

**Mathieu Magnier\***, **Jernej Jevsenak**, **Radosław Puchałka**,  
**Marcin Klisz\***

## The effect of soil conditions on climate-growth correlations at two *Pinus nigra* sites

Received: 30 August 2024; Accepted: 17 February 2025

**Abstract:** Climate change is modifying precipitation distribution and increasing drought events frequency, leading to decline in many stands. *Pinus nigra* was introduced to Poland in the 19th century as a measure to mitigate negative effects of soil pollution. This species is also known to be well adapted to drought conditions. However, its response to drought on different soil conditions remains unclear. The aim is to investigate the growth relation of *P. nigra* to drought and its resilience under the same climatic conditions but different soil types (fertile and poor soils) in central Poland. Two mature stands of *P. nigra* were selected, one on fertile soil and one on poor soil. Tree-ring data were collected and analysed to assess growth patterns and climate sensitivity. Resilience indices were calculated for seven common drought years, i.e. 1940, 1954, 1963, 1976, 2003, 2006 and 2015, to compare the impact of soil conditions on drought response. The study found similar climate-growth correlations for both soil types, with March temperatures and summer precipitation positively affecting growth, highlighting the significant influence of local climatic conditions on growth. However, resilience to drought varied between poor and fertile soil, with opposite trends observed in the drought year 1976 (characterized by dry June, wet July and dry August) and in the drought years 1963 and 2006 (characterized by wet June and dry July and August). With a higher resilience for the trees on poor soil in 1976 and a higher resilience on fertile soil in 1963 and 2006. Moreover, differences were not consistently observed: only 3 of the 7 years were significantly different. The study indicates that soil conditions partially influence the resilience of *P. nigra* to drought, but the relationship seems drought episode-dependent. Relationships between soil fertility and climate-growth dependencies are complex, and to draw more robust conclusions, further studies are needed, incorporating additional soil types.

**Keywords:** resilience, drought, water capacity, fertility, Central Poland

**Addresses:** M. Magnier, AgroParisTech Nancy, 14 rue Girardet, 54042 Nancy, France, Institut Agro Dijon, 26 Bd Dr Petitjean, 21079 Dijon, France;  <https://orcid.org/0009-0005-7079-2298>, e-mail: [mathieu.magnier@agroparistech.fr](mailto:mathieu.magnier@agroparistech.fr)

J. Jevšenak, Department for Forest and Landscape Planning and Monitoring, Slovenian Forestry Institute, Večna pot 2, 1000 Ljubljana, Slovenia;  <https://orcid.org/0000-0002-4811-3624>, e-mail: [jernej.jevsenak@gozdis.si](mailto:jernej.jevsenak@gozdis.si);

R. Puchałka, Department of Ecology and Biogeography, Faculty of Biological and Veterinary Sciences, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland, Centre for Climate Change Research, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland;  <https://orcid.org/0000-0002-4764-0705>, [puchalka@umk.pl](mailto:puchalka@umk.pl);

M. Klisz, Dendrolab IBL, Department of Silviculture and Forest Tree Genetics, Forest Research Institute, Braci Leśnej 3, Sękocin Stary, 05-090 Raszyn, Poland;  <https://orcid.org/0000-0001-9486-6988>, e-mail: [m.klisz@ibles.waw.pl](mailto:m.klisz@ibles.waw.pl)

\*corresponding authors

## Introduction

In the context of climate change, an increase in temperature is likely to lead to a change in the distribution of annual precipitation and an increase in the frequency of drought events (Intergovernmental Panel On Climate Change (IPCC), 2023). Climate change increases the mortality in many forest stands around the world (Camarero et al., 2015) due to increasing evaporative demand and weather disturbances. This does not spare Scots pine *Pinus sylvestris* L. (Camarero et al., 2015), a widespread coniferous species in Central Europe, which is sensitive to the cumulative drought effect and thus shows a declining growth pattern. To mitigate the adverse effects of climate change on coniferous forests, alternative phylogenetically closely related species may be considered. Black pine (*Pinus nigra* JF.Arnold), a coniferous species native to Southern Europe, was introduced in Central Europe in the 19th century. The introduction of this species in Poland was initially aimed at replacing the native *P. sylvestris* with a species better adapted to growth under conditions of high industrial and urban pollution (e.g. Latocha & Hawrys, 1976). It has now been recognized as a species better adapted to climate warming (Vacek et al., 2023).

*P. nigra* appears to be tolerant to moderate drought. The persistent weak negative correlation between growth and negative Standardized Precipitation Evapotranspiration Index (SPEI), which persists over time despite more frequent and severe droughts, suggests that *P. nigra* remains capable of adapting to a changing climate and performs well under favourable growing conditions (Klisz et al., 2022). Moreover, this species seems to respond relatively well to the temperate climate, with an extended period of growth in response to high temperatures. However, it seems to be sensitive to severe summer drought ( $\text{SPEI} < -2$ ), with *P. nigra* showing a negative growth correlation (Klisz et al., 2022). In addition, *P. nigra* copes better than other non-native pine species with climatic anomalies (e.g. *Pinus strobus* L.; Klisz et al., 2022) or comparable (e.g. *Pinus rigida* Mill.; Klisz et al., 2023). Indeed, the positive correlation between spring and summer rainfall and growth has increased in recent years for *P. nigra*, whereas it seems to be weakening for other non-native species (Klisz et al., 2022). *P. nigra* also exhibits less frequent intra annual density fluctuations in comparison to other alien species (e.g. *P. strobus* or *Pseudotsuga menziesii* (Mirb.) Franco), indicating a lower sensitivity to short water deficit (Klisz et al., 2022). When Klisz et al. (2022) were comparing the drought susceptibility of native and introduced pines, local conditions (i.e. soil and climate) seemed to predominate over species specific growth response. This led to the similar growth response to the end-of-winter and spring temperatures

for *P. nigra* and *P. sylvestris*. The same study showed that resilience and recovery indices were similar among different pine species under the same site conditions, suggesting that climate sensitivity is largely related to the site conditions rather than the species. One of the most important site characteristics are soil properties. Durand et al. (2020) reported positive effects of soil nutrients on tree growth. Tree growth has also been positively associated with the soil's water storage capacity, which is influenced by factors such as soil granulometry and chemical properties (Bolotov et al., 2019). For example, organic matter can enhance a soil's ability to retain water. The results on water-nutrient interaction are, however, inconsistent, with some results showing more efficient use of water with fertile soil and, on the other hand, greater sensitivity of trees to severe drought on fertile soil (Gessler et al., 2017). Indeed, according to Gessler et al. (2017), although high fertility increases the risk of hydraulic failure, and the risk of biotic attack, high fertility balances these negative effects by increasing water use efficiency. However, the extent to which soil conditions can alter the sensitivity of *P. nigra* to atmospheric drought is not sufficiently understood. Therefore, we aimed to investigate the growth reaction to drought of *P. nigra* under the same climatic conditions, but different soil types. A fertile soil, which is characterized by a predominant grain size of loose sands and weak clayey sands, but with a bedding of fine-grained materials (clays or silt) increases the abundance of nutrients and water retention. On the other hand, poor soils with high sand content, acidity, and low levels of alkaline cations such as potassium (Kabała et al., 2019) have lower soil trophic indices (SIG) compared to fertile soils. These differences in soil quality create distinct growth conditions for *P. nigra*, primarily driven by variations in water availability and nutrient status. We hypothesize that, since poor soils have fewer resources available to buffer against stress, (i) trees from a less fertile site will exhibit stronger climate-growth effects and (ii) lower drought tolerance.

## Material and methods

### Species selection and study site

The study was performed in Central-East Poland (52.09–52.11°N, 20.86–20.88°E, 167 m a.s.l.), where the State Forests National Holding is conducting experiments on the introduction of non-native coniferous species (Fig. 1). In our study, we focus on *P. nigra*, which is known to be climate-sensitive and has a broad distribution range.

Two mature stands of *P. nigra* (PINI), with an age of 114 years (1911–2024) and 110 years (1911–2020)

were selected for this study (Fig. 1, Table 1; FERTILE and POOR, respectively). FERTILE site is characterized by a mean height of 27 m, a density of 700 trees/ha and a mean diameter at breast height (DBH) of 44.62 cm. POOR site is characterized by a mean height of 19 m, a density of 800 trees/ha and a mean DBH of 36.20 cm. The study area is characterized by a cold climate, without a dry season and warm summer. In 1920–2022, the annual mean temperature was 8.3 °C, while mean annual precipitation was 506 mm (Fig. 1) (E-OBS 0.1° × 0.1° gridded climate data, version 28.0e: Cornes et al., 2018). These climate conditions are characterized as a humid continental climate. The forest type was different for the two stands, mesic coniferous for POOR and mesic mixed broadleaved for FERTILE. Moreover, POOR

and FERTILE are characterized by two different soil types, respectively an albic (poor) brunic arenosol and a cambic (fertile) brunic arenosol. According to Panagos et al. (2022), our soils have a water capacity of 95 mm and a depth between 80 and 120 cm. However, the resolution of this database does not allow for differentiation between study sites. Therefore, we used the data from Kabala et al. (2019), which provides more detailed information on soil characteristics. They clearly show a difference in water storage and fertility. FERTILE soil, predominantly composed of loose sands and weak clayey sands, contains a bedding layer of fine-grained material (clay or silt), which enhances nutrient richness and water retention. In contrast, poor soil, primarily composed of sands, is acidic and deficient in alkaline cations.

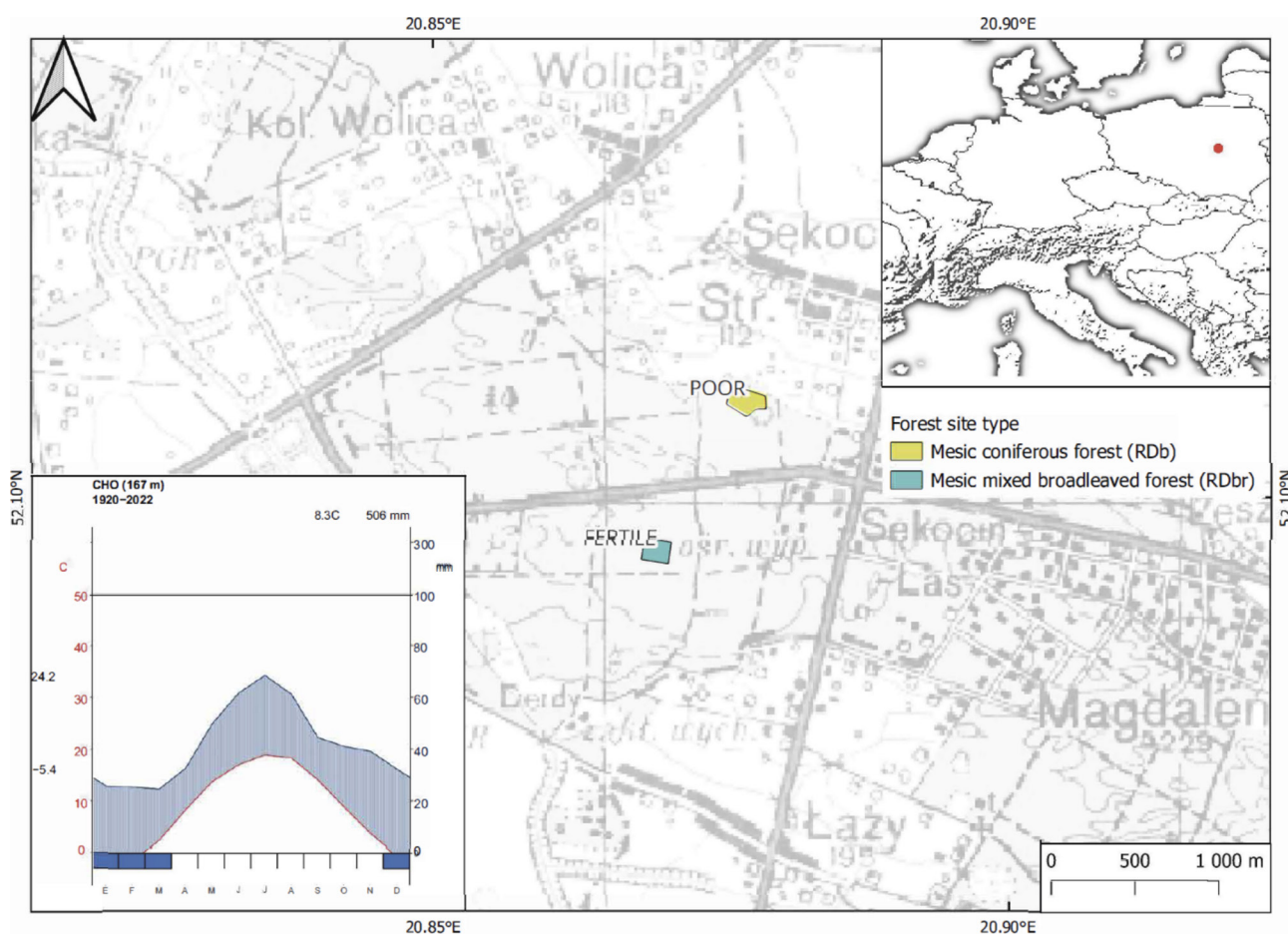


Fig. 1. Location of the study sites (data source: State Forests Information System). Panel in lower left corner: climatic diagram for the area (data source: E-OBS, version 28.0e), RDb and RDbr stand for albic (POOR) and cambic (FERTILE) brunic arenosols, respectively

Table 1. Characteristics of tree-ring chronologies: mean diameter at breast height (DBH), number of trees considered in the final chronologies (NTree), Gleichläufigkeit (GLK), mean growth rate (GR), first order autocorrelation (AR1), mean correlation between trees (RBAR), expressed population signal (EPS), signal-to-noise ratio (SNR) and subsample signal strength (SSS)

| Sites ID | Period considered | DBH (cm) | NTree | GLK  | GR (mm) | AR1  | RBAR | EPS  | SNR   | SSS  |
|----------|-------------------|----------|-------|------|---------|------|------|------|-------|------|
| POOR     | 1911–2020         | 36.20    | 20    | 0.69 | 1.27    | 0.74 | 0.42 | 0.93 | 14.24 | 0.99 |
| FERTILE  | 1911–2024         | 44.62    | 8     | 0.75 | 1.52    | 0.68 | 0.49 | 0.89 | 7.71  | 0.99 |

## Radial growth data

For each stand, 8 (for the fertile soil) to 20 (for the poor soil) sample trees, dominant or co-dominant, healthy, with no visible damage and preferably distant from the forest edge, were selected. Two increment cores, from perpendicular, random directions (the ground being flat), were extracted from each tree at breast height (1.3 m) with 5.15-mm-diameter Pressler borers. POOR and FERTILE have been sampled in 2021 and 2024, respectively. Then each core was air dried and mounted on a wooden holder and sanded progressively using sandpaper (grain size of 80, 240 and 1000). These cores were scanned at 3200 dpi using an Epson expression 10000 XL. Ring-widths were measured with an accuracy of 0.01 mm and cross-dated using CooRecorder and CDendro (Cybis Elektronik & Data AB, <https://www.cybis.se/>). Cross-dating accuracy was assessed using CDendro (Cybis Elektronik & Data AB) and `corr.rwl.seg()` function of `dplR`. The correctness of the determination of the boundaries between the annual rings was verified using a LEICA A60 binocular at  $\times 30$  magnification.

## Dendrochronological analysis

An individual annually resolved tree-ring series was created for each tree by averaging the two growth series. We successfully cross-dated all individual tree-ring series. Tree-ring series were detrended using a cubic smoothing spline approach, with a cut-off of 50% of the frequency, at a wavelength of 30 years, with `detrend()` function from the `dplR` package (Bunn, 2010). To remove the remaining temporal autocorrelation and highlight year to year growth variability, the series were prewhitened using a first order autoregressive model. We used a biweight robust mean to create the final residual chronologies with the `chron()` function from the `dplR` package (Bunn 2010). Ring width index (RWI) were calculated by dividing the observed raw value of the ring width (RW) by the value of the fitted cubic spline. To assess the quality of the established tree-ring chronologies, we calculated the following indicators (Table 1): the Gleichläufigkeit (GLK) (Buras & Wilmking, 2015), mean growth rate (GR), first order autocorrelation (AR1), which estimates the interdependence of successive rings, mean correlation among trees (RBAR), expressed population signal (EPS), signal-to-noise ratio (SNR) and subsample signal strength (SSS).

## Climate sensitivity

We adopted daily precipitation and temperature data from E-OBS  $0.1^\circ \times 0.1^\circ$  gridded climate data

from 1920 to 2023, version 28.0e (Cornes et al., 2018). To determine the statistical relations between climatic conditions and the growth of *P. nigra* on different soils, we used the `daily_response()` function of the `dendroTools` package (Jevšenak & Levanič, 2018), for the period 1921–2023 and 1921–2019 for the fertile and poor sites, respectively. This function uses a moving time window (in our case, 21 to 270 days), shorter windows help detect immediate or short-term responses of tree growth to climatic variations, such as temperature or precipitation and longer windows are designed to capture cumulative or lagged effects. To calculate the Pearson correlation coefficients between aggregated daily climatic data and RWI. We used climate data for all seasons, starting in the previous January and ending in the current November (Klisz et al., 2022).

## Resilience indices

To understand the growth response of *P. nigra* stands growing under different soil fertility conditions to extreme drought years, we used resilience indices (Lloret et al., 2011). First, we determined common negative pointer years between the two series using bias-adjusted standardized growth change method (BSGC) using the function `bsgc()` from the `dendrolAB` package (Buras et al., 2022). A year is classified as a negative pointer if  $p(\text{BSGC}) < 0.025$ , with:

$$p(\text{BSGC}) = \frac{p(\text{GSGC})^{0.93} \times p(\text{SGC})^{0.53}}{p(\text{GSGC})^{0.93} \times p(\text{SGC})^{0.53} + (1 - p(\text{GSGC}))^{0.93} \times (1 - p(\text{SGC}))^{0.53}}$$

where GSGC is the globally standardized growth change, and SGC is the standardized growth change (Buras et al., 2022).

We selected three common negative pointer years, i.e. 1940, 1976 and 2006, all of which had a SPEI3 (June–August) below 0 (Appendix 2). Additionally, we included 4 negative pointer years specific to either FERTILE or POOR soil conditions, i.e. 1954, 1963, 2003 and 2015, all of which had a SPEI3 (June–August) below 0.

Next, four different resilience indices were calculated to evaluate how the two *P. nigra* populations cope with drought conditions: resistance, recovery, resilience and relative resilience (Van Der Maaten-Theunissen et al., 2021). To calculate these indices, we used the RWI, with PreDr (pre-drought) as the average RW for the 4 years preceding the event, PostDr (post-drought) as the average RWI for the 4 years following the event and Dr (drought) as the RWI of the year itself.

We also tested different time frames for resilience calculations. However, using a shorter period did not allow sufficient time for trees to recover normal

growth, while a longer period resulted in overlaps between multiple drought years, blurring event-specific response. Finally, a four-year period was selected.

Recovery ( $R_c$ ) is defined as the ability to recover after the growth reduction during the disturbance:

$$R_c = \text{PostDr} / \text{Dr}$$

Resistance ( $R_t$ ) is defined as reversal of the reduction in growth during disturbance:

$$R_t = \text{Dr} / \text{PreDr}$$

Resilience ( $R_s$ ) is defined as the capacity to reach pre-disturbance performance levels:

$$R_s = \text{PostDr} / \text{PreDr}$$

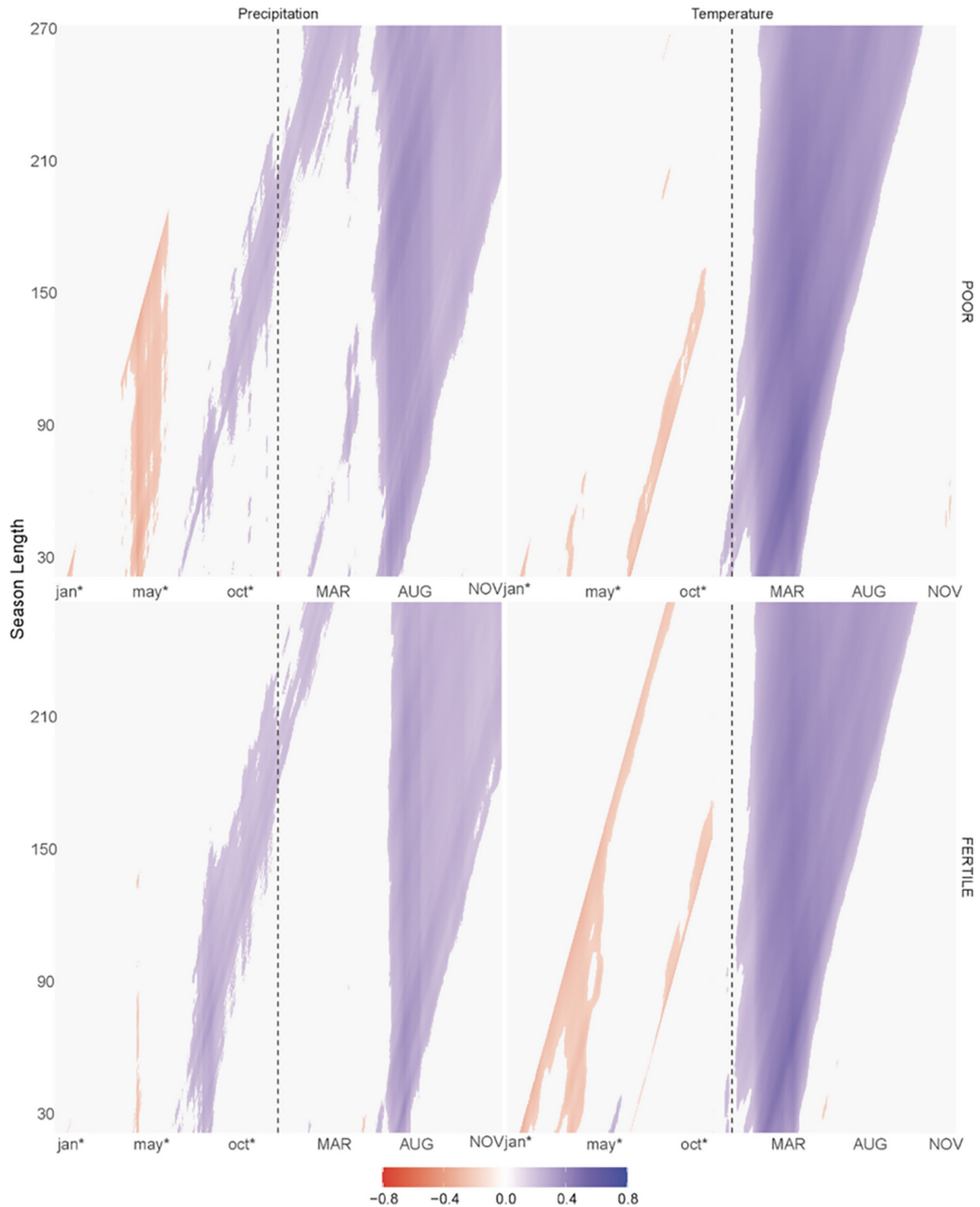


Fig. 2. Significant Pearson correlations ( $p$ -value < 0.05) between tree-ring width index and daily climatic data, precipitation on the left and temperature on the right, for the two sites, POOR at the top and FERTILE at the bottom

Relative resilience (RRs) is defined as the resilience weighted by the growth reduction experienced during disturbance:

$$RRs = ((PostDr - Dr) / (PreDr - Dr)) / (1 - (Dr / PreDr))$$

In this study, we calculated these indices using the function *res.comp()* of the PointRes R package (Van Der Maaten-Theunissen et al., 2021). The indices were then compared for each year between the sites using a Kruskal-Wallis test. All analyses were performed using R-4.4.0 (R Core Team, 2024).

## Results

### Site-specific chronologies

The different indicators calculated for our two chronologies (Table 1) are mainly similar for the two sites, the GLK is above 0.65 for the two sites. EPS is over 0.85 for the two sites, even if the fertile site is only composed of 8 trees, AR1 and RBAR are relatively similar between the two sites. However, the SNR is much lower for the fertile site, which can be the sign of a chronology of lower quality than the poor site due to the low replication (Table 1). The SSS exceeded the threshold of 0.85 at the year 1914

(Appendix 1), which was also used to truncate both chronologies.

### Climate-growth relationships

The Pearson correlations between RWI and climatic parameters were generally similar between the two study sites, but poor site showed slightly more extreme correlations (maximum of 0.52 for poor site vs 0.50 for fertile site and a minimum of  $-0.37$  vs  $-0.31$  respectively for the temperature). The most significant positive correlations with RWI were observed for March temperature for both sites (Fig. 2). A positive correlation was also observed with the precipitation of the current August and during the previous summer for the two sites (Fig. 2). However, a negative Pearson correlation with precipitation in the previous April/May was mainly visible for the site on poor soil and not for the fertile site.

### Resilience indices

Seven negative pointer years were studied, i.e. 1940, 1954, 1963, 1976, 2003, 2006 and 2015. They are characterized by different seasonality of drought events (Appendix 3). For 1976 and 2015, the drought was characterized by an extreme water deficit in June and August (SPEI around  $-2$ ) but with a break in July (SPEI around 0.5) (Appendix 3) and 1954 was

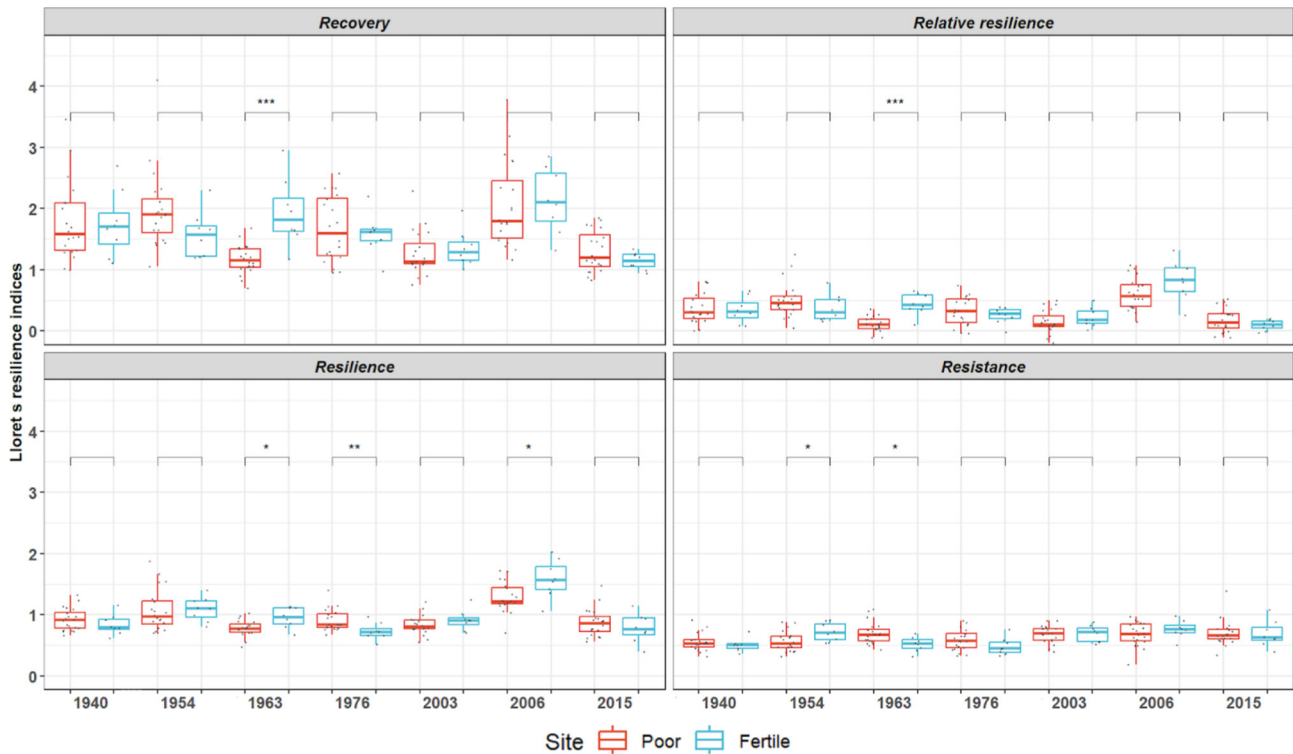


Fig. 3. Lloret's indices for seven negative pointer years 1940, 1954, 1963, 1976, 2003, 2006 and 2015: \* p-value < 0.05, \*\* p-value < 0.01, \*\*\* p-value < 0.001, in red POOR and in blue FERTILE, calculated indices are recovery, relative resilience, resilience, resistance

characterized by a positive water balance in June and July but negative in August (Appendix 3). The drought in 1963, 2003 and 2006 was characterized by a positive water balance in June (SPEI around 2) but followed with two successive months of water deficit (SPEI around  $-2$ ) (Appendix 3). The year 1940 is a unique case, as it experienced exclusively negative SPEI values in June, July and August, with approximate values of  $-1$ ,  $-2$  and  $-1$ , respectively.

The differences were significant for the resilience for 1963, 1976 and 2006. Trees on fertile site were more resilient in 1963 and 2006, and trees on poor site were more resilient in 1976 (Fig. 3).

Moreover, in 1954 the resistance was higher on fertile soil, whereas in 1963 it was higher on poor soil (Fig. 3). In both cases, relative resilience and recovery were greater on fertile soil, but only in 1963 were all four indices significantly different, making it the only year with a distinct divergence in resilience metrics.

## Discussion

We found that the resilience of *P. nigra* during the drought 1963, 1976 and 2006 differed between the two soil conditions, which can be partly explained by our hypothesis on the impact of soil fertility on drought tolerance (ii). However, the trend between these three years is opposite, emphasizing a complex relationship between growth response and soil fertility under drought conditions. In 1976, the drought was characterized by a large water deficit in June and August, with an interruption in July (Appendix 3), and this year we observed a higher resilience for the stand on poor soil (Fig. 3). The opposite trend was observed during the droughts of 1963 and 2006, where a higher resilience for the stand on fertile soil was observed (Fig. 3). These years were characterized by a positive water balance in June, yet followed by two successive months of moderate water deficit (Appendix 3).

Hence, based on our results, we cannot conclusively determine whether poor or fertile soils are more favourable for *P. nigra* growth in terms of resilience to drought conditions. The relationship between soil conditions and resilience appears to be complex, as evidenced by the fact that only three of the seven years studied showed significant differences in resilience.

## Climate growth relationships

We observed a similar sensitivity to climate on fertile and poor soils, indicating an important role of local climatic conditions on growth (Izmir et al., 2024). As observed in previous studies (e.g. Klisz et

al., 2023), spring temperatures and summer rainfall have a predominant influence on secondary growth. However, when we look at the details, trees on poor soil show a negative correlation with spring rainfall from the previous year (Fig. 2). This is probably linked to the soil's inability to store water, coupled with unevenly distributed rainfall throughout the year, leading to a loss of this water, which results in growth decline (Versace et al., 2022). Water reserves from previous years are essential for the growth of *P. nigra* (Cedro, 2006). In addition, the correlation with summer precipitation is slightly more enhanced on poor soils. This can probably be explained by the soil's low capacity to store water and the dependence of trees on rainfall during the growing season and drought reducing secondary growth (Cedro, 2006; Şahan et al., 2024). This may lead to greater sensitivity to several consecutive months of drought in summer.

## Response to drought events of 1963, 1976 and 2006

The greater resilience of the stand on fertile soil in 1963 and 2006 (Fig. 3) can be attributed to the June precipitation, which replenished the soil's water reserves (Appendix 3). This enabled the stand to better withstand drought conditions, whereas poor soil does not have the capacity to store as much water (Kabała et al., 2019). During the drought in the summer of 1976, the poor soil failed to retain water, as evidenced by the significant water deficit observed in June, a brief reprieve in July, and another substantial deficit in August (Appendix 3).

The resilience in 1976 was lower for both sites compared to 1963 and 2006.

This can be partly explained by the fact that water is a limiting factor at both sites. The poor stand, having fewer nutrients available (Kabała et al., 2019), grows less quickly than the stand on fertile soil, limiting water loss during prolonged water stress. Indeed, Gessler et al. (2017), showed that, in the event of short, severe stress (e.g. year 1976), plants on poor soils coped better. This is most likely due to the fact they are growing less and have a smaller needle area, whereas those on fertile soils are at greater risk of embolism due to the imbalance between growth and water availability. But the opposite is the case when prolonged stress occurs (e.g. 1963 and 2006; Appendix 3). Trees on poor soil may experience challenges such as reduced carbon availability and potentially face carbon starvation under stress. Whereas trees on fertile soil generally benefit from improved nutrient transport efficiency, which can support better physiological functioning (Gessler et al., 2017),

allowing greater resilience afterwards thanks to the carbon stock.

However, it should be noted that only 3 of the 7 years studied showed significant differences, even though some have similar drought patterns. For example, the year 2003, which had a similar drought seasonality to 1963 and 2006, showed no significant difference in resilience between the two sites. This suggests that additional factors influence resilience, highlighting complex interactions. These factors could, for example, be the climatic conditions of the preceding and following years, with black pine depending on rainfall in the previous year (Cedro, 2006), as previously discussed.

## Conclusion

Our study highlights that local climatic conditions have a significant influence on *P. nigra* growth. However, the trees' responses to these conditions differ depending on their underlying soil fertility levels. To gain a deeper understanding of this complex relationship, further research is needed across multiple soil types and over longer periods, including several years with drought. For future research, it would be useful to investigate a wider range of soils, as our study only focuses on two sites from the same group, the brunice arenosols. We have also only studied seven drought years, which limits the study of other drought models. But these seven years are well known in Central Europe and have also affected Scots pine (Martinez del Castillo et al., 2024). So testing how *P. nigra* copes with dry conditions when *P. sylvestris* suffers is particularly interesting in the process of introducing alternative tree species. This knowledge is essential for mitigating the adverse effects of climate change, especially given that many central European forests currently prioritize specific wood production over-optimizing forest ecosystems for existing environmental conditions. Consequently, their resilience to climate change may be insufficient.

## Acknowledgment

MM was supported by the Institut Agro Dijon as part of an internship. JJ was supported by the Slovenian Research and Innovation Agency, Program and Research Group "P4-0107".

## References

- Bolotov A, Shein E & Makarychev S (2019) Water retention capacity of soils in the Altai region. *Eurasian Soil Science* 52: 187–192. doi:10.1134/S1064229319020030.
- Bunn AG (2010) Statistical and visual crossdating in R using the dplR library. *Dendrochronologia* 28: 251–258. doi:10.1016/j.dendro.2009.12.001.
- Buras A, Ovenden T, Rammig A & Zang CS (2022) Refining the standardized growth change method for pointer year detection: Accounting for statistical bias and estimating the deflection period. *Dendrochronologia* 74: 125964. doi:10.1016/j.dendro.2022.125964.
- Buras A & Wilmking M (2015) Correcting the calculation of Gleichläufigkeit. *Dendrochronologia* 34: 29–30. doi:10.1016/j.dendro.2015.03.003.
- Camarero JJ, Gazol A, Sangüesa-Barreda G, Oliva J & Vicente-Serrano SM (2015) To die or not to die: early warnings of tree dieback in response to a severe drought. *Journal of Ecology* 103: 44–57. doi:10.1111/1365-2745.12295.
- Cedro A (2006) Comparative dendroclimatological studies of the impact of temperature and rainfall on *Pinus nigra* Arnold and *Pinus sylvestris* in North-western Poland. *Baltic forestry* 12: 110–116.
- Cornes RC, Van Der Schrier G, Van Den Besselaar EJM & Jones PD (2018) An ensemble version of the E-OBS temperature and precipitation data sets. *Journal of Geophysical Research: Atmospheres* 123: 9391–9409. doi:10.1029/2017JD028200.
- Durand M, Rose C, Dupouey J-L, Legout A & Ponton S (2020) Do tree rings record changes in soil fertility? Results from a *Quercus petraea* fertilization trial. *Science of the Total Environment* 712: 136148. doi:10.1016/j.scitotenv.2019.136148.
- Gessler A, Schaub M & McDowell NG (2017) The role of nutrients in drought-induced tree mortality and recovery. *New Phytologist* 214: 513–520. doi:10.1111/nph.14340.
- Intergovernmental Panel on Climate Change (IPCC) (2023) Climate Change 2022 – Impacts, adaptation and vulnerability: working group II contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- Izmir ŞC, Jevšenak J, Krajnc L, Hafner P & Köse N (2024) Distinct spatial patterns in climate-growth relationships, vegetation and resilience indices of Black pine (*Pinus nigra* J.F. Arnold) from its northern and southern distribution range. *Dendrochronologia* 88: 126236. doi:10.1016/j.dendro.2024.126236.
- Jevšenak J & Levanič T (2018) *dendroTools*: R package for studying linear and nonlinear responses between tree-rings and daily environmental data. *Dendrochronologia* 48: 32–39. doi:10.1016/j.dendro.2018.01.005.
- Kabała C, Charzyński P, Chodorowski J, Drewnik M, Głina B, Greinert A, Hulisz P, Jankowski M, Jonczak J, Łabaz B, Łachacz A, Marzec M, Mazurek R, Mendyk Ł, Musiał P, Musielok Ł, Smreczak B,

- Sowiński P, Świtoniak M, Uzarowicz Ł & Waroszewski J (2019) Systematyka gleb Polski. Wrocław University of Life Sciences, Wrocław.
- Klisz M, Jevšenak J, Prokopuk Y, Gil W, Mohytych V & Puchałka R (2022) Coping with Central European climate – xylem adjustment in seven non-native conifer tree species. *Dendrobiology* 88: 105–123. doi:10.12657/denbio.088.008.
- Klisz M, Puchałka R, Jakubowski M, Koprowski M, Netsvetov M, Prokopuk Y & Jevšenak J (2023) Local site conditions reduce interspecific differences in climate sensitivity between native and non-native pines. *Agricultural and Forest Meteorology* 341: 109694. doi:10.1016/j.agrformet.2023.109694.
- Latocha E & Hawrys Z (1976) Growth and development of introduced tree species in industrial regions. *Sylvan* 120: 29–38.
- Lloret F, Keeling EG & Sala A (2011) Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* 120: 1909–1920. doi:10.1111/j.1600-0706.2011.19372.x.
- Martinez del Castillo E, Torbenson MCA, Reinig F, Konter O, Ziaco E, Büntgen U & Esper J (2024) Diverging growth trends and climate sensitivities of individual pine trees after the 1976 extreme drought. *Science of The Total Environment* 946: 174370. doi:10.1016/j.scitotenv.2024.174370.
- Panagos P, Van Liedekerke M, Borrelli P, Köninger J, Ballabio C, Orgiazzi A, Lugato E, Liakos L, Herivas J, Jones A & Montanarella L (2022) European Soil Data Centre 2.0: Soil data and knowledge in support of the EU policies. *European Journal of Soil Science* 73: e13315. doi:10.1111/ejss.13315.
- R Core Team (2024) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Şahan EA, Köse N, Güner HT, Martin-Benito D, Gea-Izquierdo G, Conde M, Almagro D, Kızılaslan IS, Akkemik Ü & Dalfes HN (2024) Monitoring intra-annual wood formation of *Pinus nigra* J.F. Arnold (Black Pine) to understand the fire seasonality in Western Anatolia. *Forests* 15: 494. doi:10.3390/f15030494.
- Vacek Z, Cukor J, Vacek S, Gallo J, Bažant V & Zeidler A (2023) Role of Black pine (*Pinus nigra* J. F. Arnold) in European forests modified by climate change. *European Journal of Forest Research* 142: 1239–1258. doi:10.1007/s10342-023-01605-5.
- Van Der Maaten-Theunissen M, Trouillier M, Schwarz J, Skiadaresis G, Thurm EA & Van Der Maaten E (2021) pointRes 2.0: New functions to describe tree resilience. *Dendrochronologia* 70: 125899. doi:10.1016/j.dendro.2021.125899.
- Versace S, Bräuning A, Cherubini P, Febraro MD, Häusser M, Lombardi F, Marchetti M, Marziliano PA, Salbitano F, Szymczak S & Tognetti R (2022) New evidence for population-specific responses to drought events from tree ring chronologies of *Pinus nigra* ssp. *laricio* across the entire distribution range. *Agricultural and Forest Meteorology* 323: 109076. doi:10.1016/j.agrformet.2022.109076.