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Maksym Netsvetov [a,b,*], Yulia Prokopuk [a], Dmytrii Holiaka [c], Marcin Klisz [d], Annabel J. Porté [b], Radosław Puchałka [e,f], Maksym Romenskyy [g]

[a] Department of Phytoecology, Institute for Evolutionary Ecology, National Academy of Sciences of Ukraine, Kyiv, Ukraine
[b] BIOGECO, University of Bordeaux, INRAE, Cestas, France
[c] Ukrainian Institute of Agricultural Radiology of the National University of Life and Environmental Sciences of Ukraine, Chabany, Ukraine
[d] Dendrolab IBL, Department of Silviculture and Genetics, Forest Research Institute, Raszyn, Poland
[e] Department Ecology and Biogeography, Faculty of Biology and Environmental Protection, Nicolaus Copernicus University, Torun, Poland
[f] Centre for Climate Change Research, Nicolaus Copernicus University, Torun, Poland
[g] Department of Life Sciences, Faculty of Natural Sciences, Imperial College London, London, United Kingdom

HIGHLIGHTS

- Acute sub-lethal radiation exposure decreased Scots pine secondary growth in the two years following the accident.
- Acute sub-lethal radiation exposure jeopardized Scots pine ability to respond to extreme drought.
- Moderate radiation dose did not affect Scots pine radial growth nor its climate sensitivity.
- Lasting radiation exposure has not altered the trees' growth-to-climate relationships in the long-term perspective.
- Scots pine in Chornobyl zone is changing its response to climatic factors in a similar way to other European populations.

GRAPHICAL ABSTRACT
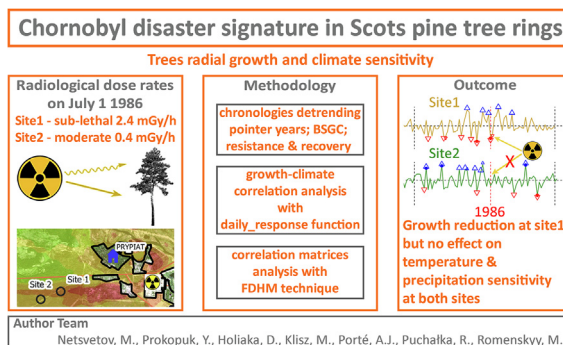
ARTICLE INFO

ABSTRACT

The extensive radioactive fallout resulting from the 1986 Chornobyl accident caused tree death near the nuclear power plant and perturbed trees communities throughout the whole Chornobyl exclusion zone. Thirty years into the post-accident period, the radiation continues to exert its fatal effects on the surviving trees. However, to what extent the continuous multi-decadal radiation exposure has affected the radial tree growth and its sensitivity to climate variation remains unascertained. In this comparative study, we measure the Scots pine radial growth and quantify its response to climate at two sites along the western track of the nuclear fallout that received significantly different doses of radiation in 1986. The common features of the two sites allow us to disentangle and intercompare the effects of sub-lethal and moderate radiation doses on the pine's growth and climatic sensitivity. We extend the response function analysis by making the first use of the Full-Duration at Half-Maximum FDHM method in dendrochronology and apply the double-moving window approach to detect the main patterns of the growth-to-climate relationships and their temporal evolution. The stand exposed to sub-lethal radiation shows a significant radial growth reduction in 1986 with a deflection period of one year. The stand exposed to moderate radiation, in contrast, demonstrates no significant decrease in growth either in 1986 or in the following years. Beyond the radiation effects, the moving response function and

FDHM enabled us to detect several mutual patterns in the growth-to-climate relationships, which are seemingly unrelated to the nuclear accident. To advance our predictive understanding of the response of forest ecosystems to a massive radioactive contamination, future studies should include quantitative wood anatomy techniques.

1. Introduction

The Chornobyl Nuclear Power Plant (CNPP) is located in the Prypiat city outskirts, northern Ukraine, surrounded by meadows and forests dominated by Scots pine (*Pinus sylvestris* L.). On April 26, 1986, two accidental explosions destroyed the core of the plant's Unit 4 and started a massive fire causing an uncontrolled release of radioactive gases, vapours, aerosols, and 'hot particles' into high altitudes for about ten days (Cherp et al., 2002). Although the bulk of the expelled radioactive material has been dispersed downwind (westward) from Prypiat (Hohenemser et al., 1986), the most extensive fallout deposition occurred in the areas adjacent to the CNPP.

The simultaneous release of short-lived and long-lived radionuclides precipitated both the acute and late radiation effects on the forests in the Chornobyl Exclusion Zone (CEZ). The radionuclides covered the crowns, bark and litter of the trees, causing a massive tree mortality near the accident's epicentre. More distantly, defoliation, morphological anomalies, and growth depression have been observed in the surviving trees (Arkhipov et al., 1994). Engaging in the plant biological cycles by replacing K and Ca in biomolecules (Goor and Thiry, 2004), the radionuclides ^{137}Cs and ^{90}Sr exert a persistent life-long influence on the affected plants.

Among various morphological features of plants, tree rings capture and retain in their structure perhaps the most reliable information on the annual and seasonal effects of the environment on tree growth (Kozlowski et al., 2012). The growth-to-environment responses can be relatively easily established from tree rings and traced back through the whole tree's life.

Early reports suggested that a decrease in trees' radial growth was due to a combination of factors in the first years after the Chornobyl accident. The impact of hot and dry weather on xylogenesis at the beginning of the growing seasons of 1986 and 1987 (Musaev, 1995) was exacerbated by the radiation-induced alteration of the growing xylem cells and cambium. The deposition of radionuclides on crowns caused defoliation, followed by a decrease in assimilates production in 1986, imprinted in the narrow tree rings from the next season of 1987 (Grodzynskyi et al., 1991; Kozubov and Taskaev, 1994; Schmitt et al., 2000). This effect hints at the two-fold possibility: the plants' climate sensitivity might be directly modulated by the impact of radiation on dividing cambium cells or indirectly through its effect on other plants' organs and through the release of hormones, especially auxins.

Gymnosperms in general are more susceptible to radiation than angiosperms (Kozubov and Taskaev, 1994). In the CEZ forests, Scots pine is one of the tree species most vulnerable to radiation. In most studies, Scots pine was reported to reduce the radial increment in 1987–1990, but not in 1986. The compensatory effect of non-structural carbohydrates accumulated in wood tissue during the 1985 season explains the absence of the growth reduction in the year of the highest background radiation level (Kozubov and Taskaev, 1994; Musaev, 1995; Schmitt et al., 2000). Also, the activation and division of the cambial cells had started before the nuclear accident (Tulik, 2001) that could partly explain the absence of any detectable growth reduction in the year of the accident.

The choice of a technique applied to the tree-ring series in order to establish the long-term growth oscillations has been shown to affect the outcome of such studies. The standardization procedures helped to reveal that after 1986 the growth rate reduction in Scots pine lasted up to 2010 and was associated with a high level of background radiation (Mousseau et al., 2013), allowing of a gross description of the radiation impact. Moreover, the scarce studies aimed to find the climatic drivers of the Scots pine growth in CEZ shortly after the accident (Musaev, 1993, 1995) were inconclusive concerning the trees' climate sensitivity because they considered

short time periods. Therefore, longer tree-ring and climate series are still needed to detect reliable correlations.

In this study, we aimed at identifying the specific seasonal periods when the climatic sensitivity of Scots pine in CEZ was highest and to test for its stability throughout the trees' life, including the 35-year-long post-accident period. We hypothesized that: (1) trees heavily exposed to radiation reduced their secondary growth in the year of the Chornobyl accident; (2) the massive radioactive contamination has altered Scots pine's sensitivity to climatic variability. We addressed these hypotheses using data from two groups of trees differing in the background radiation and absorbed doses; we used both conventional and innovative statistical techniques.

2. Materials and methods

2.1. Study area and meteorological data

The study area is located in the CEZ, in the North of Ukraine, within the natural distribution of Scots pine (Fig. 1 A). The climate of the studied area is moderately continental, with an average air temperature of 7.8 °C and an annual precipitation amount of 580 mm. During 1947–2019, the warmest and coldest months were July and January, with mean maximum and minimum daily temperatures of 25.4 °C and –8.1 °C, respectively. The coldest period lasted from November to March and the hottest from July to August. The highest precipitation amount fell in July and the smallest in January–March (Fig. 1 B). The climatic records from the local Chornobyl weather station, i.e. average temperature and amount of precipitation, were obtained at the Central Geophysical Observatory in Kyiv, Ukraine. The Standardized Precipitation Evapotranspiration Index (SPEI) data were acquired from the Global Drought Monitor (Beguería et al., 2010; Vicente-Serrano et al., 2010).

We conducted our research in the Scots pine forest hit by the westward radionuclide fallout in 1986 (Fig. 1 C). We aimed at selecting stands as similar as possible except for the radiation dose rates: we chose two sites approximately 5–7 km from the CNPP (51.38°N, 30.00°E and 51.37 N, 29.98°E) dominated by mature Scots pine trees, reaching at least 100 years in age and growing on sandy soils in similar microsite conditions (Supplementary Table S1, Fig. S4) but exposed to different background radiation. The stand at site 2 was younger and denser with a higher basal area, but the height of the trees was greater, suggesting growing conditions were slightly better here than at site 2. Before the nuclear accident in 1986, both sites were managed and since 1979 pine tapping has been practised at site 1 (Fig. 1 C), which could cause direct contamination of wood by radioactive elements depositing on the trunk wounds, even if filled with resin.

2.2. Radiation exposure measurements

To assess the radioactive contamination of stem wood, we measured the activity concentrations of biologically mobile radionuclides ^{90}Sr and ^{137}Cs in the increment cores from a subsample of the trees used in this study (three and two trees at sites 1 and 2, respectively; see Supplement 5). We estimated the temporal changes in the external dose rates at both sites using data on the soil radionuclide density contamination collected since 1986 and 1987 (Kashparov et al., 2020, 2017, Supplement 6). To obtain the current external gamma doses at the sites, i.e. the absorbed dose rate in the air, in 2020 we measured the gamma-radiation ambient dose equivalent rate (AEDR) at an elevation of 1 m using a STORA-TU RKS-01 dosimeter-radiometer (ECOTEST, Ukraine) (Table 1).

The mean values of ^{90}Sr and ^{137}Cs activity concentrations in the stem wood were relatively low, explaining the comparable external and internal
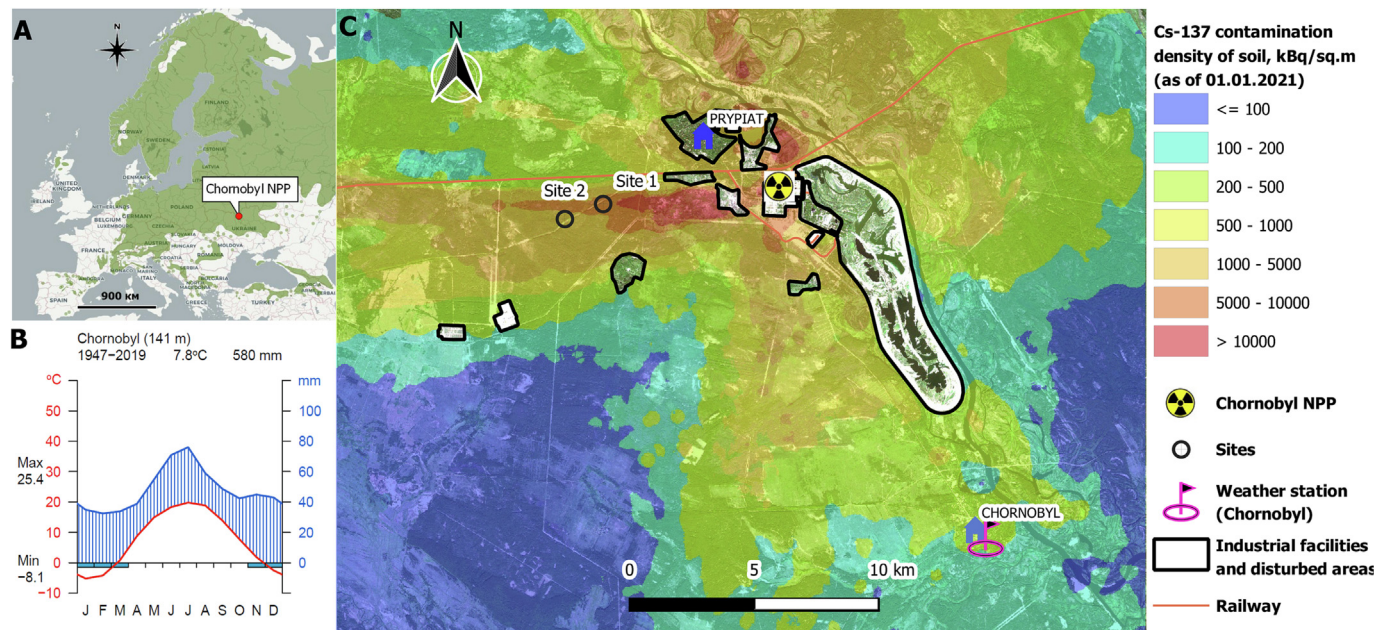
Fig. 1. Geographical and climatic characteristics of the study sites. (A) Distribution map of the Scots pine in Europe (EUFORGEN, 2009) and location of the Chornobyl nuclear power plant. (B) Walter–Lieth climatic diagram with temperature in red and precipitation in blue, constructed using data obtained at the Central Geophysical Observatory in Kyiv, Ukraine. (C) Map of the study area. The colors indicate the level of ^{137}Cs contamination of the upper soil around Chornobyl on 01.01.2021 (Kashparov et al., 2017). The sampled sites (open black dots) are located westward of the CNPP.

absorbed dose rates for the trees (Table 1) and pointing to the weakness of the transfer factor from soil to wood. However, the two sampling sites differed in the average radionuclide concentration activity by more than eight times (10.6 kBq kg^{-1} vs 1.06 kBq kg^{-1} for ^{137}Cs and 14.9 kBq kg^{-1} vs 1.78 kBq kg^{-1} for ^{90}Sr, at sites 1 and 2, respectively). The internal dose rates (10.1 µGy h^{-1} vs 1.2 µGy h^{-1}) and external dose rates (13.2 µGy h^{-1} vs 2.3 µGy h^{-1}) resulted in 23.3 µGy h^{-1} and 3.5 µGy h^{-1} total absorbed dose rates at the two sites.

Since May 6, 1986 till June 2020, the external gamma absorbed dose rate in the air at a height of 1 m from the ground surface decreased by 780–796 times, from 10,300 µGy h^{-1} to 13.2 µGy h-1 at site 1 and from 1830 µGy h^{-1} to 2.3 µGy h^{-1} at site 2 (Table 1, Supplementary Fig. S6). On June 1, 1986, according to data from the first classification of the radiation dose rates (Kozubov et al., 1991), trees in the studied sites received sub-lethal 2400 µGy h^{-1} and moderate 400 µGy h^{-1} levels of radiation.

The activity concentration of ^{137}Cs and ^{90}Sr was unevenly distributed along the trees' cores (Supplementary Fig. S5), although this was subject to variation between the trees, particularly at site 1. Regarding the decrease in external doses and the consequent weakening of the intake from the soil, the growing trend in radionuclides' activity concentrations in wood might point to their radial transfer in both directions along the trunk's radii, towards heartwood and sapwood from the parts heavily contaminated in the first years after the accident. However, such a mobility of ^{137}Cs and ^{90}Sr in plants' tissues and a decay of short-lived radionuclides do not

allow of precise reconstruction of annual variations of wood contamination; thus, we do not pursue further analyses of the radionuclide relocation events.

2.3. Sample collection and preparation

In the summer and autumn of 2020, increment cores were collected from 20 and 16 dominant Scots pine trees at sites 1 and 2, respectively. At least two cores per tree were extracted at 1.3 m stem height using an increment borer. At site 1 (Supplementary Fig. S4), cores were sampled in the undamaged parts of the tapped trees. The air-dried cores were glued into wooden holders, sanded with gradually increasing sandpaper's grit number from 80 to 320 units and scanned with a flatbed scanner (Epson Perfection V37) at a resolution of 3200 dpi. Tree-ring widths (RW) were measured with AxioVision 4.9.1 software (Carl Zeiss) at an accuracy of 0.01 mm.

The individual ring-width time series were cross-dated, matching the years of minimal and maximal growth for each core. The quality of cross-dating was checked with COFECHA software (Holmes, 1983). To reduce any age-related low-frequency variation, the individual tree's RW series were detrended using a cubic-smoothing spline with a 50 % frequency cut-off at the wavelength of 30 years (Cook and Peters, 1981; Speer, 2010) and a first-order autoregression modelling (Cook and Kairiukstis, 1990) using the *dplR* package in R (Bunn, 2010). The detrended individual series were averaged across each site to build the mean residual indexed site chronologies RWI (Fig. 2).

2.4. Tree-ring data statistics and analysis

We employed dendrochronological descriptive statistics (see Cook and Kairiukstis, 1990 for extensive description) to estimate the confidence of the sites' raw (RW) and detrended (RWI) chronologies. We used the mean inter-series correlation (Rbar) as an indicator of the common signal strength in trees throughout the stands and the first-order autocorrelation (AR1) as the indicator of the impact of the previous year's conditions. The similarity between the tree-ring series was represented by the Gleichläufigkeit (glk), i.e. the coherence coefficient (Buras and Wilmking, 2015; Eckstein and Bauch, 1969), and synchronous growth changes (sgc)

Table 1
Activity concentrations of ^{137}Cs and ^{90}Sr in wood samples and their estimated dose rates (mean ± sd) on 06.052020.

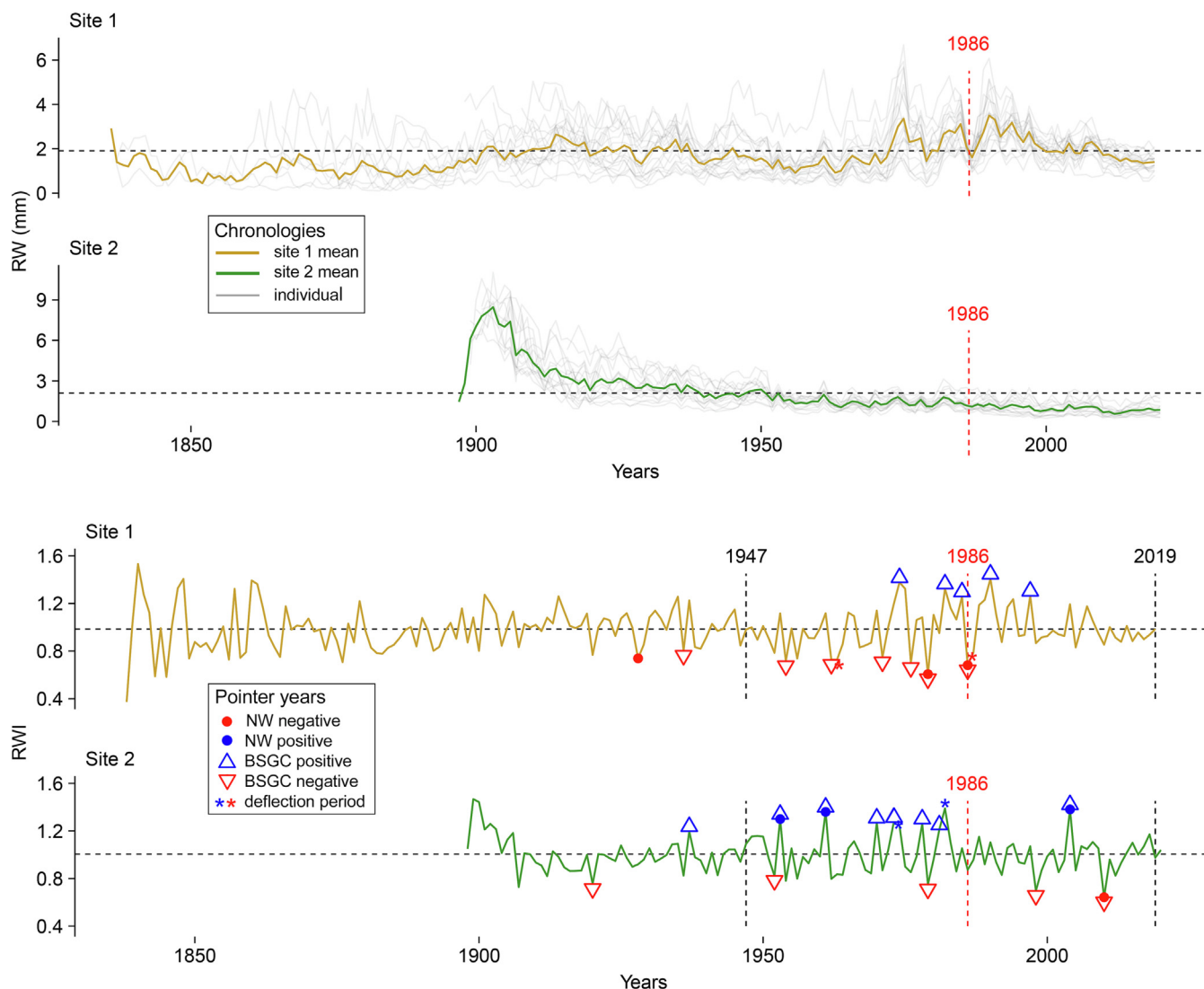| Parameters		Site 1	Site 2
Activity concentration, kBq kg^{-1} dw	^{137}Cs	10.6 ± 3.6	1.1 ± 0.3
	^{90}Sr	14.9 ± 4.5	1.7 ± 0.4
Internal dose rate, µGy h^{-1}	^{137}Cs	2.9 ± 1.3	0.3 ± 0.1
	^{90}Sr	7.3 ± 2.9	0.9 ± 0.3
	Total	10.1 ± 3.2	1.2 ± 0.3
External gamma absorbed dose rate, µGy h^{-1}		13.2 ± 1.5	2.3 ± 0.3
Total absorbed dose rate, µGy h-1		23.3 ± 3.5	3.5 ± 0.4

dw – dry wood.

Fig. 2. The raw RW (top) and detrended RWI (bottom) tree-ring chronologies. The red and blue dots and triangles on the RWI chronologies indicate the negative and positive pointer years, respectively, according to the NW method (points) and the BSGC method (triangles). The asterisks indicate deflection period, according to the BSGC method. Gray and red vertical dashed lines denote the study period and the year of the accident respectively.

coefficients. The chronologies representativeness was accessed through the expressed population signal (EPS). The statistics for the datasets were calculated for the 1947–2019 period. The computations were carried out using the *dplR* (Bunn, 2010) package in R.

We performed the pointer-year analysis (Schweingruber et al., 1990) to detect strong negative and positive changes in the chronologies and test whether they were caused by radiation or other factors. We applied two techniques: normalization in a moving window (NW) (Neuwirth et al., 2007) and the bias-adjusted standardized growth change (BSGC) (Buras et al., 2022). The NW method reveals weak, strong, and extreme pointer years through statistical normalization sensu Neuwirth of the tree-ring data series by moving a temporal window along them. The BSGC method is based on the standardized tree-ring data changes, which are bias-adjusted to the global growth changes. The BSGC method additionally estimates the deflection period, i.e. when the extreme growth deviation has not returned to normal values. In the NW method, we used a 13-year moving window for normalized growth deviations and a 0.75 threshold for the identification of event years at each site. Both approaches were applied to detrended RWI chronologies using the *pointRes* (van der Maaten-Theunissen et al., 2015) and the *dendRolAB* (Buras et al., 2022) packages in R.

The growth-to-climate analysis covered the period from 1947 to 2019, fully overlapping with continuous daily meteorological observations in the area. We used the double-moving window approach (Prokopuk et al., 2022) to assess the Scots pine radial growth-to-climate relationship. The first 31-year-wide window shifted through the whole study period (1947–2019) with a one-year offset. The second window moved through the daily temperature and precipitation data to find the aggregation period with the highest growth-to-climate correlations. The latter was performed with the *daily_response* function of the *dendroTools* package for R (Jevšenak, 2020; Jevšenak and Levanič, 2018). To evaluate the differences in the growth-to-climate relationships in the trees from the two study sites in two consecutive seasons, we applied the Full-Duration at Half-Maximum (FDHM) method (Weik, 2000) to the output of the *daily-response* function, i.e. 73 matrices corresponding to each of the 31-year windows. We defined the main patterns as the FDHM signal intensity. This technique then allowed us to quantify the varying climatic signal peaks expressed by the mean correlation coefficients. The development of the main patterns within the 73-year study period was further investigated by finding trends in the R-squared values obtained from the linear models. The change point analysis (CP-analysis) was used to identify possible changes in the growth-to-

climate relationship employing the *changepoint* package (Killick and Eckley, 2014).

The impact of drought episodes was assessed using growth resistance and recovery indices, i.e. the ratios between growth during and before the event, and growth after and before the event, respectively (Lloret et al., 2011). Calculations were achieved using the *pointRes* R package (van der Maaten-Theunissen et al., 2021) considering a three-year-long pre- and post-disturbance period. Resistance index values below 1 reveal growth depression and values over 1 reveal growth enhancement. The significance of differences in the average indices between the sites was checked using a *t*-test for independent samples.

The years of extreme droughts were identified based on the SPEI lower or equal to -2 in the period 1955–2019, covered by the SPEI data (Beguería et al., 2010; Vicente-Serrano et al., 2010). To catch the extreme drought events during the Scots pine growing season, we used the April–September SPEI values, considering 1–6-month periods. If a drought occurred in two consecutive years, we chose only the first to avoid the inclusion of a drought year in the pre-drought period. The extreme drought episodes in Chornobyl were detected in 1959 (July SPEI3 $= -2.08$), 1963 (September SPEI6 $= -2.60$), 1979 (June SPEI2 $= -2.25$), 1986 (May SPEI $= -2.33$), 1992 (August SPEI1 $= -2.11$), and 2015 (August SPEI6 $= -2.55$). All statistical calculations and plots were done in R (R Development Core Team, 2022).

3. Results

3.1. Ring width and ring width indices chronologies

At sites 1 and 2, the mean individual series length was on average 137 and 118 years, with the shortest series lengths being 100 and 105 years, respectively (Table S2), although the trees on site 2 were, on average, 20 years younger compared to the other one. The mean individual radial-growth rate and its standard deviation were higher at site 1 (Tables 2 and S2). The RW trends (Fig. 2), i.e. several increases lasting for some time, clearly show that trees at site 1 have experienced some stand disturbances, most likely selective cutting, whereas such a trend at site 2 suggests that it has experienced fewer disturbances. This is also supported by larger average stem diameter, lower tree height and basal area at site 1 (Table S1).

Both sites showed sufficient growth coherence between the trees, as reflected in Rbar (0.56 vs 0.60 for sites 1 and 2, respectively), glk (0.70 vs 0.68), sgc (0.69 vs 0.67), and the predictive power of their chronologies (EPS value >0.85). The tree growth rate and variability at site 1 were higher than at site 2 (Table 2 and Table S2). All trees displayed highly autocorrelated (Ar1 > 0.70) radial growth, i.e. the effect of the growing season conditions on the ring width was prolonged up to at least two adjacent seasons. In comparison with the raw chronologies, the detrended ones had slightly weaker statistical characteristics, yet they were still reliable (EPS > 0.85) and coherent (Rbar ≥ 0.44, glk = 0.69, and sgc = 0.69 at both sites).

Table 2
Descriptive statistics of the studied datasets for the 1947–2019 period.

Statistics	Site 1		Site 2	
	raw	detrended	raw	detrended
N.trees	20	20	16	16
Rbar	0.56	0.50	0.60	0.44
EPS	0.96	0.95	0.96	0.93
Mean	1.93	0.99	1.28	1.01
sd	0.81	0.25	0.49	0.23
Ar1	0.76	0.04	0.72	−0.02
glk	0.70	0.69	0.68	0.69
sgc	0.69	0.69	0.67	0.69

Ntrees – number of trees, *Rbar* – mean inter-series correlation, *EPS* – expressed population signal, *Mean* – average tree-ring width or ring width index, *sd* – the standard deviation of the ring width or ring width index, *Ar1* – first-order autoregression coefficient, *glk* – Gleichläufigkeit, *sgc* – synchronous growth changes.

3.2. Pointer years

The NW method applied to detrended and AR1-fitted individual Scots pine series produced a different number of pointer years, albeit partially overlapped, than the BSGC method (Fig. 2, Table S3). Site 1, which was heavily exposed to radiation, showed three negative pointer years: a weak one in 1928, and two strong ones in 1979 and 1986, with the latter corresponding to the year of the nuclear accident. No positive pointer years were identified for site 1. In contrast, site 2 had three positive pointer years: a strong one in 1953 and two extreme ones in 1961 and 2004. Only one negative pointer year (2010) occurred at site 2 and was classified as strong. At this site, no pointer year was found to be associated with the 1986 nuclear accident.

The BSGC technique revealed more pointer years at both sites as compared to the NW method. Seven negative and five positive pointer years were detected at site 1 and four negative and eight positive pointer years were established for site 2 (Fig. 2, Supplementary Table S3). For site 1, 1986, the year of the accident, was notable according to both methods. BSGC additionally identified a deflection period that lasted one year at site 1. The time needed to return to growth after the decline in 1986 at site 1, a recovery time sensu Thurm et al. (2016), ranged from 0.6 years to 7.9 years among the trees and on average was 2.6 ± 1.88 years. Both methods do not reveal any negative pointer years at site 1 after 1986.

3.3. Growth-to-climate relationships

The use of a double-moving window technique allowed us to identify the main patterns of the Scots pine growth-to-climate relationship and their changes during the study period of 1947–2019. The patterns of temperature influence on the radial growth at the two studied sites are visually similar (see the first two heatmaps in Fig. 3). In particular, the mean temperature during the dormant period extending between the prior and current growing seasons had a positive effect on RWI. In contrast, the temperature at the beginning of the current season exerted a negative impact on growth. Our analysis shows that the former pattern had a tendency to decline while the latter one strengthened during the 73-year-long study period. The main difference between the sites manifested itself in the positive effect of winter temperature, which was only weak in the middle of the study period at site 2.

The FDHM applied to the correlation distribution in the two subsequent seasons revealed that at site 1, the strongest correlations had a positive sign and appeared between DOYs 213 and 444, i.e. from prior August to current March. The highest values across the negative correlations were related to DOYs 495–533, i.e. current May–June. The linear models fitted to these correlations showed sustained significant changes in both patterns suggesting a decrease in positive correlations and an increase in negative ones (Fig. 4).

The trees at site 2 were more sensitive to high temperatures that occurred between DOYs 509–533, in May–June of the current season, than to the low temperatures during DOYs 263–352, from the end of September to December before the growing season (Fig. 3). The negative correlations displayed a significant upward trend during the studied period (Fig. 4).

Precipitation had a strong positive effect on the growth at site 1 during DOYs 438–521, from mid-March to early June (Fig. 3). The strongest negative correlations over the whole period were relative to the beginning of the previous year. Both patterns showed no significant changes (Fig. 4). At site 2, positive correlations between the trees' radial growth and precipitation in the previous year, DOYs 188–321, July to mid-November, were the most prominent among the identified growth-to-climate relationships. However, they showed a significant trend to decline (Fig. 4). The strongest negative correlations were attributed to DOYs 575–604, in August of the current growing season, with no significant changes during the studied period. The change-point testing displayed no significant abrupt changes in the R-squared values obtained from the growth-to-climate linear models at both sites, suggesting that radiation impact on trees has not substantially altered their climate sensitivity.
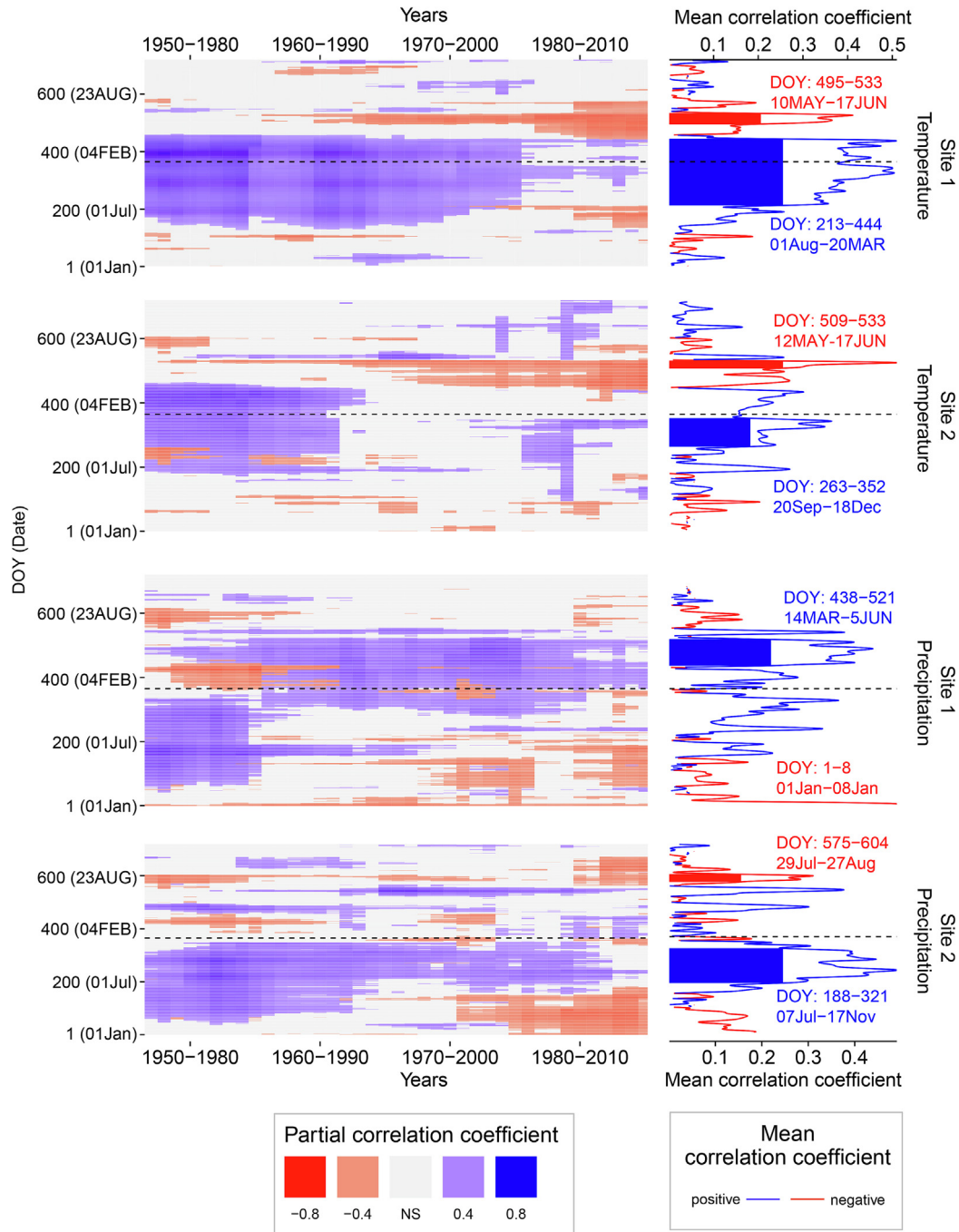
Fig. 3. Moving correlations between the Scots pine ring-width indices (RWI) and climatic variables (mean daily temperature and precipitation sums) in Chornobyl (heatmaps on the left) and mean correlation coefficients for each day in the two adjacent growing seasons (plots on the right). Correlations were calculated for the 31-year intervals moving through the study period 1947–2019 using 14–180-day windows sliding through two growing seasons (DOY – the day of a year from 1 in the prior season to 700 in the current season; the dashed line indicates the beginning of the current year). The area filled under the mean correlation plots shows the full duration at the half-maximum period used to define patterns of the growth-to-climate relationships. The dates indicated in the right column of plots correspond to the periods of the highest positive and negative correlations.

3.4. Resistance to drought and recovery periods

The drought effect on tree growth was the most prominent in 1979 (Fig. 5) when an extreme drought occurred in the early growing season, impacting radial growth at both sites. The tree resistance index dropped deeper at site 1 than at site 2, i.e. 47 % vs 27 %, respectively. The second notable drought effect occurred in 1986 when extreme drought coincided with the Chornobyl nuclear accident in the early season. In line with the pointer year analysis, which defines 1986 as a pointer year only for site 1, the trees' growth resistance was statistically stronger at site 2. The resistance index decreased here by 21 %, while at site 1, it weakened by 41 %. The recovery period was longest at site 1 in 1986 (on average 2.6 years vs 1.7 years at site 1), albeit the difference between the sites was statistically indiscernible. The extreme drought episodes in 1959, 1963, 1992, and 2015 neither coincided with pointer years nor overlapped with deflection periods.
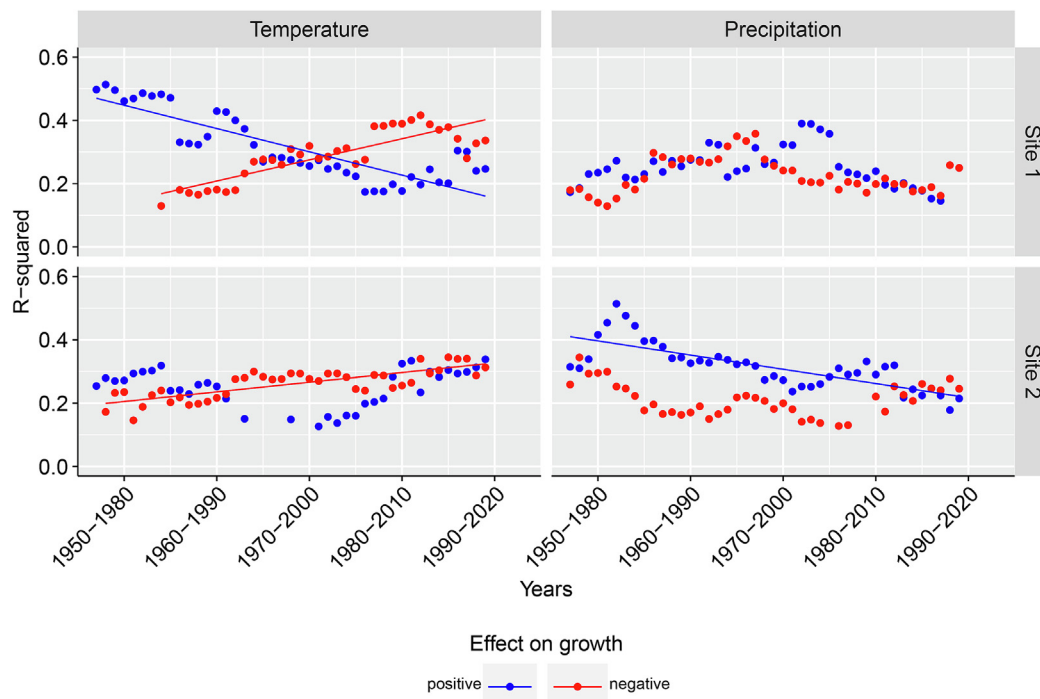
Fig. 4. Temporal changes in the maximal R-squared for each 31-year time interval (see Fig. 3). The lines denote a significant ($p < 0.05$) linear trend. Blue and red colors are used to distinguish the positive and negative effects exerted on the radial growth by climatic variables.

4. Discussion

The published details of the Chornobyl accident indicate a significant spatial dispersal of the radioactive contaminants both in the immediate vicinity and more distantly from CNPP. The initial explosion in the Unit 4 of CNPP deposited fragments of uranium dioxide fuel pellets, or 'fuel particles', mainly westward along a 100-km-long and 1-km-wide strip (Kashparov et al., 2004). The abnormally high temperature of the reactor core prior to its explosion has facilitated the evaporation of volatile fission products (Grishanin, 2010). Coupled with dust particles, radionuclides were lifted by convection, and carried with the atmospheric flow over large distances (Steinhauser et al., 2014). Apart from the short-lived radionuclides, >50 % of ^{137}Cs and around 90 % of ^{90}Sr were released from within the fuel particles (Kashparov et al., 2003; Krouglov et al., 1998). These are relatively large and chemically stable (Kashparov et al., 2004). As the distance travelled by a nuclear fuel particle depends on its weight, the area around CNPP became mostly contaminated by the large-sized and hard-to-dissolve fuel particles.

Our research was performed at two study sites where a natural coniferous forest still exists after the nuclear accident at CNPP in 1986. Both sites are located on the radioactive fallout path stretching to the west from CNPP but at different distances from the explosion epicentre (see Fig. 1). The difference in proximity from CNPP is reflected in the dose rates at the two sites (see Supplementary Fig. S6).

4.1. The effect of radiation on the pine growth near CNPP

The external absorbed radiation dose rate at site 1 on June 11,986 was inferred to be 2.4 mGy h^{-1}, whereas at site 2 its value was much lower, 0.4 mGy h^{-1}. According to the empirical observations (Kozubov et al., 1991) near CNPP in 1986 and in Kyshtym, Eastern Ural, where a less devastating nuclear accident happened in 1957, the highest acute radiation doses were 80–100 Gy and beyond. Note that the doses mentioned from here are the estimates. In Chornobyl on June 1, 1986, these extreme doses corresponded to the dose rates of gamma radiation at 1 m height from the soil surface >4 mGy h^{-1}. Such doses were lethal for the trees

(Kozubov et al., 1991, 1994; Kukarskih et al., 2021). The sub-lethal dose of 30–40 Gy (2–4 mGy h^{-1}) caused necrosis of bud and twigs followed by morphological abnormalities, radial growth reduction or cessation in the consequent few years. The moderate dose that is in the range of 5–6 Gy (0.4–2 mGy h^{-1}) resulted in a partial loss of leaves, morphological abnormalities, and vertical growth suppression. In comparison, a minor dose of <1 Gy (<0.4 mGy h^{-1}) led to vertical growth suppression and some increase in DNA aberration rate. Except for tree mortality, almost the same effects of such doses have been reported from Fukushima forests (Yoschenko et al., 2018). This suggests that site 1 received a sub-lethal dose in 1986 (see Table 1, Supplementary Fig. S6) while site 2 was obviously exposed to a moderate radiation dose.

In the year of the accident, 1986, the growth was impacted at site 1, but not at site 2 (see Fig. 2). The outcome of the radiation exposure in Chornobyl's forests was mediated by the distribution of the initial dose between leaves, meristematic cells, and stem cambium. The current consensus on the cause of the decline of pine growth in the aftermath of the Chornobyl accident is the loss of foliage and damage of buds that shrunk the stock of carbohydrates and the accessibility of assimilates (Musaev, 1995; Schmitt et al., 2000; Tulik and Rusin, 2005). In coniferous forests in the nearest vicinity of CNPP, crowns were the parts of trees that faced the radioactive fallout first and consequently got exposed to the highest level of radiation from the short-lived radionuclides. This led to a loss of leaves and meristem damage followed by growth reduction in the next few years after the accident. Where leaves were still functioning, at least partly, the direct radiation effect on the xylogenesis induced a growth reduction in 1986 (Musaev, 1995). This effect was observed at site 1, where the RWI was reduced in 1986 (see Fig. 2). On the other hand, cambium cells seem to have received moderate doses of radiation in the first few days after the accident in comparison with the leaves. At site 2, this would imply that in the season of 1986, the radial growth continued, as long as non-structural carbohydrates were made available by the functioning of remaining leaves. In the next few years, the depleted stock of carbohydrates and foliage loss resulted in a more pronounced radial growth reduction (Holiaka et al., 2020; Musaev, 1995; Schmitt et al., 2000) comparable to that observed in trees at site 1.
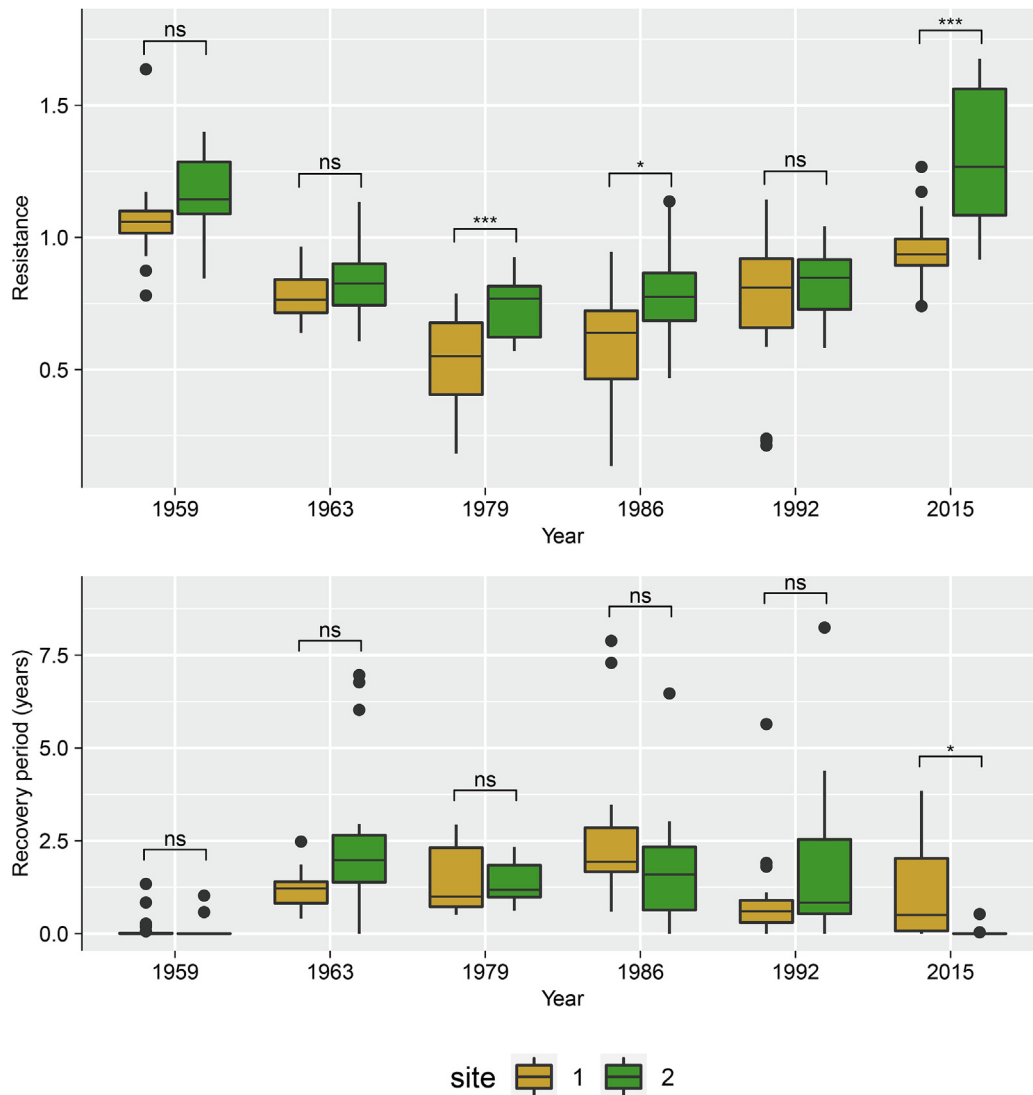
Fig. 5. Scots pine growth resistance (above) in the years of extreme droughts. The recovery period (below) indicates the period during which the growth has reached the growth level of the last three years before the extreme drought event. In the box plots, the lower and upper hinges denote the 25th and 75th percentiles, the horizontal lines denote the median values, the whiskers extend from the hinges to the largest and smallest values within the 1.5 inter-quartile range, and the points indicate outliers. Horizontal square brackets denote *t*-test for the site's growth indices; ns – non-significant, $* - p \leq 0.05$, $*** - p \leq 0.001$.

The season in which the initial contamination took place can vastly determine the long-lasting consequences due to the acute radiation exerted by the decaying short-lived radionuclides. The Kyshtym nuclear accident in September 1957 occurred when the growing season had almost ended; it resulted in the delayed growth response in the survived trees by 2–5 years (Kukarskih et al., 2021). The timing of the CNPP explosion overlapped with the early growing season of Scots pine resulted in the aggravated radiation impact, as cells are most vulnerable to the ionizing factors during their proliferation. Where the high dose of radiation did not kill the trees, it caused morphological and histological abnormalities after 1986 (Arhipov et al., 1994; Tulik, 2001). Note that the Fukushima Daiichi nuclear accident in March 2011 also occurred in the early growing season. Despite striking similarities, there is no information on the radial growth changes yet available from Japan. Should such reports appear in the future, it would present a unique opportunity to corroborate the Chornobyl study.

4.2. Pointer years, growth resistance and recovery

We used the pointer year analysis and calculated the indices of growth resistance and recovery to test whether radiation caused growth reduction in pines at both study sites. Our research also inter-compared the years of depressed growth caused by factors other than radiation. The growth and functioning of conifers are largely dependent on the prior season's growing conditions and the amount of accumulated non-structural carbohydrates. The significance of growth in the prior season is reflected in the high values of the autoregressive-model coefficients for chronologies from both studied sites (see Table 1). To minimize the prior-year effect, we performed the pointer year analysis of the prewhitened growth series, i.e. detrended by the autoregressive (t-1) model. This technique revealed a greater reduction of RWI at site 1 than at site 2 in 1986 (see Fig. 5). Hence, the difference in the radiation effect between the sites that received sub-lethal and moderate doses was 14 %, albeit the radiation impact on RWI at site 2 was non-significant according to the pointer year analysis. Other pointer years than 1986 were reported in different regions within the Scots pine range, e.g. in Ukraine (Koval, 2021), Poland (Malik et al., 2012), Lithuania (Edvardsson et al., 2015), and Latvia (Matisons et al., 2019). The periods of tree growth depression did not always coincide across the species range that likely reflects the varying spatial patterns of drought or other growth-limiting factors. Indeed, growth depressions could be triggered or enhanced not only by the global weather events but also by the variation

of environmental factors on a regional or local scale (Buras et al., 2022). The same phenomenon could partly explain the discrepancy in pointer years between our two studied sites (see Fig. 2).

The most prominent drought effect in a pointer year shared by both sites occurred in 1979, when drought extended over a vast area from the Baltic region to the Caucasus in the early growing season (Beguería et al., 2010; Vicente-Serrano et al., 2010). In May 1986, an extreme drought matched the negative pointer year only at site 1 (see Fig. 2). That could be an effect of the high dose radiation exposure, but growth resistance at site 1 was always lower than at site 2 for all studied drought years, before and after the Chornobyl accident (see Fig. 5). The radiation effect on tree growth observed at site 1 might have overlapped with the drought response and was partially masked out by the latter. Thus, as suggested earlier, the growth reduction could not fully indicate radioactive contamination as the only acting factor (Musaev, 1995). Therefore, we can speculate that a combined effect of drought and a high dose of ionizing radiation caused the decrease in growth at site 1. More, site 1 has not been marked by any negative pointer year after the accident, even during an extreme drought in 1992 and 2015, suggesting improved resistance in trees that survived after the accidence.

4.3. The improbable effect of tapping

In the 1979–1985 period, resin tapping was performed at site 1, which could impede the establishment of the radiation effect on growth. Indeed, previous works have shown a negative impact of tapping on pine growth (Chen et al., 2015; Papadopoulos, 2013). The tapping, however, has been reported to alter radial growth only along the damaged portion of the stem and stimulate the growth of its intact part (van der Maaten et al., 2017; Zaluma et al., 2022). No effect on yearly growth changes and response to climate variability has been reported for maritime pine (Génova et al., 2014). In our investigation, at both studied sites, no significant negative pointer years were found between 1980 and 1985, suggesting the absence or negligible consequences of the tapping at site 1 (see Fig. 2 and Fig. 5).

4.4. Growth-to-climate relationships

Apart from the increased drought response at site 1, we found no sign of radiation influence on the climatic growth sensitivity, in line with the research from the Kyshtym nuclear accident area in the Ural (Kukarskih et al., 2021). Meanwhile, our results provide an insight into the climatic factors limiting the Scots pine growth.

Throughout the Scots pine natural distribution range, including the southernmost populations, the main or at least one of the most significant growth-limiting factors was the winter cold. In our investigation, a positive correlation between growth and temperature was found for a wide time interval from the end of the prior growing season to March of the current season (see Fig. 4); this effect was weaker at the beginning and end of the noted period but remained statistically significant from December to January. A similar winter temperature effect has been reported for the populations located not only at the northern edge of the species range (Elferts, 2007; Helama et al., 2014; Hordo et al., 2009; Matisons et al., 2019) but also in its eastern part (de Grandpré et al., 2011; Shestakova et al., 2017; Tabakova et al., 2020), centre (Bauwe et al., 2013; Koprowski et al., 2012; Waszak et al., 2021), and the southern margin (Bozkurt et al., 2021; Michelot et al., 2012; Özel et al., 2021; Panayotov et al., 2013; Sánchez-Salguero et al., 2015). Mountain populations in Spain were shown to suffer also from the combined effect of frost and solar radiation heating shoots and foliage during winter, although this effect depended on the local conditions such as altitude, slope exposition, and tree position in the stand (Camarero et al., 2015).

A warm winter can facilitate tree growth in various ways, enhancing the carbon stock. Indeed, higher winter temperatures expand the growing season by prolonging the functional activity of the plant: during mild winter days, the increase in water uptake by the roots (Mellander et al., 2004) or

the use of water storage from the stem (Troeng and Linder, 1982) can enable the stomatal opening, compensating for the non-stomatal-transpiration water loss (Peguero-Pina et al., 2011); it also allows the reactivation of the photosynthetic machinery earlier in the season (Chang et al., 2021). Thus, a winter temperature increase can reduce the depletion of carbohydrates or even result in positive carbon gain in overwintering trees. More resources can then be made available for the upcoming xylogenesis. These processes explain the positive effect of winter temperature on growth observed at both sites. However, the recurring freeze–thaw events can cause xylem embolism and a long-term decrease in the hydraulic functions of Scots pine (Peguero-Pina et al., 2011). The more a tree is exposed to solar radiation, the more vulnerable it becomes to cavitation (Camarero et al., 2015). In addition, the light captured by needles during frost events can produce radicals damaging the assimilation apparatus. In Scots pine, this is normally prevented by the double system of photon's energy dissipation and cyclic electron transport (Yang et al., 2020). However, higher winter temperatures could impose physiological or anatomical damage following a too early reactivation of the needle photochemistry (Chang et al., 2021). While a warmer winter still promotes the forthcoming xylogenesis, the observed reduction of this effect (see Fig. 3, Fig. 4) could be due to the interplay of the positive and negative mechanisms mentioned above. This highlights the enhanced potential risks of winter climate warming on tree growth in the future.

Summer temperature and precipitation relationships with radial growth established in our research are consistent with the earlier studies on Scots pine (Misi et al., 2019), particularly at the southernmost limit of its range or drought-prone sites. The negative impact of summer temperature on tree growth is becoming more prominent at both Chornobyl's sites (see Fig. 3), obviously due to increased evapotranspiration and reduced soil water availability in summer. However, the highest positive correlation between growth and precipitation was attributed to March–June at site 1 and July–November of the previous season at site 2, emphasizing the importance of these two periods for the radial growth of Scots pine. The low water availability in the previous growing season affects primordia initiation of the shoot apical meristems that develop into leaves, influencing the assimilation rate and consequently the radial growth in the next season (Lanner, 2017). On the contrary, radial growth directly responds to changes in the soil-water availability immediately in the current season (Feichtinger et al., 2014).

5. Conclusions

This work provides a valuable insight into the Scots pine's response to the radioactive exposure in the aftermath of the Chornobyl nuclear accident. We found that the acute sub-lethal radiation dose had a dual effect on the trees: it decreased their radial growth and jeopardized the physiological ability of the trees to respond to the extreme spring and summer drought in the year of the accident. The use of dendrochronological approaches allowed us to assess the potentially lasting effect of radiation that has not altered the trees' growth-to-climate relationships. The established patterns share many common features with other populations of Scots pine throughout its natural distribution range. The double-moving-window analysis provided a snapshot of the current changes of Scots pine climatic sensitivity, contributing to understanding the species response to its future evolving environment. Our results, however, point to a non-specific growth response to radiation and highlight the need for reliable indicators of radioactive contamination, particularly at the level of wood anatomy. This would foster our capacity to predict the overarching consequences of the radioactive contamination of forest ecosystems.

CRediT authorship contribution statement

MN: Conceptualisation, Formal analysis, Writing – original draft, Visualization; YP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, and Editing; DH: Funding acquisition, Data curation, Formal analysis, Investigation,

Methodology, Visualization, Writing – original draft, and Editing; MK: Conceptualization, Funding Acquisition, Writing – original draft, and Editing; RP: Conceptualization, Writing original draft, and Editing; AJP: Funding Acquisition, Writing original draft, and Editing; MR: Conceptualization, Writing original draft, and Editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163132.

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