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Urban Forestry and Urban Greening

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<https://doi.org/10.1016/j.ufug.2024.128599>

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## Original article

# Urbanization associated with greater tree growth declines in urban than in rural forests

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## ARTICLE INFO

## Keywords:

Climate sensitivity

Growth trend

Urban forest

*Robinia pseudoacacia*

*Pinus thunbergii*

Tree-ring

Qingdao

## ABSTRACT

As temperatures continue to rise, the effects of climate variation and urbanization on tree growth are not entirely clear. This study compared the radial growth and climate sensitivity of black locust (*Robinia pseudoacacia*) and black pine (*Pinus thunbergii*) in urban forest parks and rural mountain areas in Qingdao, eastern China. Results from four tree-ring width chronologies indicate significant disparities in growth and climate sensitivity between urban and rural areas for both tree species. Trees in urban areas grew slower, likely due to greater water stress. Specifically, urban black locust growth was limited by water availability during the current growing season (April–September), while urban black pine growth was constrained by water availability in the late-growing season (August–September) of the previous year. Growth-trend analysis revealed a significant decline in tree growth since the early 21st century, with urban trees showing a more pronounced decline, highlighting that recent warming and drying likely affected by urbanization and inhibited urban tree growth. Identifying and planting tree species adapted to the changing climate is important for long-term urban forest management. Irrigation of the existing trees to reduce water stress is important to retain the current tree canopy during a several-decade period of transition to more urban tolerant tree species.

## 1. Introduction

Urbanization changes that increase impervious surfaces typically lead to higher surface temperatures in urban environments in contrast to rural surroundings (Mahmood et al., 2014; Pan et al., 2023). This urban heat island effect (Arnfield, 2003; Corburn, 2009; Tan et al., 2010) may exacerbate stress on urban trees due to water deficits caused by elevated temperature (Farrell et al., 2015; Fu et al., 2019). Consequently, trees in urban environments may face greater reductions in growth and vitality than their rural counterparts (Rötzer et al., 2019; Kabano et al., 2021; Franceschi et al., 2023).

Urbanization leads to urban climate warming, which can reduce the growth of certain urban trees (E. Meineke et al., 2016; Nitschke et al., 2017; E. K. Meineke and Frank, 2018). For example, Warner et al. (2024) found that urbanization aggravated the climate sensitivity of broad-leaved tree species in the eastern United States, and Nitschke et al.

(2017) reported a decline in the health of local deciduous species in Melbourne, Australia under drought conditions caused by urbanization. Hence, trees growing in urban areas provide a setting for studying tree growth characteristics under climate variation (McDonnell et al., 1997; Q. Li, 2020; Calvin et al., 2023). Spatiotemporal differences in tree growth and health between urban and rural areas may occur as a result of a higher temperature and drought gradient between these locations.

Increased air temperature as a result of greater impervious surfaces potentially increases evapotranspiration, resulting in greater water loss (Ponte et al., 2021; Dervishi et al., 2022). Water stress may lead to decreased tree vitality and growth with a potential difference along an urban-to-rural gradient (Gao et al., 2023). Currently, there is still little evidence about how urbanization and climate variation impact tree growth. Therefore, studying the differences in tree growth between urban and rural areas is crucial to quantify the potential response of trees in urban forests to forthcoming climate variation.

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<https://doi.org/10.1016/j.ufug.2024.128599>

Received 27 May 2024; Received in revised form 17 November 2024; Accepted 20 November 2024

Available online 23 November 2024

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Existing studies show that trees in urban environments are more sensitive and vulnerable to climate variation compared to those in rural areas (Hunt and Watkiss, 2011; Moser-Reischl et al., 2017; Schneider et al., 2022). Urbanization alters tree-growing conditions, creating drier environments that negatively impact tree growth (Czaja et al., 2020). The increased temperature in urban sites may increase transpiration and water deficits, and lead to stomatal closure and reduced photosynthesis potentially creating negative carbon balances. Moreover, extreme heat may cause damage to leaves (Moser-Reischl et al., 2016) and cause crown dieback and ultimately tree death. Additionally, elevated CO<sub>2</sub> concentration and increased air pollution levels (e.g., nitrogen deposition) may positively or negatively affect tree growth (Bussotti et al., 2014). Soil compaction may also affect tree root growth and exacerbate soil moisture deficits and in turn tree water deficits (Bartens et al., 2008).

Yet, in spite of the combined effects of urbanization and climate variation that may negatively impact tree growth, some studies suggest that trees in urban environments may show positive growth effects compared to those in rural areas (Moser-Reischl et al., 2017; Pretzsch et al., 2017; Dahlhausen et al., 2018; Smith et al., 2019; Sonti et al., 2019). Previous research has largely focused on climate stress effects on tree growth, whereas few studies compared the growth differences of different tree species in urban and rural areas due to climate variation. The growth of black locust in Germany has significantly decreased due to the influence of urban heat (Moser et al., 2016; Franceschi et al., 2023). The growth characteristics of black locust in southwestern Poland indicated a high water requirement (Kalbarczyk and Ziemiańska, 2016), and its annual tree-ring width showed a significant negative trend under the urban heat island effect (Kalbarczyk et al., 2016). In central Europe, black pine (*Pinus nigra*) could better resist the negative effects of heat wave and drought (Vacek et al., 2023). However, drought in Eastern Europe reduced the stability of black pine (*Pinus nigra*) forests, with growing season precipitation being the most crucial climatic factor for its growth (Devi et al., 2023). Further research from new areas is needed to clarify how these two species respond to climate variation in urban and rural environments.

The aim of our research was to examine how urbanization and climate variation jointly affect tree radial stem growth in urban and rural areas in Qingdao, where the effect of climate variation on tree growth has yet to be studied. Initially, we explored the key climatic factors that limit the radial stem growth of two common tree species in the urban and rural forests. We hypothesize that temperature will be a key climate factor limiting tree growth, with urban trees being more sensitive to temperature variations than those in rural areas. Secondly, we investigated the growth trends of these two species in urban and rural environments. We expected urban trees to grow slower than rural trees because they face higher temperatures and more drought-like episodes due to impervious surfaces. We evaluated our hypotheses by analyzing tree-ring width data from 49 plots for the two dominant species *Robinia pseudoacacia* (black locust) and *Pinus thunbergii* (black pine) commonly distributed in urban forest parks and rural mountainous areas. Our study helps clarify the adaptability of tree species growing in urban and rural locations to current climate variations and extends dendrochronology research in the region, providing an approach that others can replicate.

## 2. Materials and methods

### 2.1. Study area and regional climate conditions

The study occurred in Qingdao China, located in the southeastern part of the Shandong Peninsula, eastern China (35° 35'N - 37° 09' N, 119° 30'E - 121° 00' E), covering a total land area of 10,654 km<sup>2</sup> (Yang et al., 2019). The terrain in this region features higher elevations in the east and lower elevations in the west, ranging from 0 to 1133 m above sea level. Sited adjacent to the west of Jiaozhou Bay and bordered by the

Yellow Sea to the south, the area is characterized by a temperate monsoon climate with the annual average temperature of 12.6 °C with cold winters (average temperature of 0.9 °C) and warm summers (average temperature of 23.3 °C) (Yang et al., 2023). In recent years, the urban area of Qingdao has experienced much urbanization and a significant 1–2 °C increase in temperature (Ma et al., 2013). The extreme high temperature recorded is 38.9 °C, while the extreme low temperature is –16.9 °C (Li, 2023). The mean annual precipitation ranges from 600 to 800 mm (Ma and Guo, 2020).

Temperature and precipitation vary between urban and rural areas in Qingdao (Fig. 1; Fig. S1). The urban locale tended to be warmer and drier during the growing season between 1980 and 2020. An analysis of the fitting of annual average climate parameters revealed significant increasing trends in urban and rural temperature, but no significant trends were seen in precipitation in both urban and rural areas (Fig. S1).

### 2.2. Forest resources

The natural vegetation in this region is predominantly characterized by warm temperate deciduous broad-leaved forests, with a diverse range of species found across urban and rural areas. Dominant planted tree species include *Pinus thunbergii*, *Pinus densiflora*, *Robinia pseudoacacia*, *Cedrus deodara*, and *Metasequoia glyptostroboides*, while common companion species include *Prunus cerasifera*, *Zelkova serrata*, *Quercus serrata*, *Ginkgo biloba*, *Acer buergerianum*, and *Syringa* species (Dong et al., 2021). Currently, the plant communities in the mountainous areas mainly consist of forest plantations, established using aerial seeding and planted seedlings in the late 1960s, and secondary forests developed from natural regeneration of the planted forests. The urban forest parks in the hilly parts of Qingdao city, predominantly comprise cultivated stands of black locust and black pine established before the middle of the 20th century (Jiang et al., 2021). Consequently, in this study, the deciduous black locust and the coniferous black pine were chosen because they are common trees in both rural and urban locations.

### 2.3. Plot design

The study area was divided into urban and rural areas based on impervious surface area (Fig. 2). The investigated black locust and black pine forests from rural mountainous areas usually receive negligible forest management, except for removal due to the pine wilting disease caused by *Bursaphelenchus lignicolus*. Whereas the forest plantations from urban forest parks occasionally gain additional water through irrigation and understory vegetation removal in winter. To minimize the forest management effect, urban forest park plots were selected from areas

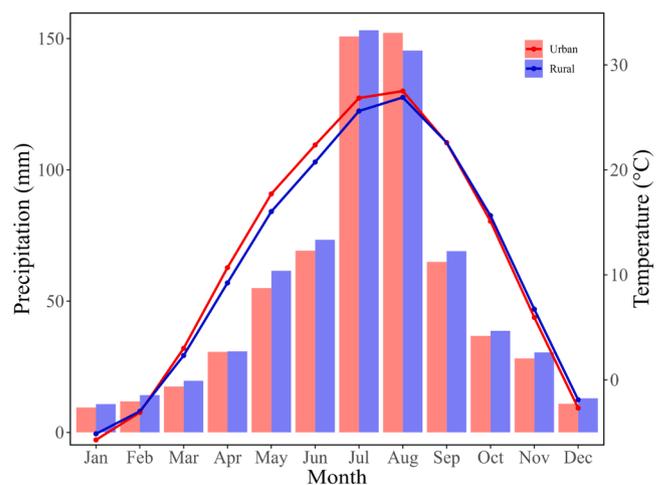
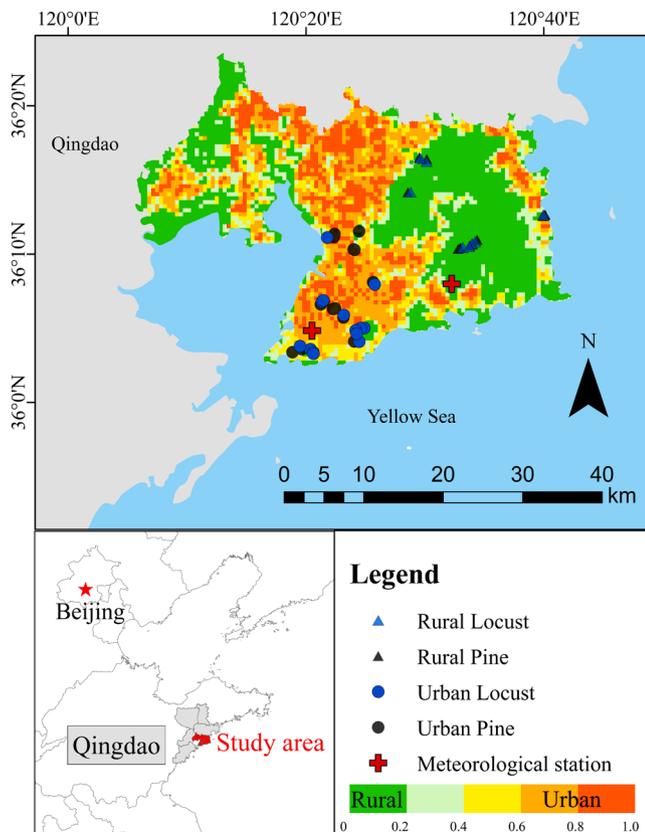


Fig. 1. Monthly average precipitation (bar) and temperature (line) of the studied urban and rural areas from 1980 to 2020 in Qingdao, China.



**Fig. 2.** Distribution of the geographical locations of tree-ring sampling plots in both urban and rural areas within Qingdao, eastern China. The legend includes a color bar ranging from 0 to 1.0, indicating the increasing proportion of impervious surface area, with green representing rural areas and orange or red representing urban areas.

with minimal human disturbance. In 2019, 13 standard plots of 600 m<sup>2</sup> (20 m × 30 m) were established for each black pine and black locust in the rural areas. Likewise, in 2023, 12 black pine plots and 11 black locust plots were set up in urban areas (Fig. 2; Table S1). All plots were dominated by the study species, reflected by the basal area exceeding 85 % in all plots for the study species (Table S2). Hereafter, the two species and monocultures are written as urban pine, urban locust, rural pine, and rural locust, respectively.

#### 2.4. Tree-ring sample collection and processing

Tree-ring chronologies followed methods by Fritts (1976). One to two cores were collected using growth increment borers from healthy, dominant, and pest-free trees at a standard height (approximately 1.3 m) in 2019 for rural sites and in 2023 for urban sites, respectively. A total of 626 increment cores were collected from 342 trees at urban and rural sampling sites (Table 1).

Sample preparation, cross-dating, and chronology development followed standard dendrochronological techniques. After air-drying, each tree core was fixed in a wooden holder and polished with progressively finer sandpaper, ranging from 200 to 1000 grit, until annual rings were clearly visible under a microscope (Speer, 2010). Tree-ring widths were determined with precision using a LINTAB 6 stereomicroscope, achieving a 0.001 mm accuracy. TSAP-win (RinnTech, Heidelberg, Germany) software was utilized for cross-dating, employing visual curve matching and statistical tests to identify missing or false tree-rings (Rinn, 2010). Additionally, COFECHA was employed to assess the cross-dating accuracy of the rings on each core against all others by calculating inter-series correlations, which measures overall dating

**Table 1**

Site and chronology statistical parameters of black pine and black locust in urban and rural sites from Qingdao, China. The dendrochronological statistics were derived from the span of each chronology. MS, AC1, Rbar, and EPS were computed following detrending. AGR, annual radial growth rate; SD, standard deviation; MS, mean sensitivity; AC1, first-order autocorrelation; SNR, signal-to-noise ratio; Rbar, mean inter-series correlation; EPS, expressed population signal.

Description	Urban		Rural	
	Black pine	Black locust	Black pine	Black locust
Altitude (m a.s.l.)	46–118	37–121	72–440	69–456
Number of plots	12	11	13	13
Number of trees	79	67	98	98
Number of cores	150	103	189	184
First year	1958	1969	1958	1964
Last year	2022	2022	2020	2020
Mean age (year)	42	29	30	31
Mean AGR (mm/yr)	1.871	2.489	2.257	2.748
Median AGR (mm/yr)	1.631	2.152	2.050	2.438
SD AGR (mm/yr)	1.161	1.388	1.182	1.516
MS	0.423	0.376	0.354	0.384
AC1	0.494	0.412	0.506	0.431
SNR	16.046	5.729	7.786	7.343
Rbar	0.273	0.324	0.272	0.236
EPS	0.94	0.85	0.89	0.88

reliability (Holmes, 1983). For cores that did not reach the pith, a scanner (Epson 12000XL) was used to scan samples at a resolution of 1200 dpi. The length and year of pith loss were estimated from the arc near the pith using CooRecorder software (Maxwell and Larsson, 2021), allowing for accurate age estimation of each annual ring (Rozas, 2003). All subsequent analyses were conducted using R (R Core Team, 2022).

#### 2.5. Standardization and chronology development

Tree-ring width series contain non-climatic signals. To remove non-climatic factors like tree age, genetic traits, and competition, while preserving low-frequency climate variations, a spline curve function correlated with tree age was applied to detrend the tree-ring series using the package 'dplR' (Bunn, 2008). Chronological statistical parameters including mean sensitivity (MS), first-order autocorrelation (AC1), inter-series correlation (Rbar), and expressed population signal (EPS) were employed to assess the quality of the resulting tree-ring chronology (Fritts, 1976; Wigley et al., 1984). Principal Component Analysis (PCA) was performed using the "FactoMineR" package in R to identify common signals in the chronologies and assess the inter-relationships over the common period between them (Lê et al., 2008). Calculating the residual chronology helps eliminate autocorrelation effects caused by biological inertia between consecutive years, which could otherwise obscure potential climate information (Cook, 1985).

#### 2.6. Climate-growth relationships

Climate data including monthly precipitation and temperature in this study were selected from the Qingdao Meteorological Station (36°04'N, 120°20'E, 76 m a.s.l.) and Laoshan Meteorological Station (36°10'N, 120°25'E, 46.8 m a.s.l.) for the period 1980–2020. Three-month and six-month Standardized Precipitation Evapotranspiration Index data (SPEI3 and SPEI6) for the same period were calculated using the "Thornthwaite" model with monthly mean temperature, precipitation, and latitude (Thornthwaite, 1948). These indices were computed using the 'spei' package in R (Vicente-Serrano et al., 2010). Self-calibrating Palmer Drought Severity Index (scPDSI) data were extracted through the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013) for grid points covering the entire study area (36.0–36.5°N, 120.0–120.5°E) at a 0.5° resolution for the same period (Harris et al., 2020). The bootstrapped correlation coefficients between

tree-ring width residual chronologies and climate variables for the period 1980–2020 were calculated by applying the 'dcc' function in the 'treeclim' R package (Zang and Biondi, 2015). Considering the lagged response of tree growth to climate factors (Fritts, 1976), a climate window spanning 15 months (from August of the preceding year to October of the current year) was selected for climate response analysis. Seasonal influences, including winter (WIN, pDec-Feb), spring (SPR, Mar-May), summer (SUM, Jun-Aug), and the growing season (GS, Apr-Sep) (Etzold et al., 2022) were also analyzed. To clarify the impact of seasonal climate on tree radial growth, we conducted seasonal correlation analysis utilizing the 'seascorr' function within the 'treeclim' R package (Zang and Biondi, 2015). In this analysis, partial correlation with precipitation served as the primary variable and temperature as the secondary variable. The stability of the correlation analysis between residual chronologies and climate variables over time was assessed using a 20-year moving window and a two-year step length with the 'treeclim' R package (Zang and Biondi, 2015).

## 2.7. Growth trend

Basal Area Increment (BAI) was utilized to characterize tree growth, as it accurately reflects annual trunk biomass (LeBlanc and David, 1990). BAI for each tree per year was calculated from annual tree-ring widths using the 'bai.in' function in the R package 'dplr' (Bunn, 2008):

$$BAI_n = \pi (R_n^2 - R_{n-1}^2) \quad (1)$$

where  $R_n$  is the radial radius of the tree in year  $n$ , while  $R_{n-1}$  denotes the radial radius in the preceding year. A site-level BAI chronology was formed by averaging the BAI series for each tree within each site.

For the growth trend analysis, we applied the approach developed from a previous study (Gaire et al., 2023). Generalized additive mixed models (GAMMs) were used to detrend the BAI series, eliminating trends linked to age-related growth and individual tree size (Wood, 2017). Since the original BAI series contains climate information and non-climate information, the non-climate information mainly includes the growth trend of trees with age and also contains the competition among trees. When analyzing the growth trend of trees, the non-climate information needs to be removed. Therefore, we used the Generalized Additive Mixed Model (GAMM) to detrend. GAMM is used to detect the change in the trend of tree radial growth rate, and the influence of annual rings and individual size on radial growth is considered. Logarithmic transformation was applied to BAI values to improve their distributional normality. Below is the structural framework of the GAMMs model:

$$\log(BAI) \sim \log(BA) + s(\text{Age}) + (1|\text{TreeID}) + \text{corAR1} \quad (2)$$

where BAI (basal area increment,  $\text{mm}^2/\text{year}$ ) is the dependent variable, while BA (basal area,  $\text{mm}^2$ ) and Age (tree age, years) are the independent variables. TreeID serves as a random factor for each tree. We incorporated a continuous ordered autoregressive structure corAR1, utilizing year as a temporal covariate and TreeID as a grouping factor, to account for temporal autocorrelation in the model (Gaire et al., 2023).

Using the GAMMs model to simulate BAI residuals for analyzing the variation trends in the growth rate of tree species in each site using the "mgcv" package (Wood, 2017). Below is the formula for calculated BAI residuals:

$$BAI_{\text{residuals}} \sim \log(BAI_{\text{observed}}) - \log(BAI_{\text{predicted}}) \quad (3)$$

We assessed the variation trends in BAI residuals over the years utilizing a linear mixed-effects model (LME) implemented with the "lme4" package in R (Pinheiro et al., 2007).

$$BAI_{\text{residuals}} \sim \text{Year} + (1|\text{TreeID}) + \text{corAR1} \quad (4)$$

where BAI residuals represent the basal area increment residuals from GAMM, with TreeID as a random factor for individual trees.

We utilized a linear mixed-effects model (LME) to examine the impact of BAI residuals in urban and rural areas in interaction with the calendar year serving as a covariate (Gaire et al., 2023). This model aimed to identify disparities in growth trajectories between the urban and rural sites:

$$BAI_{\text{residuals}} \sim \text{Year} \times \text{Site} + (1|\text{TreeID}) + \text{corAR1} \quad (5)$$

where Year and Site are considered fixed factors, and Year  $\times$  Site is an interaction between two fixed factors (Gaire et al., 2023).

To discern shifts in the growth trend, we employed the "segmented" R package (Muggeo, 2017) to pinpoint breakpoints within the residuals of individual BAI series. By analyzing the density distribution of these breakpoints, we identified years exhibiting mean frequencies across all trees (Gaire et al., 2023). Consequently, the BAI residuals were partitioned into two sub-periods to deepen the analysis of growth trends.

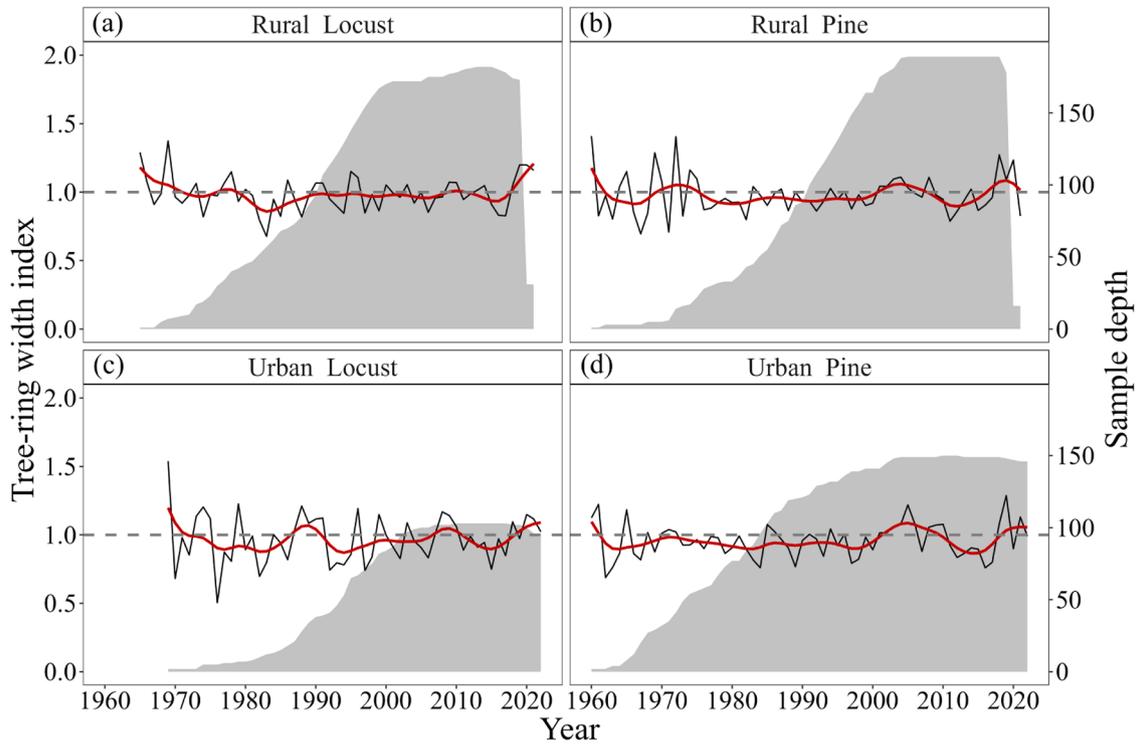
## 3. Results

### 3.1. Growth patterns of black locust and black pine in urban and rural areas

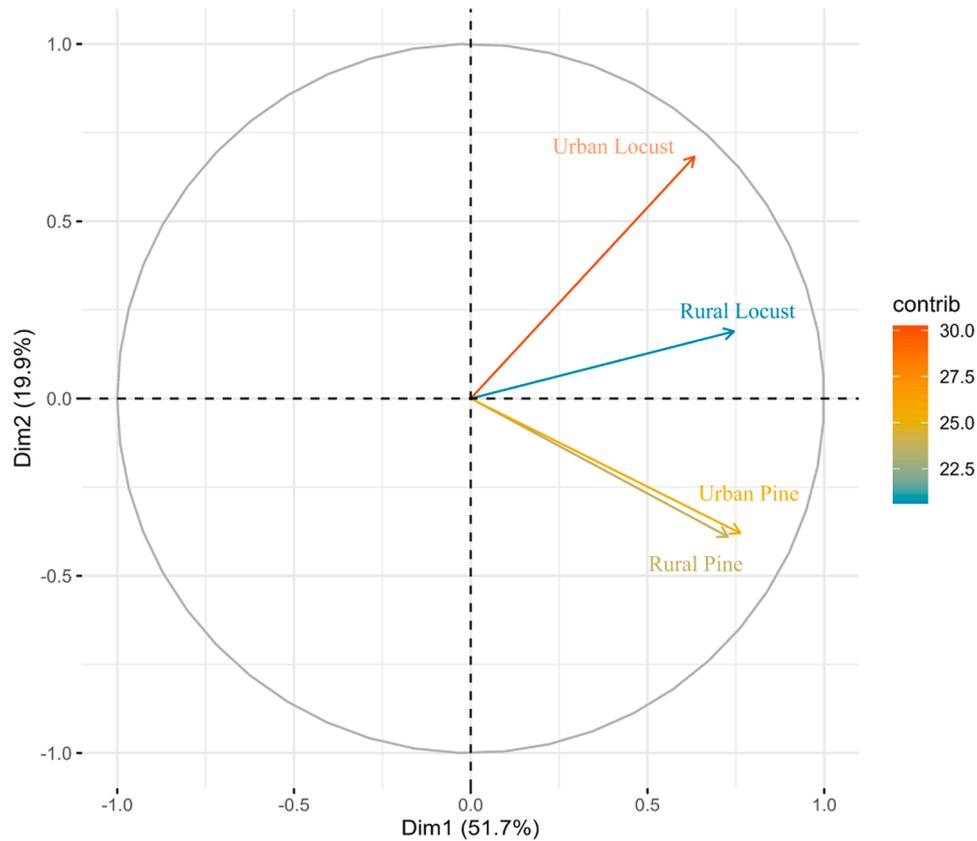
The average radial stem growth rates were generally higher in rural areas than in urban areas (Table 1). The tree-ring width chronologies of two species studied in urban and rural areas spanned from 54 to 65 years. Locust trees grew faster than pine trees, with the annual average growth rates ranging from 2.49 to 2.75  $\text{mm}/\text{yr}$  for locust and from 1.87 to 2.26  $\text{mm}/\text{yr}$  for pine. Moderate values of first-order autocorrelation (AC1) indicated the potential impact of climate on tree radial growth from the previous year to the current year. High mean sensitivity (MS) values suggested that tree-ring chronologies might be highly sensitive to climatic and environmental factors. All chronologies met the critical threshold of 0.85 for the expressed population signal (EPS), suggesting high reliability and suitability for fitting analysis with climate factors. Moderate mean inter-series correlation (Rbar) values demonstrated synchrony in interannual growth variability among individual trees in our study sites. Tree-ring chronologies of both species exhibited similar growth patterns, with consistent interannual growth fluctuations (Fig. 3). PCA analysis showed that PC1 and PC2 accounted for 51.7 % and 19.9 % of the shared variance, respectively (Fig. 4). PC1 reflects common growth variations shared by temporal climate variation, while PC2 primarily highlights the differences between urban and rural areas. The growth of rural and urban locusts, as well as rural and urban pines, followed similar patterns (Fig. 4), indicating an analogous growth trend for both black pine and black locust regardless of the locations.

### 3.2. Climate-growth relationship

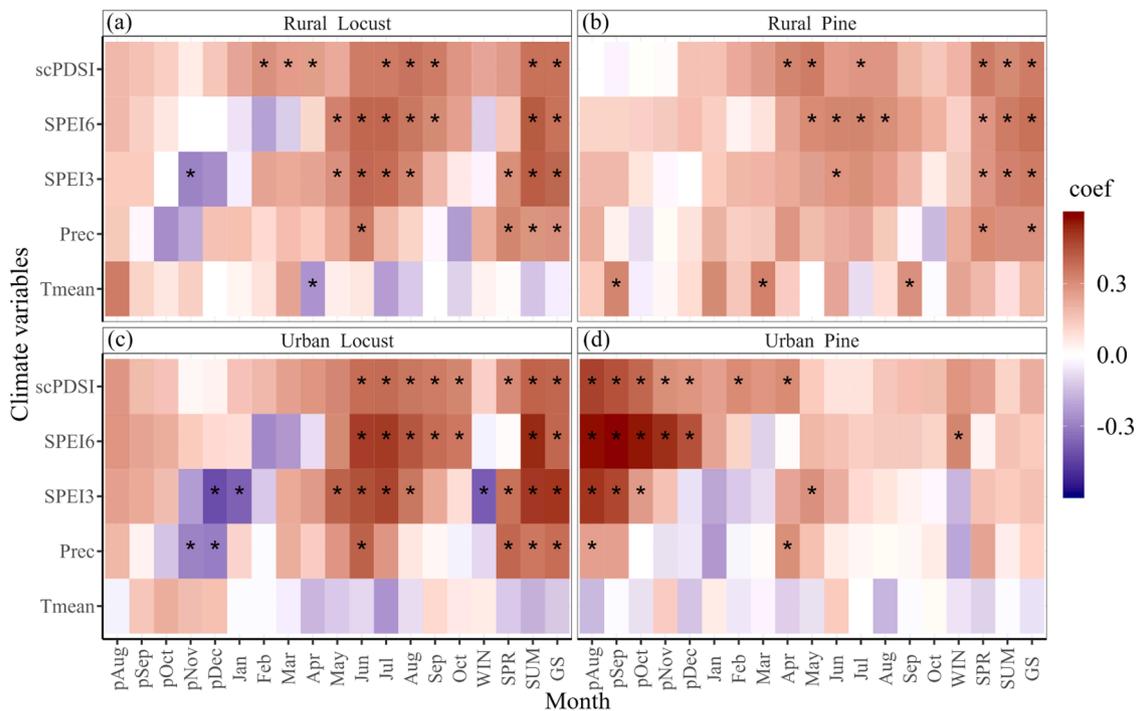
Bootstrapped Pearson's correlation analysis between residual chronologies and climate factors indicated different radial growth responses to climate between the urban and rural areas. Water availability during the growing season was the primary limiting factor for the growth of both tree species (Fig. 5). Positive relationships between the chronologies and moisture (i.e., Prec, SPEI3, SPEI6 and scPDSI) were observed during the growing season (April-September), with significant positive correlations observed for both rural and urban locust (Fig. 5a, c), as well as rural pine (Fig. 5b). Stem growth of locust trees was primarily positively influenced by moisture during the growing season (Fig. S2a, c). Instead, stem growth of urban pines correlated positively with moisture during the previous year's late growing season (from August to September) (Fig. 5d). The growth of locust correlated negatively with growing season temperature in both rural and urban areas (Fig. 5a, c), whereas pine growth correlated negatively with growing season temperature in urban areas (Fig. 5d) and positively in rural areas (Fig. 5b). The seasonal climate response confirms that moisture is the primary factor limiting stem growth for both two tree species of rural and urban



**Fig. 3.** Tree-ring width residual chronologies of black locust and black pine in urban and rural areas of Qingdao, China. The black line represents the tree-ring width index while the red solid line represents the 20-year spline smoothing filter. Shaded area indicates sample depth (number of cores).



**Fig. 4.** Principal component analysis of residual chronologies of the black locust and black pine from the urban and rural areas for the common climatic period 1980–2020.

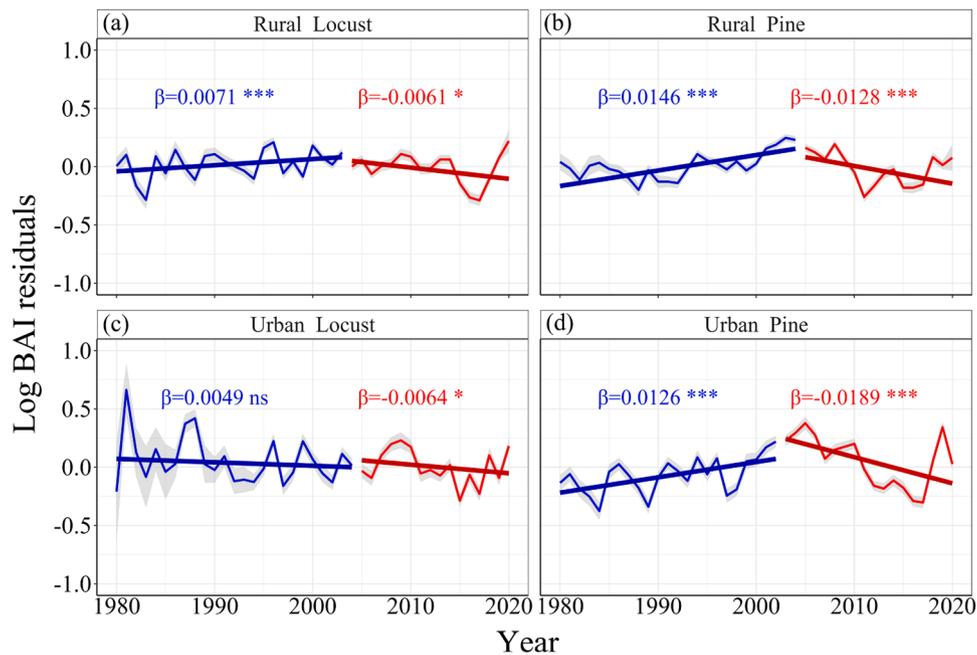


**Fig. 5.** The correlation diagram shows the relationship (Pearson correlation coefficient) between climate variables and four tree-ring width chronologies of black locust and black pine in rural and urban areas during the period 1980–2020. scPDSI, SPEI6, SPEI3, Prec, and Tmean represent self-calibrated Palmer drought severity index, six-month standardized precipitation-evapotranspiration index, three-month standardized precipitation-evapotranspiration index, precipitation, and mean temperature, respectively. Seasons: winter (WIN, pDec-Feb), spring (SPR, Mar-May), summer (SUM, Jun-Aug), and the growing season (GS, Apr-Sep) are used to analyze seasonal responses. Asterisks indicate significant correlations ( $p < 0.05$ ).

areas, but urban areas being more affected (Fig. S2).

Moving correlation analysis indicated that the relationships between tree growth and moisture remained stable over time for both tree species (Fig. S3). In both urban and rural areas, the growth of locust showed stable correlations with growing-season temperature (Fig. S3a, c;

Fig. S4a, c), while the growth of pine exhibiting unstable temperature sensitivity (Fig. S3b, d; Fig. S4b, d). Moreover, trees in urban and rural areas reacted with different intensities of response to moisture (Fig. S3a, c), with urban locust showing a stronger moisture sensitivity (Fig. S3c) and urban pine exhibiting a stronger response to moisture during the



**Fig. 6.** Growth trends (log BAI residuals) of urban and rural trees for the common period 1980–2020. The trends are shown in two sub-periods: (a) 1980–2003 (blue) and 2004–2020 (red) for rural locust, (b) 1980–2004 (blue) and 2005–2020 (red) for rural pine, (c) 1980–2004 (blue) and 2005–2020 (red) for urban locust and (d) 1980–2002 (blue) and 2003–2020 (red) for urban pine. Gray-shaded areas indicate 95 % confidence intervals. Asterisks represent significant correlations (ns:  $p > 0.05$ , \*:  $p < 0.05$ , \*\*\*:  $p < 0.001$ ).

late growing season of the previous year than rural pine (Fig. S3d). Therefore, compared to rural trees, urban trees are more sensitive to seasonal water availability (Fig. S3, S4).

### 3.3. Growth trends

During the period 1980–2020, the BAI chronologies of both tree species exhibited a declining trend after reaching a peak in the early 21st century (Fig. S5). Based on the density distribution of breakpoints in BAI residuals during the common period of 1980–2020, urban locust and rural locust were determined to have breakpoint years in 2005 and 2004, while the years of 2003 and 2005 were identified for urban pine and rural pine (Fig. S6). The growth trends of the two species were detected by fitting the linear mixed-effects model on BAI residuals derived from GAMM detrending (Fig. 6; Fig. S7; Table S3). At the early stage, both locust and pine showed stable growth trends in two different areas, yet their growth significantly declined recently ( $p < 0.05$ ) (Fig. 6). The interaction of site and year as covariates for urban and rural locusts showed a significant downward trend in recent growth ( $\beta = -0.0060$ ,  $p < 0.05$  during 2004–2020;  $\beta = -0.0077$ ,  $p < 0.05$  during 2005–2020) (Tables S4). Also, the recent growth of urban and rural pines exhibited a similarly significant decreasing tendency ( $\beta = -0.0174$ ,  $p < 0.001$  during 2003–2020;  $\beta = -0.0126$ ,  $p < 0.001$  during 2005–2020) (Tables S5). This indicates the growth trend has converted from increasing in the past to decreasing in the recent 15 years.

## 4. Discussion

### 4.1. Influence of urbanization and climate variations on tree radial growth

The statistical parameters (MS, EPS, Rbar) of the four chronologies from urban and rural tree species clearly indicate their potential for dendroclimatic research and represent the population in the study area. The growth parameters of the tree species (AGR, SD, and AC1) exhibited a declining trend from rural to urban areas, suggesting a significant lagged effect of climate on tree growth (Fritts, 1976) (Table 1). PCA analysis demonstrated that the chronologies of black locust and black pine captured common climate signals associated with climatic variations, with the first principal component explaining 51.7 % of the variance (Fig. 4).

Contrary to our first hypothesis, the main climatic factor limiting the growth of trees in urban and rural areas is not temperature but water stress during the growing season being the primary limiting factor. Although urban temperature is higher than rural temperature (Fig. 1; Fig. S1), we found that the radial growth of urban and rural trees was mainly affected by water availability (Fig. 5). The results revealed that temperature-induced drought stress has not yet emerged. However, the weak sensitivity of tree radial growth to temperature is referred to as "divergent" (Keyimu et al., 2021), and this phenomenon has been observed in numerous forest sites globally over the past few decades (D'Arrigo et al., 2008; Williams et al., 2011; Keyimu et al., 2020). The diminished correlation between tree radial growth and thermal factors can be elucidated from a physiological standpoint. Firstly, the elevated urban temperature accelerates transpiration rates, affecting the vapor pressure between leaves and stomata, and increasing evaporation demands (Friedrichs et al., 2009). This leads to the closure of leaf stomata to reduce water loss, subsequently impacting CO<sub>2</sub> absorption (Lloyd and Farquhar, 2008), lowering carbon assimilation rates, and ultimately hindering tree radial growth. Additionally, higher temperature increases soil evaporation, depleting soil moisture, reducing water and nutrient absorption by roots, limiting activity in the cambium layer, and eventually decreasing nutrient storage. Under drought stress, this may impede tree development (Xu et al., 2012). In this study, the direct effects of temperature on stem growth were relatively small, compared to the indirect effects of higher temperature leading to increasing

transpiration demands, soil desiccation, and ultimately, tree dehydration hindering growth.

Our finding confirmed that urban climate variation has a negative impact on the radial growth of black locust and black pine in urban areas, which is mainly attributed to differences in water stress conditions. Adequate precipitation during the summer contributes significantly to the formation of latewood in trees and is crucial for water transport (Zhao et al., 2017; Yang et al., 2024). Gillner et al. (2014) found that precipitation and scPDSI during the growing season primarily influence the radial growth of trees in urban areas, while temperature plays a secondary role. As a fast-growing species, black locust consumes a large amount of soil water (Liu et al., 2010; Mantovani et al., 2014). Keyimu et al. (2021) found that the lower spring precipitation imposed restrictions on the radial growth of *Robinia pseudoacacia* in that year's period and its radial growth benefited more from climate variation and was stressed by water supply in semi-humid regions. Moreover, sufficient rainfall in the preceding summer and autumn can accumulate the necessary carbohydrate reserves for radial growth in the following year (Galiano et al., 2011; Michelot et al., 2012), and it is essential for the dense formation of earlywood in the subsequent year (Barbaroux and Bréda, 2002; Cheng and Liu, 2015). Studies have shown that increasing water stress due to urban climate variation had a negative impact on the growth of *Pinus thunbergia* (Barbet-Massin and Jiguet, 2011; Tíscar and Linares, 2011; Vacek et al., 2023). Rocha and Holzkämper (2023) reported that the growth of *Pinus sylvestris* in urban areas was primarily controlled by the water stress during the growing season and site conditions. It was also found that the radial growth of *Pinus tabulaeformis* responded strongly to SPEI and scPDSI during the previous and current summer and autumn seasons in Beijing (Li et al., 2022). Consistent with other studies, we found that the growth of urban locust and urban pine is strongly positively correlated with moisture variables during the growing season (April–September) and at the end of the previous year's growing season, respectively (Fig. 5). Therefore, sufficient water is crucial for black locust and black pine growing in urban areas and urban trees are more subjected to water stress. This likely explains why we have observed a strong positive correlation between radial growth and moisture availability in urban areas.

The response of tree radial growth to moisture (Prec, SPEI03, SPEI06, scPDSI) remains largely consistent in both urban and rural areas from 1980 to 2020, while the importance of moisture availability has been increasing in urban areas and unstable in rural areas in recent years (Fig. S3). One earlier study on the temporal climate response of urban trees in Germany showed a significant positive correlation between the growth of urban *Platanus orientalis* and moisture utilization during the summer months over time (Gillner et al., 2014). Keyimu et al. (2020) conducted a moving correlation analysis of *Quercus mongolica* in Beijing, which demonstrated that with the climate warming, the correlation between trees and precipitation in spring and summer had increased since the end of the 20th century, and precipitation had become the dominant regulating factor. Rakthai et al. (2020) revealed that in the context of climate variation, the growth of *Pinus latteri* has exhibited increased sensitivity to water availability in the past 30 years. Compared with other studies on the temporal stability of tree growth, it can be inferred that variations exist in the response of tree radial growth to climate between two different regions, primarily reflecting species- and site-specific factors. These findings further suggest the potential negative impact of recent urban warming and drying trends on tree growth.

### 4.2. Trends of tree growth to urbanization

Using tree-ring width data, we can directly calculate the radial growth rate and growth trend of trees, which can more accurately and directly reflect the historical growth characteristics of trees (Yang et al., 2022). As we predicted, the increase in urban temperature, resulting in water stress, had a negative impact on the growth of urban trees. Our research found that the radial growth rate of urban trees was less than

that of rural trees (Table 1). Similarly, the growth of two species had declined at a higher rate in urban areas than in rural areas with a significant decreasing trend since the beginning of the 21st century (Fig. 6, Table S4, S5). Moser et al. (2017) found that the growth of urban trees was suppressed by factors such as low water use availability, rising surface temperature, pollution, and soil compaction. Other studies have shown that the warming associated with climate variation in summer caused a decline in the growth of black pine (Doğan and Köse, 2019; Janssen et al., 2018), and the growth rate of black locust in urban areas was also reduced (Dervishi et al., 2022). Our findings were consistent with the reported results that urban climate variation led to a decrease in the growth rate of black locust and black pine in warmer and drier environments, and its possible mechanism is that rising temperature would increase transpiration demand leading to water stress, thus limiting tree growth (McClung and Ibáñez, 2018; Salerno et al., 2015; Talchabadel et al., 2018). Especially in the growing season, the growth declines from decreased photosynthetic capacity as soil water becomes limiting from intensified transpiration and evaporation as the temperature becomes higher and a resulting decreased soil available water (Chang et al., 2017). While internal factors within trees cannot be ruled out, external factors such as climate variation, urban irrigation, and urban pollution could be additional driving factors (Roetzer et al., 2000).

Studies on urban tree growth around the world have found that the growth of trees is also inhibited by urban climate (Cregg and Dix, 2001; Moser-Reischl et al., 2016; Moser-Reischl et al., 2018). The research indicates that the ongoing rise in urban temperature is causing a warming and drying trend in the climate, leading to water stress during the growing season for *Quercus robur* and *Quercus cerris*, resulting in slower growth in trees (Romagnoli et al., 2018). Clark and Kjelgren (1990) suggested that urban environments often exhibit characteristics of high surface runoff and low infiltration rates, which reduce soil moisture content and thus inhibit tree growth. Conversely, many studies have documented that trees growing in urban areas are promoted by the increase in urban temperature. Moser et al. (2017) found that *Quercus nigra* in Houston grew better in urban areas, and Searle et al. (2012) reported that the climate in urban areas was more suitable for the growth of *Quercus rubra* in New York than in rural areas. Arndt et al. (2015) found that trees showed a high growth rate under urban heat stress. Differences from studies in other urban areas suggest that the main factors influencing tree growth trends are locations, climate, and species differences within the study area (Roy et al., 2012; Pretzsch et al., 2017).

#### 4.3. Limitations and suggestions for urban forest management

Our findings highlight the crucial role of dendrochronology in measuring urban tree growth and assessing tree species' vulnerability to a warming climate and the effects of land use change, such as greater impervious surfaces. The results offer valuable insights for urban forest planning. The study is limited to the response of annual tree growth to urban climate change only from tree-ring width data. We did not compare soil properties on the potential effect on tree growth among the urban and rural plots, which may explain some variation among the sites. Additionally, due to the specific environmental conditions of Qingdao as a coastal rapid urbanization area, it might limit the generalizability of our findings to other regions. However, this study adds to the literature by a study in an area lacking the data we collected. Reinmann et al. (2020) found that urbanization aggravated the negative impact of heat stress on the above-ground carbon assimilation in the early growing season of broad-leaved trees. The negative impact of urbanization and climate variation on urban forests is an important aspect for urban forest planning and management.

Remote sensing datasets (e.g. NDVI) are not included in this study, and they should be integrated with tree-ring research for effective urban forest management. The next step will be to systematically analyze xylem cell structure characteristics (such as tracheid number, tracheid

area, cell wall thickness, etc.) at the cellular level using wood anatomy. This approach will allow us to capture intra-annual changes in tree growth and gain a comprehensive understanding of the physiological response mechanisms of trees under the environmental conditions of urbanization and climate variation.

Due to urbanization and climate variation, urban temperatures are expected to rise, further intensifying water stress on urban trees. Although these challenges are significant, arboricultural practices such as mulching, soil improvement, and precise irrigation optimized to meet species-specific needs (Nitschke et al., 2017) can promote the resilience and sustainable development of urban forests. Maintaining existing canopy cover is also crucial for reducing water loss and enhancing drought tolerance in trees (Warner et al., 2024). In urban planting plans, mixing drought-intolerant and drought-tolerant species (E. K. Meineke and Frank, 2018) can enhance forest structure diversity, supporting urban ecosystem stability. Additionally, implementing 'sponge city' landscape designs that retain rainwater can further improve green space resilience (Adresi et al., 2023).

## 5. Conclusions

This study reveals how urbanization and climate variation interact to affect the growth of tree species in Qingdao, a rapidly urbanizing area. To our knowledge, it is the first study that provides an approach for established tree-ring width chronologies of black locust and black pine in both urban and rural areas in this region and to analyze the relationship between tree growth and climate factors, as well as the growth trend variations. Results indicate that both species are adversely affected by urban climate conditions. For black locust, the inadequate moisture during the growing season in urban areas was the main limiting factor for growth, while for black pine, the climate response in urban areas exhibited a lag effect, indicating that the moisture limitations in the late-growing season of the previous year are the main limiting factor for growth. The negative growth trend observed in urban areas in recent decades for both species may be driven by water constraints caused by rising urban temperatures, and we found that growth rates of urban locust and urban pine decreased more rapidly than rural locust and rural pine. With the urban sprawl, urban temperature will continue to rise, inevitably exposing urban trees to increased temperatures and adversely affecting their growth. At present, urban managers can improve soil water use availability through irrigation, which is the fastest way to alleviate the drought stress of urban trees.

## CRedit authorship contribution statement

**Huicui Lu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Frank Sterck:** Writing – review & editing, Visualization, Validation. **Haifang Li:** Writing – review & editing, Funding acquisition. **Zexin Fan:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Zaw Zaw:** Writing – review & editing, Visualization, Software. **Jinming Yang:** Writing – review & editing, Resources, Investigation. **Qian Wu:** Software, Investigation, Formal analysis, Data curation. **Richard J Hauer:** Writing – review & editing. **Raoqiong Yang:** Writing – review & editing, Software. **Zongshan Li:** Writing – review & editing, Visualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This study was supported by National Natural Science Foundation of China (31800374), Qingdao Science and Technology Foundation for Public Wellbeing (grant number 23-2-8-cspz-10-nsh), and Shandong Provincial Natural Science Foundation (ZR2019BC083). We acknowledged Ao Liu, Ruxiao Wei, Nuanyang Zhou, and many other students assisting in the field plot design and tree core samplings.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ufug.2024.128599](https://doi.org/10.1016/j.ufug.2024.128599).

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