High frequency of albinism and tumors in free-living birds at Chernobyl

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Abstract

The effects of radioactive contamination on the phenotype of free-living organisms are poorly understood, mainly because of the difficulty of capturing large numbers of individuals for quantifying rare events such as albinism and tumors. We hypothesized that the frequency of abnormalities like albinism and the frequency of radiation-induced disease like cancer would increase with the level of background radiation, the two markers of radiation would be positively correlated, and that the reduction in abundance of animals would be greater in species with a higher frequency of albinism and tumors if these markers reliably reflected poor viability. Here we analyzed the frequency of albinistic feathers and tumors in a sample of 1669 birds captured during 2010-2012 in eight sites around Chernobyl varying in level of background radiation from 0.02 to more than 200 μSv/h. We recorded 111 cases of partial albinism and 25 cases of tumors. Nominal logistic models were used to partition the variance into components due to species and background radiation. Radiation was a strong predictor of the two markers in birds, with a small, but significant effect of species for albinism. The slope of the relationship between abundance and radiation in different species of birds was significantly negatively correlated with the frequency of albinism and tumors, as expected if a common underlying cause (i.e. radiation) affected both variables. These findings are consistent with the hypothesis that background radiation is a cause of albinism and tumors, albinism and tumors are biomarkers of radiation exposure, and that high frequencies of albinism and tumors were present despite the low viability of birds with these conditions.

Keywords: Albinism; Chernobyl; Population decline; Radiation; Tumors

1. Introduction

Radioactive contamination is known to increase mutation rates with significant effects on phenotype [1,2]. A recent review suggests that natural populations may be almost an order of magnitude more sensitive to ionizing radiation that previously predicted by laboratory models [3], implying that natural variation in radiation [4], but also low-dose radioactive contamination from Chernobyl and other nuclear accidents cause significant changes in the appearance of animals and other organisms [2]. Abnormalities are disproportionately common in radioactively contaminated areas [2,5-10]. For example, Møller [7] reported for barn swallows *Hirundo rustica* from Chernobyl abnormal barbs in feathers preventing feathers from fusing normally. This novel condition was associated with a significant delay in reproduction, suggesting that the condition had significant fitness costs. Likewise Hesse-Honegger & Walliman [10] reported elevated levels of abnormalities in bugs from contaminated areas including the vicinity nuclear power plants. Recently, we have documented this abnormality in several bird species in 2012, more than 25 years after the Chernobyl disaster. Furthermore, Møller et al. [8] reported elevated frequencies of ten different kinds of abnormalities in barn swallows from Chernobyl compared to frequencies in four local and more distant control populations. These abnormalities included changes in patterns of coloration, morphology and shape of feathers, and malformed or missing digits, beaks and eyes. Such abnormalities were rare or completely absent in control populations despite very large sample sizes, nor have they been described in the extensive literature on this study species anywhere throughout its range [8,9].

Albinism is the result of absence of melanin pigments from tissue, with the frequency typically being extremely low in free-living organisms (e.g. [11,12]). In particular small and inbred populations show an increased frequency of albinism in accordance with the expectation that albinism is caused by a recessive allele [13-17]. Barn swallows from Chernobyl have a highly elevated frequency of partial albinism reaching 13-15%, this albinism is of germline origin as determined from a significant parent-offspring resemblance, and barn swallows with this condition suffer from reduced survival prospects [18]. That was also the case in another study of birds [19]. A disproportionate fraction of partial albinism in the barn swallow occurs in the facial red plumage, but hardly any in the dark blue plumage of the neck, back, wings and tail [20,21]. Individual barn swallows with partially albinistic plumage had on average lower mean phenotypic values than other individuals [21], as also reported for another bird species [19].

A fraction of invasive cancers in humans is caused by radiation exposure that includes non-ionizing radiation and in particular ionizing radiation (e. g. [22,23]). Natural variation in background radiation due to radon and other radioactive elements has significant impact on the incidence of cancer in humans [4,24]. The incidence of all cancers caused by ionizing radiation increases with effective dose [25]. Many kinds of cancer often take a long time to develop (i.e. have long latency periods), implying that long-term effects on cancer incidence from radioactive contamination from Chernobyl are not yet detectable. Serdiuk et al. [26] and Cardis & Hatch [27] reviewed the extensive evidence for other cancers being linked to radiation due to the Chernobyl catastrophe. However, next to no information exists on cancers in free-living vertebrates although their short generation time would provide insights into long-term effects that cannot yet be studied in humans.

The objectives of this study were to determine (1) the relationship between the incidence of albinism and tumors, respectively, and background radiation, using a large database of free-living birds captured at

Chernobyl during 2010-2012. In other words, we intended to assess the reliability of the rate of albinism and the incidence of tumors as biomarkers of species decline due to radiation exposure. Because the lifespan of most free-living animals with abnormalities is short [8,18,21] due to elevated risk of predation, field estimates of prevalence of abnormalities are by definition conservative. If mortality related to abnormalities tumors was a major cause of disappearance of individuals from free-living populations, we should expect that a smaller number of individuals remained in contaminated areas in species with a high frequency of abnormalities. Therefore, the second objective of this study was (2) to investigate the relationship between the slope of the relationship between abundance and background radiation for different species of birds and the relative frequency of albinism and tumors.

2. Material and methods

2.1. Study areas

We captured birds in mist nets at eight sites around Chernobyl on 25 May-5 June 2010-2012 [28,29]. We used a total of 35-45 mist nets each 12 m long for two consecutive days at each of the study sites (i.e. one evening and one morning capture session). All birds were banded with a numbered aluminum band for individual identification, and they were subsequently sexed and aged according to standard criteria [30], measured, sampled for blood and released after sperm collection. As a control sample from uncontaminated areas in Europe APM captured 35,578 birds in mist nets near Brønderslev, Denmark, during 1969-2012.

2.2. Frequency of albinism and tumors in birds

Upon capture all individuals were examined by APM for the presence of deviations from normal phenotype by careful examination while recording twenty morphological measurements and three measures of abundance of parasites on each individual [31]. The overall procedure lasted 5-6 minutes per bird and was similar in all study sites. (1) Partial albinism refers to the presence of single or a few white feathers in the otherwise reddish brown or dark blue plumage [21]. This trait is maintained across moults in adults [21]. (2) Tumors were externally clearly visible lumps of hard tissue (with a diameter of more than 0.5 cm) on the outside of the body. These structures included papillomas on the legs as shown in Fig. 2. APM likewise recorded cases of albinism and tumors in the sample of birds from Denmark using exactly the same procedures. We provide summary statistics for the frequency of abnormalities and tumors in each species, and the slopes of the relationships between abundance and background radiation for each species in Electronic Supplementary Material Table S1.

2.3. Breeding bird censuses

The point count census method provides reliable information on relative abundance of birds [32-35]. It consists of counts lasting 5 minutes during which the number of birds seen or heard was recorded. APM conducted these standard point counts during May-June 2006-2009 in Chernobyl. The fact that one person made all counts eliminates any variance in results due to inter-observer variability. The counts were made approximately the same dates and at the same time of the day each of the four years. Møller & Mousseau [34] provide further information on the methods and potentially confounding variables that were taken into account in the analyses. We have previously tested the reliability of our counts by letting two persons independently perform counts, and the degree of consistency was high for both species richness and abundance (details are reported by Møller & Mousseau [34].

2.4. Background radiation

We measured radiation in the field and cross-validated these measurements with those reported by the Ukrainian Ministry of Emergencies. Once having finished the 5 minutes point count we measured radiation levels at ground level directly in the field at each point where we censused birds using a hand-held dosimeter (Model: Inspector, SE International, Inc., Summertown, TN, USA). We measured levels 2-3 times at each site and averaged the measurements. We cross-validated our measurements against governmental measurements published by Shestopalov [36], estimated as the mid-point of the ranges published. This analysis revealed a very strong positive relationship (linear regression on log-log transformed data: $F = 1546.49$, d.f. = 1,252, $r^2 = 0.86$, $P < 0.0001$, slope (SE) = 1.28 (0.10)), suggesting that our field estimates of radiation provided reliable measurements of levels of radiation among sites.

Handheld Geiger counters are likely to provide reliable measures of background contamination levels of radionuclides for gamma sources, and to a lesser degree for beta emitters, if the Geiger detector is in close proximity to the source. However, characterization of alpha emitters usually requires more complex measurement methods that are usually only tractable in a laboratory setting due to the short transmission distance of alpha particles in air.

Given the different characteristics of radionuclides in the environment at Chernobyl, field measurements of contaminant levels are likely to underestimate biologically relevant radiation levels when the main exposure pathway is via ingestion. Similarly, background radiation measures in the areas of Chernobyl closest to the reactor (e.g. the Red Forest) very likely underestimate biologically relevant doses given the abundance of alpha emitting actinides (e.g. plutonium isotopes) that were differentially deposited in this area. That said, Gashchak et al. [37] have previously reported that internal dose of small birds captured in Chernobyl is strongly positively correlated with external dose, accounting for more than 50% of the variance in internal dose, suggesting that gamma radiation measurements are a reasonable proxy for total exposure at least for the sorts of comparative analyses reported here, and that results will be conservative with respect to any reported associations with radiation levels.

2.5. Statistical analyses

Using Generalized Linear Models, we previously estimated the slope of the relationship between abundance and background radiation using $\log_{10}$-transformed abundance for each species at each observation point and $\log_{10}$-transformed radiation level for each species [38]. We used nominal logistic regression to relate the incidence of albinism and tumors to background radiation level after inclusion of species as a factor. These two models showed no significant lack of fit. We subsequently related the slope of the relationship between abundance and background radiation to the squareroot-arcsine-transformed prevalence of albinism and tumors in different species of birds, weighting each species estimate by sample size. Models were weighted by sample size (the number of individuals) to account for the fact that sample sizes differed and hence the precision of the estimate differed among species. Most statistical analyses assume that data points provide equally precise information about the deterministic part of total process variation, i.e. the standard deviation of the error term is constant over all values of the predictor variable [39]. Garamszegi & Møller [40] showed that bias due to variation in sample size is a large problem in comparative analyses and was similar to considering species as statistically independent observations. If this assumption of even sampling effort is violated, weighting each observation by sampling effort allows the use of all data, giving each datum a weight that reflects its degree of precision due to sampling effort [40-42]. This procedure will also allow both rare and common species to be included and hence avoid any bias in sampling due to rarity. All analyses were made with JMP version 10.0 [43].

3. Results

We recorded in total 111 cases of albinism and 25 cases of tumors in 1669 birds captured in the surroundings of Chernobyl, or 66.5 cases of albinism and 15.0 cases of tumors per 1000 birds. This compared with rates of 8.9 cases of albinism and 0.0 cases of tumors per 1000 birds in Denmark (N = 35,578 individual birds). The mean relative frequency of albinism across all species in Chernobyl was 0.066 (SE = 0.008), N = 63 species, while mean relative frequency of albinism was 0.102 (SE = 0.014) when only considering the 13 species with at least one case of albinism. Likewise, the relative frequency of tumors was 0.015 (SE = 0.003) for all species, but 0.025 (0.008) in the 10 species with at least one case. A Kendall rank order correlation analysis showed a weak, but significant positive correlation between the presence of albinism and tumors in the 1669 individual birds from Chernobyl (Kendall $\tau = 0.086$, $P = 0.0005$). There was also a significant positive relationship between prevalence of albinism and prevalence of tumors across species of birds in an analysis using species as observations weighted by sample size ($F = 34.42$, d.f. = 1,61, $r^2 = 0.36$, $P < 0.0001$, slope (SE) = 1.153 (0.197)).

Therefore, we proceeded by investigating the relationship between each of the two kinds of abnormalities and background radiation, while taking the non-independence of individuals among species into account by including species as a factor. There was a significant positive effect of radiation on the occurrence of both albinism and tumors (Fig. 2A and B; Table 2). In addition, there was a significant species effect in the analysis of albinism (Table 1). Odds ratios and their 95% confidence intervals are reported in Table 1. Unit odds ratios per unit change in radiation were 0.738 (95% CI 0.624, 0.867) for partial albinism and 0.486 (95% CI 0.310, 0.713) for tumors.

If background radiation was the underlying cause of the increase in abnormalities and the reduction in abundance, we should expect a negative relationship between the slope describing the intraspecific relationship between abundance and radiation and the relative frequency of the two kinds of abnormalities (i.e. the species most affected by radiation are also more prone to abnormality and cancer). Mean slope for the 63 species was -0.062 (0.010), differing significantly from zero (one-sample t-test, t = -6.21, d.f. = 62, $P < 0.0001$). Indeed, the slopes for different species were negatively related to relative frequency of albinism in a model weighted by sample size (Fig. 3A; $F = 11.13$, d.f. = 1,61, $r^2 = 0.15$, $P = 0.0015$, slope (SE) = -0.124 (0.037)). Likewise, slopes for different species were negatively related to relative frequency of tumors in a model weighted by sample size (Fig. 3B; $F = 10.92$, d.f. = 1,61, $r^2 = 0.15$, $P = 0.0016$, slope (SE) = -0.923 (0.279)). Exclusion of the single species with an extremely high estimate of frequency of tumors (hoopoe *Upupa epops*) did not change the conclusion ($F = 14.75$, d.f. = 1,60, $r^2 = 0.20$, $P = 0.0003$, slope (SE) = -0.274 (0.071)).

4. Discussion

The main findings of this study of albinism and tumors in free-living birds in the Chernobyl region were that (1) albinism and tumors were more common than previously reported, (2) the frequency differed among species, (3) the frequency increased with level of background radiation, and (4) species with the most severely depressed populations in contaminated areas were also the species that had the highest frequency of albinism and tumors. These findings have important implications for estimation of the frequency of abnormalities, but also for their consequences at the population level.

Albinism is a rare condition in free-living animals [14], with the highest frequencies reported for island or marginal populations [16,17]. Because it is likely that albinism has a recessive genetic basis, we should expect to find more cases in populations with significant inbreeding. Here we have shown that the high frequency of ca. 15% albinism previously reported in populations of barn swallows around Chernobyl [21] can be generalized to other species of birds. The mean frequency was 6.6% of all individuals across all species of birds, which compared with a frequency of 0.9% in birds from uncontaminated areas in Denmark. For the barn swallow we have previously shown using historical records that the prevalence of partial albinism was lower before the accident [21]. Several studies have suggested that albinism is associated with significantly reduced viability [18,19,21]. Therefore, albinism is likely to be under-represented in our study because albinistic individuals are more prone to mortality before being captured than are individuals with normal plumage. We have also shown that the prevalence of albinism in different species of birds is a significant predictor of the impact of background radiation on population size in the surroundings of Chernobyl. Møller et al. [29] reported for contamined areas in Chernobyl severely reduced survival rates of the same species of birds that we have studied here.

Ionizing radiation is a significant cause of cancer in humans (e. g. [22,23,27]), and even natural variation in background radiation due to radon and other isotopes has significant impact on the incidence of cancer in humans [4,24]. Cancer often takes long time to develop, implying that long-term radiation effects of Chernobyl in terms of cancer may not yet be detectable. An exception is thyroid cancer because it appeared early after the Chernobyl accident in 1986 due to exposure to radioactive iodine that was released in large amounts, but only has a short half-life of less than ten days [27]. Next to no information is available on radiation-induced cancers in free-living organisms although their short generation time would provide insights into long-term effects that are not yet detectable for humans. Tumors need less time to reach a detectable or a lethal size in smaller organisms [44]. Here we have shown a frequency of 1.5% of birds having tumors in the neighborhood of Chernobyl, while not one single case was recorded in a much larger sample of birds captured in uncontaminated areas in Denmark. Thus the frequency of tumors in birds is elevated in Chernobyl. The true frequency in the population will depend on the viability cost of tumors. If we assume that tumors result in premature death in wild birds, then the true prevalence must be significantly higher than the 1.5% recorded in our study. We can also expect that the relationship between slope of the relationship between abundance and radiation in different species of birds and the prevalence of tumors constitutes an under-estimate of the true relationship due to differential mortality of individuals with tumors. Finally, we have shown that the frequency of albinism and the frequency of tumors were positively correlated across individuals but also across species. Again, this is what would be expected if the two conditions have a common underlying cause.

There was evidence of an increase in the frequency of albinism and tumors with increasing background radiation in birds. We have previously reported that the prevalence of albinism in the barn swallow increases with the level of background radiation, and that uncontaminated control populations in Ukraine and elsewhere in Europe have low frequencies of albinism [7,8,18]. The frequency of tumors increased with the level of background radiation, accounting for a small, but significant amount of variance. Small birds typically have a generation time of two years or less, implying that the 26 years since the Chernobyl disaster equals 13 generations or more. In contrast, this period only equals a single generation in humans. The high frequencies of albinism and tumors reported here for birds may be attributed to accumulation of mutations over time, high metabolic rates resulting in high rates of ingestion of radionuclides, genomic instability or a combination of these factors. Mutations may accumulate across generations with consequences for the development of disease including cancer [26,45]. Likewise, genomic instability caused by radiation can render genomes unstable across generations with accumulating effects [45-47]. Either way the findings reported in this study suggest that the accumulation of effects of radiation recorded in birds is significant, and they suggest that similar accumulation across generations may cause an increase in the frequency of tumors and other medical conditions in other classes of animals including humans.

Ellegren et al. [18] reported that the survival prospects of barn swallows with albinism were severely reduced compared to that of individuals with normal plumage. If it turned out that the probability of survival is linked to albinism in birds in general, then we may consider the field estimates of albinism to be conservative. Greater risk of mortality in albinistic birds should translate into an under-estimate of the prevalence of albinism. It should also imply that the reduction in abundance of birds at high levels of background radiation should be greater in species with a higher prevalence of albinism (and tumors). Indeed, slopes of the relationship between abundance and level of background radiation were significantly negative, as previously reported for birds breeding around Chernobyl [34,38]. Interestingly the slopes for different species were negatively related to the relative frequency of albinism and tumors. These relationships must be considered conservative due to the disappearance of individuals with albinism and tumors.

Biological indicators of radioactive contamination under field conditions include the abundance of many different taxa of animals [48], the frequency of albinism [5,8,21] and other abnormalities [8], the amount of genetic damage [50], the frequency of abnormal sperm [51], impaired sperm movement behavior [52] and reduced reproductive variables and survival rate of birds [53]. It is important to cross-validate such indicators as a test of their reliability, as already provided for censuses of different animal taxa [48]. Here we have shown that the occurrence of albinism and tumors in birds are weakly positively correlated among individuals, but also among species. In addition, we have shown that the frequency of albinism and tumors in different species of birds is negatively correlated with the reduction in abundance of different species of birds at high levels of radiation. These findings provide important cross-validation for different indicators of radioactive contamination. Future studies investigate whether particular ecological and life history traits predict variation across species in frequency of tumors under conditions of radioactive contamination, similarly to what has previously been done for data on population trends of different species of birds [34]. For example, rapid growth rate and large body size can positively predict cancer incidence, and selection of the capacity to fight cancer – also called cancer selection – may well vary with life history of different species of animals [44].

In conclusion, we have shown that albinism and tumors are frequent in many species of birds in the surroundings of Chernobyl, the frequency increases with background radiation level, and species that have decreased the most in abundance are also the species with higher frequency of albinism and tumors. These estimates exceed frequencies reported for humans and suggest that albinism and tumors may accumulate in frequency over time.

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Legends to figures

Fig. 1. Location of the eight study sites in relation to background radiation level (Cu/km^2) around Chernobyl, Ukraine.

Fig. 2. Birds with albinistic feathers and tumors from Chernobyl as indicated by the arrows. (a) is a barn swallow *Hirundo rustica* with a normal plumage and no tumors, while (b) is a barn swallow with albinistic feathers, (c) – (h) are different species of birds with albinistic feathers, while (i) – (x) are different species of birds with solid tumors clearly visible from the outside.

Fig. 3. Occurrence of (A) albinism and (B) tumors in individual birds in relation to background radiation level (μSv/h). The individual observations are shown together with the regression lines and 95% confidence intervals.

Fig. 4. Slope of the relationship between abundance and radiation (μSv/h) and frequency of (A) albinism and (B) tumors in different species of birds. The estimates for different species are shown with circles proportional to sample size.

Fig. 1

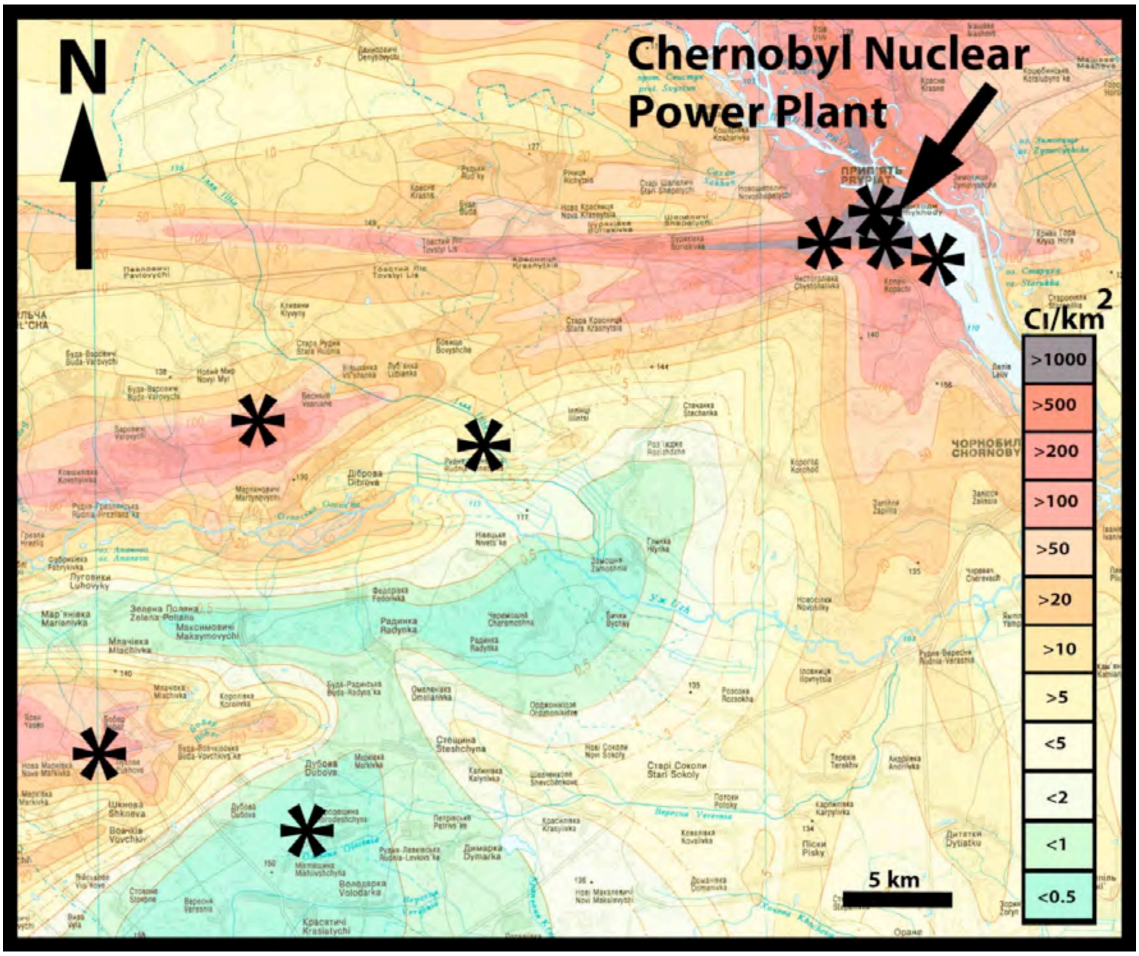
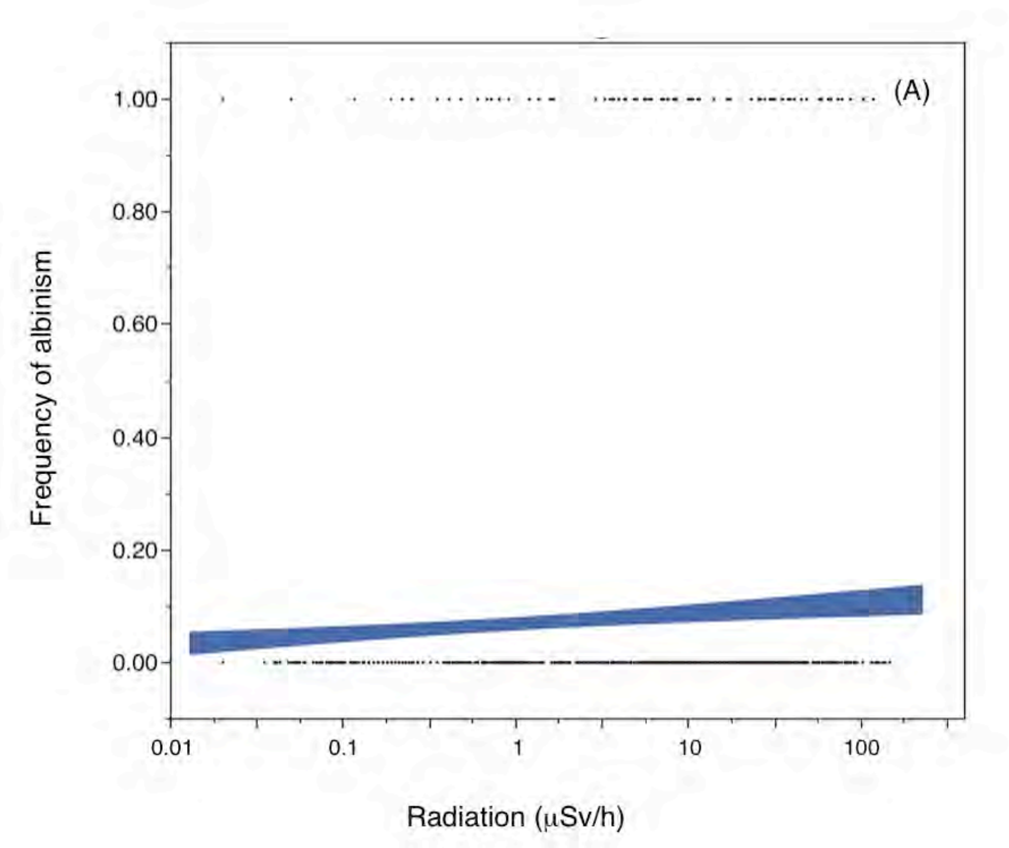
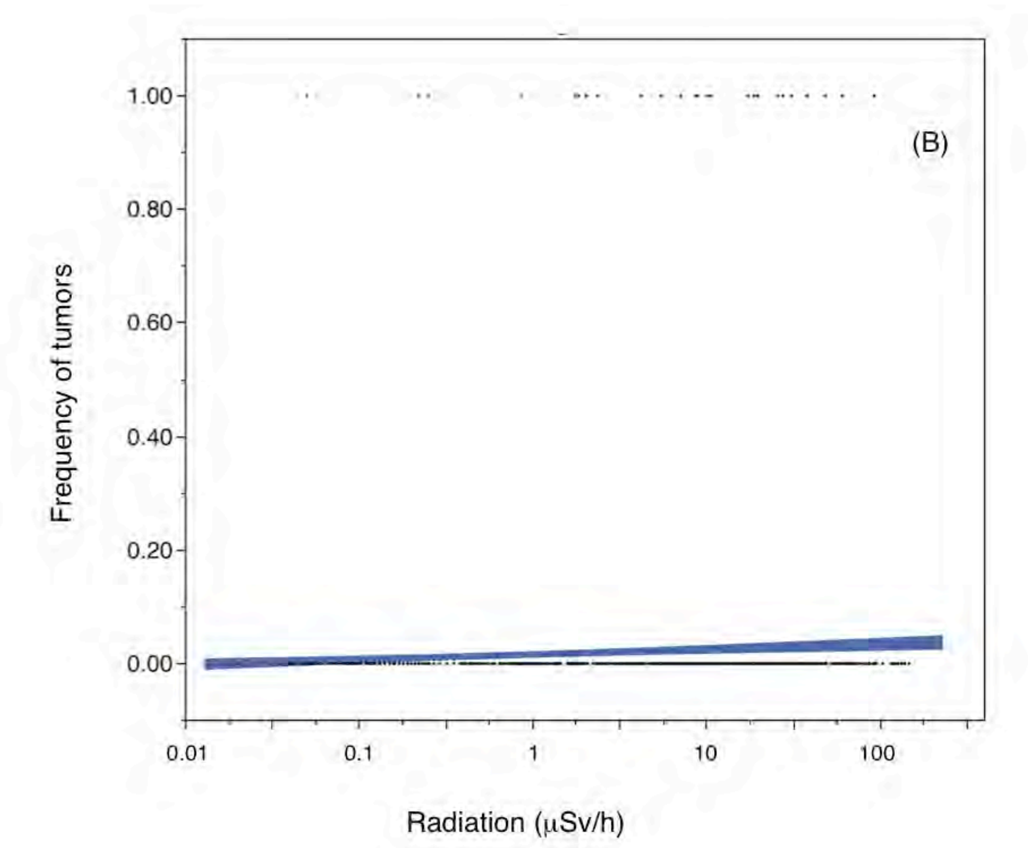

Chernobyl Nuclear
Power Plant
N
Ci/km2
>1000
>500
>200
>100
>50
>20
>10
>5
<5
<2
<1
<0.5
5 km

Fig. 2

Fig. 3

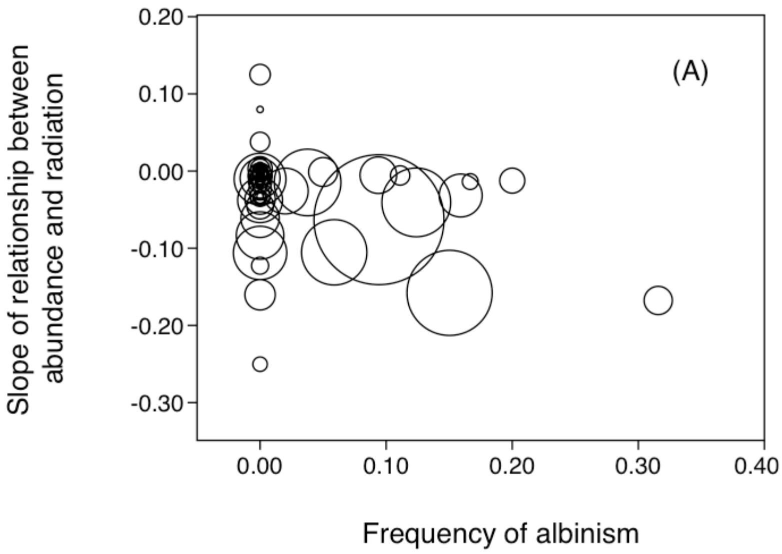


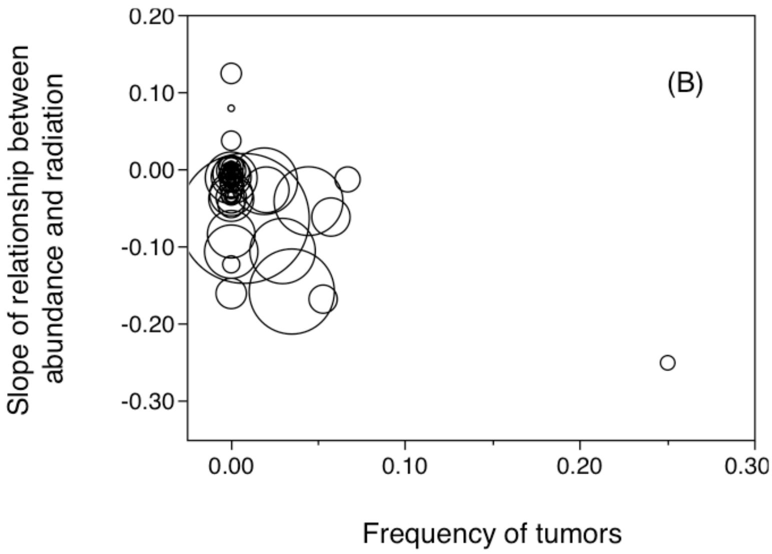
(A)
Frequency of albinism
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.1
1
10
100
Radiation (μSv/h)



(B)
Frequency of tumors
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.1
1
10
100
Radiation (μSv/h)

Fig. 4


0.20
0.10
0.00
-0.10
-0.20
-0.30
Slope of relationship between abundance and radiation
(A)
0.00
0.10
0.20
0.30
0.40
Frequency of albinism


0.20
0.10
0.00
-0.10
-0.20
-0.30
Slope of relationship between abundance and radiation
(B)
0.00
0.10
0.20
0.30
Frequency of tumors