated under conditions of radioactive contamination, or that high density allowed detection of radiation effects. This suggests that standard breeding bird censuses can be used as an informative bio-indicator for the effects of radiation on abundance of animals.

1. Introduction

The biological consequences of natural variation in background radiation levels remain largely unexplored. The average annual worldwide radiation dose is around 2.4 mSv, with a typical range of 1–10 mSv (IAEA, 2006), although variation in background radiation levels varies by more than a factor ten across depending on composition of the underground rock. This variation is associated with significant incidence of cancer and cancer-related mortality in humans (e.g. Lubin and Boice, 1997), testifying to the fact that there may be significant impacts of natural variation in radiation across living beings (e.g. Heidenreich et al., 2000; Moiseev et al., 1973; Pimentel et al., 2003).

Numerous radiation accidents have taken place or been reported, with the total number of radioactive releases worldwide being counted in the hundreds. Although most of these incidents have been minor, more than ten have released large amounts of radioactive material. These include at least three in the former Soviet Union, Three Mile Island in the US and nuclear test sites in the US, Russia, Algeria, China, India, Australia, and the Pacific. To date, the single largest radiation accident is that at Chernobyl on 26 April 1986 that resulted in the emission of at least 9.35×10^3 to 1.25×10^4 peta-Becquerels to the environment (Yablokov et al., 2009). The most important isotopes and their half-lives were iodine (^{131}I, 8 days), strontium (^{90}Sr, 29 years), cesium (^{137}Cesium, 30 years) and plutonium (^{239}Pu, 24,110 years). Coincidentally, the soils of northern Ukraine have some of the lowest levels of natural background radiation in the world at around 0.02–0.03 μSv/h (Ramzaev et al., 2006) making the Chernobyl fallout particularly apparent in this part of the world, but also making the consequences particularly severe due to lack of adaptation to background radiation.

Given our generally poor knowledge of the effects of these two causes of radiation on the biota there has been surprisingly little study of the biological consequences (Møller and Mousseau, 2006, 2008, 2009). The notion that low-level radiation has an effect on the abundance or performance of animals is controversial due to the difficulty of extrapolating from high level to low-level exposure (e.g. Chadwick et al., 2003; Moss et al., 2006; Tubiana et al., 2006), as are the effects of low-level radiation on disease including cancer (e.g. Brenner et al., 2003; Prasad et al., 2004). For example,

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exposure to chronic and acute radiation has different effects (e.g. Wickliffe et al., 2003). Numerous laboratory studies have investigated effects of radiation on model systems including cell cultures (e.g. Chadwick et al., 2003; Liang et al., 2007; Sykes et al., 2006). Laboratory model systems traditionally utilize controlled environmental conditions, but also providing benign and ad libitum access to food and other resources. In contrast, field assessment of biological effects of low-level radiation relies on the fact that environmental conditions in the field typically are sub-optimal in terms of food, predation risk, and risk of parasitism, and animals typically have to work hard to meet their requirements (review in Møller et al., 1998). For example, carotenoids and other antioxidants are typically limiting under field conditions (e.g. Møller et al., 2000), with important consequences for free radical scavenging and ultimately for damage to DNA and other biologically significant molecules (e.g. Halliwell and Gutteridge, 1999; Leffler, 1993). Radiation increases the level of oxidative stress (e.g. Bonisoli-Alquati et al., 2010a,b; Bazhan, 1998; Ben-Amotz et al., 1998; Chaialo et al., 1991; Ivaniota et al., 1998; Kumerova et al., 2000; Lykholat and Chernaya, 1999; Neyfakh et al., 1998a,b). Thus, species that use antioxidants for biological needs other than free radical scavenging caused by radiation such as deposition in eggs and plumage and use during migration and dispersal have been found to suffer the most from elevated levels of background radiation (Møller and Mousseau, 2007b). Several studies have indicated that the presence of high levels of carotenoids may reduce mutation rates (reviews in Ferguson, 1994; Krinsky and Denek, 1982; Møller et al., 2000; Sies, 1993; Valko et al., 2004). We might also consider that mildly deleterious mutations will have benign effects under lab conditions, but more serious consequences under adverse environmental conditions. This line of argument suggests that biologically relevant estimates of effects of low-level radiation are best obtained from free-living organisms under natural environmental conditions. This also raises the possibility of using standard census techniques (e.g. Voříšek et al., 2010) for assessment of effects of low-level radiation on free-living organisms.

The primary objective of this study was to identify biological indicator(s) of background radiation level. To this end we conducted extensive field censuses of nine different animal taxa in the surroundings of Chernobyl in Belarus and Ukraine during 2006–2009, with some of these results already having been published. Because many different biotic and abiotic environmental factors can affect census results, we also recorded biotic and abiotic factors known to potentially influence census results and entered these into statistical models describing the relationship between abundance and level of background radiation. A second objective was to test the repeatability of radiation effects on abundance among years. A third objective was to test the extent to which natal dispersal and mean population density affected the relationship between radiation and abundance. Three possible scenarios were set out a priori for dispersal: Either dispersal may bring immigrants to suitable habitat with low population density thereby obscuring any relationship between radiation and abundance or, dispersal may permit individuals to escape locally deleterious conditions. Alternatively, dispersal may be costly in terms of production of free radicals from physical activity and/or from immune response to novel antigens (Møller and Mousseau, 2007b). Similar effects have been reported in many other taxa (Møller et al., 2000). Given that antioxidants used for neutralizing free radicals may be used to eliminate the negative effects of radiation on general health and on mutations in particular (e.g. Bazhan, 1998; Ben-Amotz et al., 1998; Chaialo et al., 1991; Ivaniota et al., 1998; Kumerova et al., 2000; Lykholat and Chernaya, 1999; Neyfakh et al., 1998a,b; Bonisoli-Alquati et al., 2010b), taxa with long-distance dispersal are predicted to suffer more from such costs (i.e. antioxidant limitation) than taxa with short dispersal distances. Low levels of abundance will invariably prevent detection of strong effects for statistical reasons because small mean values generally are associated with small variances. Therefore, it is crucial to include data for several years to ensure that the abundance estimates exceed low mean abundances.

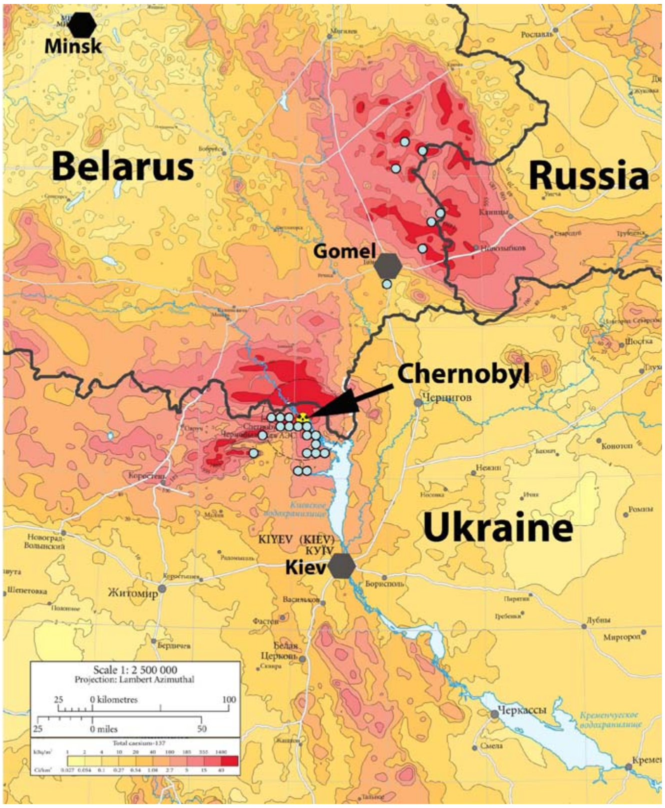

Fig. 1. Location of census areas and levels of background radiation around Chernobyl. Partly developed from European Union (1998).

2. Methods

2.1. Study sites

APM (wearing a radiation protection suit in the most contaminated areas) conducted standard point counts during 29 May–9 June 2006, 1–11 June 2007, 29 May–5 June 2008 and 1–6 June 2009, with each count lasting 5 min during which the number of spider webs, and the number of individual grasshoppers, dragonflies, bumblebees, butterflies, amphibians, reptiles and birds seen or heard were recorded (Møller, 1983; Bibby et al., 2005). The census was conducted within the Chernobyl Exclusion Zone or in areas adjacent on the southern and western borders with a permit from the Ukrainian authorities and in areas in southern Belarus around Gomel (breeding seasons 2006–2009) (Fig. 1). A total of 254 points (breeding season 2006), 235 points (breeding season 2007), 237 points (breeding season 2008) and 159 points (breeding season 2009) were located at ca. 100 m intervals within forested areas (excluding successional stages of secondary forest due to abandoned farming (these areas are still almost exclusively open grassland)). All sampling sites were identified using GPS coordinates, and samples for 159 sites were recorded in all four years.

We censused birds at the end of May and the beginning of June when most individuals reach their annual maximum of singing activity, making censuses of breeding birds highly reliable (Voříšek et al., 2010). We directly tested the reliability of our counts by letting two persons independently perform counts. The degree