Trees
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Tree rings reveal extent of exposure to ionizing radiation in Scots pine *Pinus sylvestris*

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Abstract Tree growth has been hypothesized to provide a reliable indicator of the state of the external environment. Elevated levels of background ionizing radiation may impair growth trajectories of trees by reducing the annual growth. Such effects of radiation may depend on the individual phenotype and interact with other environmental factors such as temperature and drought. We used standardized growth rates of 105 Scots pine *Pinus sylvestris* located near Chernobyl, Ukraine, varying in the level of background radiation by almost a factor 700. Mean growth rate was severely depressed and more variable in 1987–1989 and several other subsequent years, following the nuclear accident in April 1986 compared to the situation before 1986. The higher frequency of years with poor growth after 1986 was not caused by elevated temperature, drought or their interactions with background radiation. Elevated temperatures suppressed individual growth rates in particular years. Finally, the negative effects of radioactive contaminants were particularly pronounced in smaller trees. These findings suggest that radiation has suppressed growth rates of pines in Chernobyl, and that radiation interacts with other environmental factors and phenotypic traits of plants to influence their growth trajectories in complex ways.

Keywords Chernobyl · Growth · Interaction between stressors · Ionizing radiation · Tree height · Tree rings

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Introduction

On 26 April 1986, one of the Chernobyl nuclear power plant reactors exploded and a nuclear fire burned for 10 days releasing between 9.35×10^3 and 1.25×10^4 PetaBq of radionuclides into the atmosphere. By contrast, the Three Mile accident in PA, USA on 27 March 1979 released just 0.0005 PetaBq. Although many of these radionuclides either dissipated or decayed within hours, days or weeks [e.g., iodine-131 (^{131}I)], cesium-137 (^{137}Cs) still persists today in the environment even hundreds of kilometers from Chernobyl (Shestopalov 1996; Zakharov and Krysanov 1996; Møller and Mousseau 2006; Yablokov et al. 2009). Likewise, strontium-90 (^{90}Sr) and plutonium-239 (e.g., ^{239}Pu) isotopes are common within the Chernobyl Exclusion Zone and in areas in Russia and Belarus. Given the 30, 29 and 24,000 years half-life for Cs-137, Sr-90 and Pu-239, respectively, these contaminants are likely to be of significance in the health of plants and animals including humans for many years to come. This accident provides a unique, but relatively unexploited opportunity to study the effects of ionizing radiation under field conditions. Many recent studies have documented the large effects of radiation on the abundance and reproductive success of different taxa (e.g., Møller and Mousseau 2007a, b, 2008, 2009). In particular, the accident provides a unique opportunity to conduct common garden or reciprocal transplant experiments (e.g., Kovalchuk et al. 2000) that will allow tests of environmental and genetic effects of radiation, and hence tests of adaptation to radiation.

Trees are particularly suitable for studies of the negative impact of environmental conditions (such as ionizing radiation) on growth, because growth parameters of the same individual are stored permanently in tree rings and these can readily be compared between years with and without exposure to the environmental condition, while simultaneously using trees in control areas as untreated controls (e.g., Ceulemans and Mousseau 1994; Cherubini et al. 2003; Ufar 2007). Previous studies of the effects of radiation on tree growth are few and the scope of these studies is very limited. Based on subjective and qualitative assessments, Arkhipov et al. (1994) suggested that doses of less than 0.1 Gy did not cause any immediate visible external damage to trees, although internal damage was not quantified. Although many studies have indicated that radioactive fallout from nuclear tests or nuclear bombs can be traced in tree rings, this effect may vary among radioactive isotopes due to differences in migration among isotopes across the tree trunk (e.g., Kagawa et al. 2002). Schmitt et al. (2000) showed for a very small sample of *Pinus sylvestris* pine trees grown near Chernobyl that xylem formation decreased during 1987–1989, but had recovered by 1990. Ionizing radiation had no direct effect on the cambium in 1986, but affected the differentiation of xylem mother cells in that year. Schmitt et al. (2000) concluded that reduced wood formation was due to massive loss of needles in 1986 rather than uptake of radiobiologically active elements, although this conclusion was based on only three trees felled at 1, 8 and 20 km from Chernobyl. Woodwell and Miller (1963) reported that pitch pine *Pinus rigida* exposed to chronic levels of radiation for several years in the 1950s at the Brookhaven facility reduced the width of growth rings, with reductions being the greatest at the base of the tree. This reduction was affected by the size of the crown and climate, with trees with large crowns showing small effects, and such effects increasing in years with greater climate perturbations. Again, these results were based on just a few trees making it difficult to draw general conclusions.

The objectives of our study were to investigate to what extent radiation from Chernobyl affected means and variances in the growth rate of trees. We relied on comparisons of growth rate before and after 1986 in the same individual trees, using the additional design feature of including trees that ranged in exposure from normal background radiation of 0.05 μSv/h to 34.5 μSv/h, or an increase in level of radiation by almost a factor 690 compared to normal background radiation. This sampling design allowed us to assess the change in mean and variance in growth rate before and after 1986 for a large number of trees. Scots pines were not often found in areas of contamination above 30 μSv/h, having been killed by exposure during the disaster with little or no recruitment in the more highly contaminated areas since that time.

All previous studies of the effects of radiation on growth rate suffered from problems of small sample sizes, and we avoided this problem by studying more than 100 trees across 12 different sites. A second objective of our study was to investigate the effects of alpha and beta radiation compared to gamma radiation on trees differing in size, assuming that small trees would be more susceptible to the negative impact of radiation (Woodwell and Miller 1963) because they could only extract water and nutrients from the topmost part of the soil where most of the radioactive material resided (Shestopalov 1996). A third objective was to investigate variation in annual mean growth rates due to radiation and other environmental factors, because radiation is not the only possible environmental stressor and the effects of radiation could interact with other stressors. In fact, we expected that radiation would have an effect on growth rate, but that this effect would be exacerbated by the impact of other environmental factors such as high temperatures and drought in the sandy soils of Chernobyl. We used Scots pine as a study organism because it is common and widespread in the region, but also because previous studies have shown that these pines are more susceptible to the negative impact of radiation than many other species of trees (Arkhipov et al. 1994; Kal'chenko and Fedotov 2001; Kal'chenko et al. 1993a, b; Kovalchuk et al. 2003; Rubanovich and Kal'chenko 1994; Shevchenko et al. 1996).

Methods

Study sites and choice of study specimens

A radiation protection suit was worn in the most contaminated areas. With permission from the Ukrainian authorities, we collected tree cores from Scots pine during 30 January to 5 February 2009 within the Chernobyl Exclusion Zone or in areas adjacent on the southern and western borders ensuring that we covered a wide range of radiation levels (Fig. 1). A total of 8 Scots pine trees from each of 14 different sites, in total 112, were selected based on their size, to enhance the likelihood of sampling trees older than 30 years of age and hence present before 1986. We could

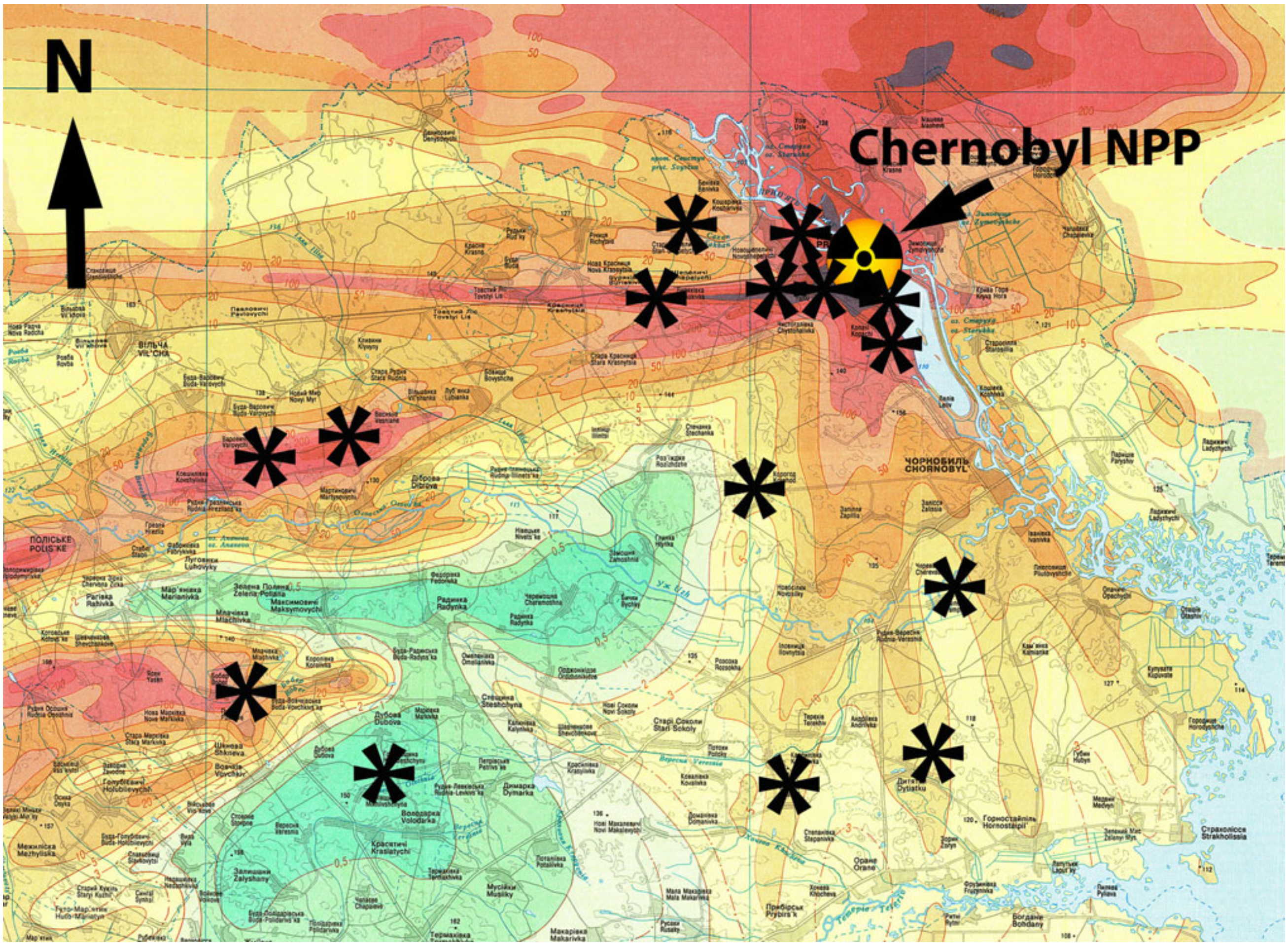

Fig. 1 Location of Scots pine trees and levels of background radiation at the ground level from Cs-137 around Chernobyl. Partly developed from Shestopalov (1996)

not record tree rings for seven of these trees because the tree core disintegrated, resulting in a final sample of 105 trees. All trees were at the edge of forests and all were undamaged, because we excluded trees that had lost major branches, had large holes or showed signs of fungal attack.

Tree cores and phenotype of trees

We extracted tree cores at a height of 1.5 m using a 7 mm increment borer (Suunto). We measured the height of trees at an accuracy of 0.5 m using a Nikon hypsometer. The diameter of the tree at 1.5 m was measured at an accuracy of 1 cm with a DBH tape. Tree cores were subsequently removed and stored for later treatment and measurement at the laboratory.

Quantifying tree growth rates

We used standard dendrochronology methods (Cook and Kairiukstis 1990) and digital imaging software to measure the annual growth rings and quantify tree growth rates before and after the 1986 Chernobyl accident. Tree increment cores were properly oriented and mounted in grooved wooden boards. Increment cores were then sanded with successively finer grades of abrasive paper until a polished surface was obtained and individual cell walls were clearly visible under a 20× dissecting microscope. Cores were then scanned at a 1,200 dpi resolution on a flatbed scanner (Canon, Canoscan 8800f). To ensure suitable detail to be captured in the digital images, a dissecting microscope was used to compare each core to its scanned image. The digital imaging software, (CooRecorder 7, Cybis Elektronik and Data AB, http://www.cybis, Larsson 2008a), was used to register coordinates for the annual growth ring boundaries in the scanned images. The distances between annual ring boundary coordinates were recorded at an accuracy of 0.1 mm and used to calculate raw annual growth rates. We used the software program CDendro (Larsson 2008b) to standardize the annual growth rate by applying the Baillie and Pilcher normalization and negative exponential detrending procedure that uses a 2-year running average to calculate the proportion of growth attributable to the current year relative to the previous year, followed by the use of a negative exponential regression of within-tree variation in growth to remove (i.e., detrend) the effects of systematic changes in growth as the tree ages. Standardized data were used to control the effects of tree age and site-specific conditions (e.g., soil type) on annual tree ring width, allowing comparisons among differently aged trees and sampled sites. Thus, we derived standardized growth rates and detrended growth rates as a second standardized measure of tree growth rate. All annual growth rings were dated to year based on the time of collection. All measurements were made blindly with respect to the level of background radiation for the trees.

To quantify measurement errors, we randomly chose 18 cores and scanned each twice, and each image was digitized twice. Repeatability R between scans was 0.99 (SE = 0.00), $F = 2{,}129.80$, $d.f. = 450, 1{,}349$, $r^2 = 0.999$, $P < 0.0001$, and repeatability between digitizing events was 0.99 (SE = 0.00), $F = 2{,}117.79$, $d.f. = 452, 1{,}347$, $r^2 = 0.999$, $P < 0.0001$.

Measuring background radiation levels

We measured radiation levels in the field and cross-validated these with measurements by the Ministry of Emergencies, at ground level at each tree using a handheld dosimeter (Model: Inspector, SE International, Inc., Summertown, TN, USA). We measured levels two to three times at each site and averaged the measurements. Such data have previously been validated with correlation against data from governmental measurements at ground level published by Shestopalov (1996), estimated as the midpoint of the ranges published. These analyses showed a high degree of consistency between the two methods (Møller and Mousseau 2007a). Radiation levels vary greatly at a local scale due to heterogeneity in deposition of radioactive material after the Chernobyl accident (Fig. 1; Shestopalov 1996).

Dosimetry

A subsample of 44 trees was used to estimate radionuclide activity within cores using gamma spectrometry. All measurements were conducted using a Berkeley Nucleonics SAM940 radionuclide identifier system equipped with a 10 × 10 cm NaI detector housed within a "cave" comprising about 1,200 kg of lead shielding. This amount of shielding resulted in a very low background radiation level of about 7.5 gcps, thus permitting very high sensitivity. System calibration was accomplished using a 0.204 microCi source. Counts were recorded for the known source to produce a calibration factor used to convert the counts from unknown samples to Ci. The source was approximately the same size and shape as the samples and was placed in the same configuration for reading as the samples, thus ensuring the same geometry. Cores were usually counted between 2 and 12 h, depending on the expected activity levels, with higher activities requiring shorter counting times for measurement. Twenty-cm-long cores were cut into four 5-cm pieces to fit atop the scintillation detector. The average 20-cm^3 core had a dry mass of 0.81 g. A subsample of 12 cores was counted twice to determine the repeatability of measurements. Activity measurements on these cores was highly repeatable [linear regression: activity (2) = 0.034 + 1.056 * activity (1); $F = 7.39$, $d.f. = 1, 10$, $P < 0.0001$, $r^2 = 0.92$]. The outer 5-cm pieces for 13 cores were counted individually to assess whether radionuclides were evenly distributed throughout the core or concentrated toward the outer regions of the tree trunk. Gamma spectra generated for each sample were inspected and compared to a background reference spectrum. ^{137}Cs activity was estimated by integrating the activity above the background threshold at 662 keV, the energy level for ^{137}Cs photon decay products. Following counting, cores were weighed on a Mettler electronic balance and individual mass was used to standardize radioactivity across samples for most samples. Small pieces of some cores were destroyed during the measurement process and a mass based on the average for all cores was used to estimate mass for these damaged samples.

Meteorology

We used the E-OBS gridded dataset (version 2.0) maintained by the European Climate Assessment & Dataset (ECA&D) for studying temperature and rainfall (Haylock et al. 2008). We calculated mean temperature and rainfall for the main growing season April–August for each year.

Statistical analyses

The background radiation level was $\log_{10}$-transformed. We developed statistical models to assess the relationship between standardized growth rate and radiation, as implemented in the statistical software JMP (SAS 2012). We tested for differences in the mean growth rate using Welch ANOVA, while simultaneously testing for the significance of a difference in variance among years using Bartlett's test.

We tested for differences in means and variances in growth rates in relation to the level of background radiation using a repeated-measures design that allowed for tests among periods. Means and standard deviations were recorded for the five 5-year periods 1981–1985, 1986–1990, 1991–1995, 1996–2000 and 2001–2005.

We developed three generalized linear models. First, we developed a model of the relationship between the mean standardized tree growth rate in 1981–1985 and 1986–1990, using a repeated-measures design to partition the effects of radiation and period. We used a similar model for standard deviation in standardized tree growth rate for the two periods. Second, we used a model of the difference in standardized growth rate between 1981–1985 and 1986–1990 as the response variable, and radiation, height and their interaction as predictors. Third, we developed a full-factorial model of standardized growth rate as the response variable, and background radiation, temperature, rainfall, period (1950–1985 vs. 1986–2008) and their two-way interactions and the only three-way interaction that approached statistical significance as predictors.

We calculated the mean residual standard growth rate for different years and used these data in a logistic regression model with suppressed growth (1—suppressed growth less than −0.10 for mean standardized growth rate, 0—for normal growth) as the response variable, and period (0—before 1986, 1—1986 or later), temperature, precipitation and their two-way interactions as predictors.

A more detailed investigation of the relationship between radioactivity contained within the tree cores and annual growth rates was performed by calculating the mean difference in absolute growth (mm per year) for the 5 years after the disaster versus the growth for the 5 years before 1986 and relating this to the level of radioactivity measured within each tree core (Fig. 5b). To minimize the potential effects of tree size on changes in growth, only large trees older than 10 years (mean = 22.6 years) at the time of the accident in 1986 were included.

We evaluated the magnitude of associations using effect sizes estimated as Pearson product–moment correlation coefficients. Cohen (1988) proposed explicit criteria for evaluation of small (Pearson $r = 0.10$, explaining 1 % of the variance), intermediate (9 % of the variance) and large effects (25 % of the variance).

Results

We measured 3,758 tree rings from 105 Scots pines. Annual growth increments were on average 2.93 mm (SE = 0.03, median 2.55 mm, range 0.12–13.49 mm). Residual growth rates were on average −0.042 (SE = 0.004, median = −0.014, range −2.46 to 0.71). Detrended standardized annual growth (det_bail) was on average −0.038 (SE = 0.004, median = −0.010, range 0.707 to −2.456). These two standardized growth rates were strongly positively correlated (Pearson $r = 0.999$), and, therefore, we used det_bail in all subsequent analyses (these are listed as standardized growth rates in the rest of the paper). Individual annual standardized growth rates had a lognormal distribution (KSL test, $D = 0.00$, $P = 0.15$). Trees were 7–25 m tall, mean 15.6 m (SE = 0.4, median = 15.8 m), had a diameter of 19–49 cm, mean 29.3 cm (SE = 0.52, median = 29 cm), and were 9–94 years old, mean 42.1 years (SE = 0.3, median = 42 years).

Radioactivity within tree cores varied from below detection levels to as high as 23,738 (SE = 135) Bq/kg of cesium-137 on measuring the full 20-cm core (Table 1). The highest readings were from trees located in the Red Forest area. The average activity across all measured cores was 3,530 Bq/kg (SE = 895). Radionuclides were not evenly distributed across cores with approximately 46 % of total core activity found within the outer 5 cm of the core (liner regression, outer activity = −0.005 + 0.464 * Total activity, $F = 207.2$, $d.f. = 1, 11$, $P < 0.0001$; $r^2 = 0.95$). The highest estimated activity for outer wood cores was 65,815 (SE = 374) Bq/kg (Table 1).

The Cs-137 activity measured from the tree cores was highly correlated with background radiation levels at the base of the tree measured using a handheld Geiger counter [linear regression, log(Activity (Bq/kg)) = 1.33 + 1.70 * log(Background), $F = 93.3$, $d.f. = 1, 42$, $P < 0.0001$, $r^2 = 0.68$; Fig. 2], indicating that simple field measurements of background radiation provide a reliable estimate of the likely dose experienced by the tree.

The change in tree growth rate at the time of the Chernobyl accident is clearly visible in pine logs from the Chernobyl Exclusion Zone (Fig. 3). Growth varied significantly among years (Welch ANOVA: $F = 4.54$, $d.f. = 90, 115.12$, $P < 0.0001$), with significant differences in variance among years (Bartlett's test, $F = 5.37$, $d.f. = 90$, $P < 0.0001$). While growth varied little during 1914–1985 ($F = 1.86$, $d.f. = 67, 806.84$, $P = 0.0062$; $F = 2.08$, $d.f. = 67$, $P < 0.0001$), there was considerably greater variation during 1986–2008 ($F = 15.72$, $d.f. = 22, 807.33$, $P < 0.0001$; $F = 15.72$, $d.f. = 22$, $P < 0.0001$). In fact, the variance during 1986–2008 was significantly greater than during 1914–1985 (variance ratio test, $F = 1.19$, $d.f. = 1{,}521, 2{,}173$, $P < 0.0001$).

Closer inspection of mean annual values revealed severely depressed growth less than −0.10 in 1987–1989, and again in 1992, 1996, 2003 and 2006 (Fig. 4). In contrast, there was only a single year with clearly elevated growth greater than +0.10 (1982). The probability of having 3 years in a row with depressed growth (1987–1989) was 7/29 years = 0.2414 to the third power, which equals 0.0141. A logistic regression with a poor year with reduced growth as the response variable (a score of 1—poor year, 0—normal year) and period (before or after the accident in 1986), temperature, rainfall and all two-way interactions as predictors produced a significant model

Table 1 Radiation activity levels for Scots pine trees in the vicinity of the Chernobyl nuclear power plant

Location	Background radiation (μSv/h)	Full core (Bq/kg)	SE	Outer 5 cm (Bq/kg)	SE
Red Forest	25.1	23,738	135	65,815	374
Red Forest	18.6	19,917	169	27,499	233
Red Forest	18.9	17,545	292	44,171	736
Red Forest	16.7	15,362	129	39,007	328
Red Forest	21.4	14,383	171	18,312	218
Red Forest	17.7	13,303	145	21,443	233
Korohod	34.5	6,322	126	11,489	230
Vesniane	10.6	6,072	164	11,928	322
Korohod	26.9	3,928	123	8,131	254
Red Forest	23.5	3,828	153	6,199	248
Korohod	26	3,692	119	6,105	197
Korohod	8.1	3,172	198	6,190	387
Red Forest	16.7	2,961	141	4,737	226
Red Forest	16	2,896	152	5,253	276
Red Forest	16	2,840	123	2,868	125
Fish pond	3.6	2,796	164	1,891	111
Red Forest	13	2,438	163	5,342	356
Red Forest	11	1,168	130	2,247	250
Korohod	9.1	1,005	167	2,121	353
Red Forest	12	949	136	2,743	392
Vesniane	17	943	157	1,212	202
Korohod	31.8	897	112	1,973	247
Korohod	9.9	873	146	1,566	261
Yampil	0.17	568	189	948	316
Vesniane	18.7	510	128	458	114
Fish pond	4.7	435	145	748	249
Vesniane	7.3	423	141	682	227
Red Forest	11	296	99	566	189
Red Forest	11	291	146	506	253
Prypiat	1.4	182	182	257	257
Varo	1.5	181	181	395	395
Prypiat	2.8	178	178	318	318
Stari	0.6	146	146	240	240
Stari	0.7	146	146	240	240
Stari	0.8	146	146	240	240
Varo	4	146	146	240	240
Dytiaku	0.18	146	146	240	240
Krashytichi	0.09	146	146	240	240
Bobor	0.8	146	146	240	240
Bobor	1.3	146	146	240	240
Varo	3	0	0	0	0
Krashytichi	0.08	0	0	0	0
Bobor	1.4	0	0	0	0
Pisky	0.11	0	0	0	0

Full-core estimates are for complete 20-cm cores that reflect average tree activity, while activity levels for the outer 5 cm are on average significantly more radioactive on a per weight basis reflecting a higher concentration of Cs-137 in the cambium and the bark

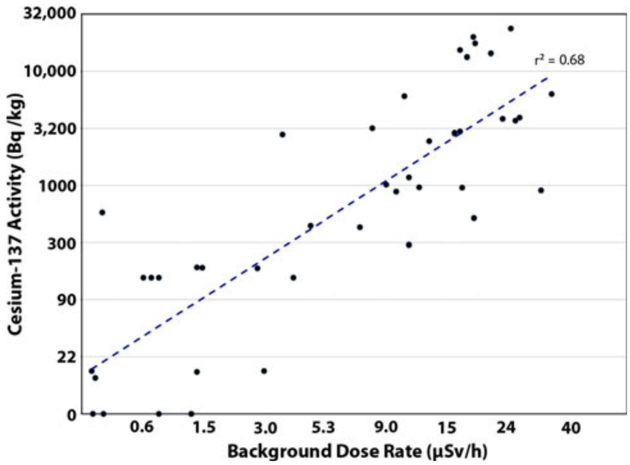

Fig. 2 The relationship between Cs-137 activity (Bq/kg dry weight) in tree cores and background radiation level (µSv/h) at the base of each tree

Fig. 3 Difference in width of tree rings in pine logs from Chernobyl. The year of the accident in 1986 is clearly visible from the change in the color of the wood

($\chi^2 = 13.68$, $P = 0.033$) that fitted the data ($\chi^2 = 25.55$, $P = 0.95$). There was a significant effect of period ($\chi^2 = 9.35$, $P = 0.0022$), while all other effects were small and not significant (likelihood-ratio $\chi^2 < 0.45$, $P > 0.50$). Among the 23 years 1986–2008, there were 7 years with significant correlations between standardized annual growth (det_bail) and background radiation (1986, 1988,1989, 1990, 1996, 1998, 2006), while 1.15 would be expected by chance. The mean correlation coefficient was only −0.075 (SE = 0.031), which was significantly different from zero (one-sample *t* test based on *z* transformed Pearson correlation coefficients: $t = -2.45$, $d.f. = 22$, $P = 0.023$).

Repeated-measures ANOVA revealed a highly significant negative effect of background radiation on mean growth rate, a significant effect of period (1981–1985 vs. 1986–1990) and a significant interaction (Table 2). This is as expected, if tree growth was reduced only after 1986 and

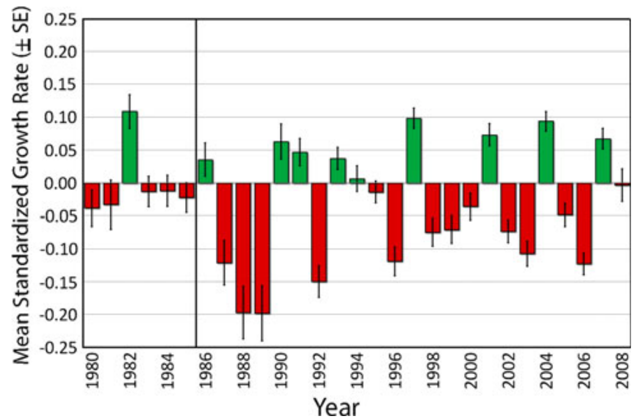

Fig. 4 Mean (+SE) annual standardized growth rates of 105 Scots pine trees around Chernobyl during 1980–2008. Severely depressed growth is visible during 1987–1989 and also in several subsequent years

only in trees from contaminated areas. A second repeated-measures ANOVA revealed a significant positive effect of background radiation on variation in growth rate as reflected by the standard deviation (Table 2). In addition, there was a significant effect of period and a significant interaction.

When analyzing the level of depression of standardized growth after and before 1986, we found that growth was disproportionately reduced at high radiation levels with an effect size that was intermediate (Table 3; Fig. 5a). Background radiation levels explained 13 % of the variance in standardized tree growth. There was a highly significant negative relationship between the change in mean growth rate and the radioactivity measured within tree cores [linear regression: change in mean growth rate = −0.42 radioactivity in the wood (Bq/kg) + 0.91; $F = 6.87$, $d.f. = 1, 23$, $P = 0.016$] indicating that growth was significantly lower following the disaster for trees with contaminated wood

Table 2 Repeated-measures analysis of variance of mean and standard deviation in residual standardized growth rate in relation to background radiation level, period and their interaction for 105 Scots pine trees

Source of variation	Factor	*F*	*d.f.*	*P*	Slope (SE)
Means					
Between subjects	Radiation (*R*)	25.39	1, 103	<0.0001	−0.052 (0.011)
Within subjects	Period (*P*)	7.89	4, 100	<0.0001	
	R × *P*	6.75	4, 100	<0.0001	
Standard deviations					
Between subjects	Radiation (*R*)	16.15	1, 102	<0.0001	0.061 (0.006)
Within subjects	Period (*P*)	7.35	4, 99	<0.0001	
	R × *P*	7.90	4, 99	<0.0001	

Table 3 Difference in mean residual standardized growth rate of Scots pine trees between 1986–1990 and 1981–1985 in relation to the level of background radiation, tree height and their interaction

Variable	Sum of squares	*d.f.*	*F*	*P*	Slope (SE)
Radiation (*R*)	0.184	1	9.48	0.003	−0.050 (0.016)
Height (*H*)	0.043	1	2.20	0.141	0.005 (0.003)
R × *H*	0.109	1	5.60	0.020	0.009 (0.004)
Error	2.356	101			

The model had the statistics $F = 6.79$, $d.f. = 3, 101$, $r^2 = 0.17$, $P = 0.0003$

relative to trees of low levels of contamination in the wood. The level of radioactivity in wood accounted for 23 % of the variance in standardized tree growth (Fig. 5b). Standardized growth was particularly reduced by radiation in small trees (Fig. 5c).

Growth rate improved in warm and especially in rainy years, and this effect was stronger when it was both warm and rainy as shown by the temperature by precipitation interaction (Table 4). The effects of temperature exacerbated the effect of radiation as shown by the temperature-by-radiation interaction. The effect of temperature changed in 1986, as shown by the interaction between temperature and period. Thus, the effects of radiation were mediated by the impact of temperature and drought. The other effects including the interactions were either not significant or marginal effects.

Discussion

The main findings of this study of growth rate of Scots pine were that reduced growth increments and increased variance in the size of growth increments were associated with elevated levels of background radiation. The magnitude of the radiation effect depended on the size of trees, because small trees showed disproportionately reduced growth when exposed to radiation compared to large trees. Other environmental stressors (e.g., temperature and low annual precipitation) interacted with radiation to reduce growth. While our data showed a 3-year continuous effect of radiation on growth suppression, our observations indicated greater variation in annual growth after 1986 and suppressed growth in 1992, 1996, 2003 and 2006. Indeed, standardized growth rate was significantly related to background radiation in 8 years, with a significant mean effect across all years, suggesting a continual mean effect of the Chernobyl accident that extends to the present. This effect size of an intermediate magnitude of 0.30 is similar to the mean effect size of 0.28 found across all meta-analyses in the biological sciences including meta-analyses of the effects of CO_2 on plants (Møller and Jennions 2002). This conclusion is supported by the fact that these exceptionally poor years in terms of growth are not associated with elevated temperatures or drought, nor could we document any interaction between weather and radiation.

The degree of suppression of the mean level of growth during 1986–1990 (post-Chernobyl) compared to 1981–1985 (pre-Chernobyl) of individual trees was caused by radiation interacting with tree height, with radiation effects being disproportionately greater in small compared to large trees. There are several possible interpretations. First, more than 90 % of all radioactive material is located in the topmost 20 cm of the soil. Short trees having shallow root systems that do not extend deep into the soil may extract more radionuclides than tall trees with deep root systems. Second, growth rate effects may be more readily discerned in small trees given the larger absolute growth rates in short trees (Koch et al. 2004). Third, this may be caused by an interaction related to differential effects of radiation on mycorrhizae, which may significantly influence radionuclide uptake (Dighton et al. 2008).

The mean growth rate of Scots pines from Chernobyl varied significantly among years, with a highly significant difference in variance among years. High levels of variation in growth were much more pronounced during 1986–2009 following the accident in 1986 than during

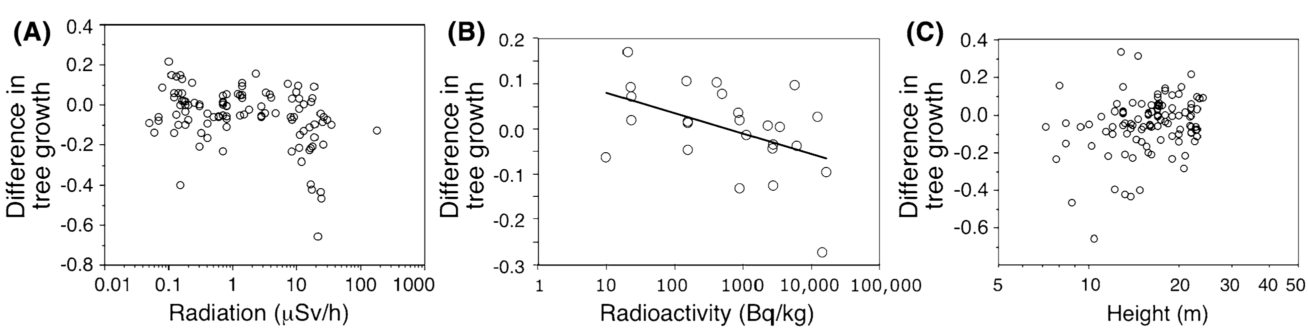

Fig. 5 Difference in mean standardized growth rate of 105 Scots pine trees around Chernobyl between 1986–1990 and 1981–1985 in relation to **a** background radiation level (μSv/h), **b** radioactivity of the wood (Bq/kg) and **c** height of trees (m)

Table 4 Relationship between residual standardized growth rate of Scots pine trees between 1950 and 2008 in relation to the level of background radiation, temperature and rainfall during April–August, and whether the data were obtained before or after 1986

Variable	Sum of squares	*d.f.*	*F*	*P*	Slope (SE)
Temperature (*T*)	0.277	1	4.59	0.032	0.011 (0.005)
Precipitation (*P*)	1.213	1	20.08	<0.0001	0.054 (0.012)
Radiation (*R*)	0.077	1	1.28	0.26	−0.005 (0.005)
Before/after 1986 (*B*)	0.003	1	0.05	0.82	0.001 (0.005)
$T \times P$	0.647	1	10.55	0.0012	0.048 (0.016)
$T \times R$	0.472	1	7.67	0.0056	−0.015 (0.005)
$T \times B$	0.643	1	10.45	0.0012	0.016 (0.005)
$P \times R$	0.176	1	2.86	0.091	0.020 (0.012)
$P \times B$	0.034	1	0.56	0.46	0.009 (0.012)
$R \times B$	0.570	1	9.26	0.0024	−0.016 (0.005)
$T \times P \times B$	0.172	1	2.80	0.094	−0.026 (0.016)
Error	223.788	3,636			

The model had the statistics $F = 5.69$, $d.f. = 11, 3{,}587$, $r^2 = 0.02$, $P < 0.0001$

1914–1985. Suppression of growth occurred during three subsequent years 1987–1989, and during 1992, 1996, 2003 and 2006, and this suppression was associated with radiation, but not significantly with temperature, precipitation or their interactions with radiation. Increasing variance in growth can be a consequence of increasing age and stem diameter (e.g., Fritts 1976; Carrer and Urbinati 2004) although this explanation is difficult to reconcile with a sudden change in mean and variance in standardized tree growth in 1986. Schmitt et al. (2000) reported suppressed xylem growth in Scots pine during 1987–1989, but not during 1986, when the accident happened in spring. The probability of having three consecutive years of suppressed growth was significantly less than expected randomly, suggesting that the run of 3 years of suppressed growth during 1987–1989 was exceptional. Given that radiation effects were not observed in all years after 1986, we can conclude that other stressors interacted with radiation to suppress growth. We hypothesize that the annual weather patterns interacted synergistically with spatially congruent patterns of site conditions (e.g., the sandy soils of Chernobyl) and levels of Cs-137 deposition at the landscape scale to produce significant growth suppression. This hypothesized interaction is supported by our observations of greater variation in annual growth after 1986 and suppressed growth in 1992, 1996, 2003 and 2006, when both spatial and temporal patterns of environmental stressors matched to produce effects on growth. Repeated-measures analyses of variance confirmed these conclusions by demonstrating that means were reduced and variances increased during some but not all periods, that these effects were related to radiation, and that radiation effects differed among periods. Thus, our data show a 3-year continuous effect and ongoing effects for more than 20 years, which likely extends to the present.

There are uncertainties concerning the nature of Chernobyl effects on tree growth including the mechanisms underlying the effects of radionuclides on tree growth. The effects on somatic and germline mutation rates are well documented (Arkhipov et al. 1994; Kal'chenko and Fedotov 2001; Kal'chenko et al. 1993a, b). The physiological mechanisms of uptake of mixtures of radionuclides by plants remain poorly known, as are the relative effects of external exposure to radiation versus internal exposure to radioactive heavy metals that are carried through the xylem to growing tissues. Our observation of a dose-dependent response provides support for the hypothesis that radionuclides are in large part responsible for our results. By using a sampling regime that included a relatively large number of samples with a wide spatial distribution with respect to contamination level (Fig. 1.), we were able to test our hypothesis. In other words, depressed growth was observed in trees exposed to even small levels of Chernobyl-derived radioactive contaminants exceeding the natural background level by a factor ten independently of distance from the reactor site and this is most parsimoniously explained by a direct effect of radioactive contaminants on growth.

Although we only investigated the effects of radiation on growth rate, pines were clearly also affected in terms of composition of the wood (Fig. 2). Changes in quality and quantity of wood may not only have important implications for decomposition and use as a construction material, but also for forest fires that are known to be a significant threat by redistribution of radionuclides to inhabited areas even far outside the Chernobyl Exclusion Zone (Kashparov et al. 2000; Yoschenko et al. 2006a, b). The very high activity levels of Cs-137 in tissues of trees in highly contaminated areas reported here further emphasize the need for investigation concerning the potential impacts of forest fires on the dispersal of radionuclides in populated regions.

In conclusion, we have demonstrated a landscape-scale effect of severely reduced growth in Scots pine during three consecutive years following the nuclear disaster at Chernobyl, and recurrently in several subsequent years when environmental stressors were spatially and temporally congruent. Given that significant levels of radionuclides were dispersed across 200,000 km^2 in Europe as a consequence of the Chernobyl disaster, these findings suggest that there may be ecosystem-scale impacts on productivity that have not previously been suggested.

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