

# London Plane Bark Exfoliation and Tree-Ring Growth in Urban Environments

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**Abstract.** Background: Bark exfoliation is a common feature of London planes (*Platanus × acerifolia*) that reportedly increases during periods of drought-induced stem shrinkage. Here, we explore the spatial patterns and potential drivers of plane bark exfoliation in Mainz, a central European city of 220,000 inhabitants, following the exceptional summer drought of 2018. Methods: We estimate the degree of bark exfoliation of 349 urban plane trees across the city and use stem microcores to analyze their tree-ring widths from 2006 to 2019. Further to impervious cover, settlement structure and vegetation cover in the vicinity of each tree, we investigate the relationships between bark exfoliation and tree, site, and climate factors. Results: Results indicate that plane bark exfoliation correlates significantly with tree size and inner bark width (both  $p < 0.001$ ) but is independent of impervious cover and local site conditions. Similarly, stem growth does not change within the city underlining the resilience of London planes to cope with highly diverse urban site conditions. Plane tree-ring widths were only weakly associated with exfoliation estimates ( $p < 0.05$ ) but strongly controlled by cold season temperatures ( $p < 0.001$ ). Conclusion: As tree growth was also not affected by summer drought, potential detrimental effects by limited infiltration, increased runoff and altered evaporation are of less concern for the plane trees in Mainz. Projected winter warming is likely to enhance urban plane growth in upcoming decades.

**Keywords.** Dendrochronology; Mainz, Germany; *Platanus × acerifolia*; Urban Warming.

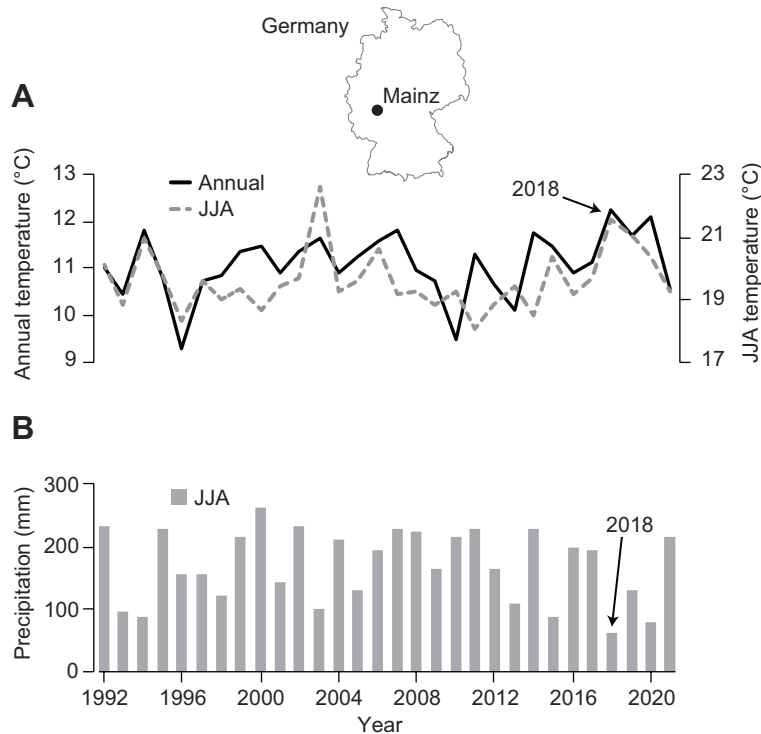
## INTRODUCTION

London plane (*Platanus × acerifolia*) is one of the leading tree species in European cities capable to grow across a range of climate zones (Henry and Flood 1919; Browicz 1964; Mimet et al. 2009). It has been described to be resilient to urban pollutants, infestations, and severe drought (Dineva 2004; Ivanová et al. 2007; Pourkhabbaz et al. 2010; Gillner et al. 2015; Yang et al. 2015; Adamska 2019), and mitigates heat stress through transpiration-induced cooling, which is particularly effective during periods of high atmospheric evaporative demand (Bowden and Bauerle 2008; Ennos 2012; Lindén et al. 2015; Sanusi and Livesley 2020). Transpiration-induced cooling even remains operational during nighttime when stable nocturnal boundary layers typically limit air mixing (Lindén et al. 2016).

*Platanus × acerifolia* is the result of manifold hybridization and bark phenotypes vary largely in response to changing provenances and seed propagation (Sax

1933). All plane stems are characterized by episodic bark exfoliation, however, which has been described to be more pronounced during periods of drought-induced stem shrinkage (Kozłowski and Pallardy 1997; Milks et al. 2017). If summer drought did not occur for several years, trees may build up a thick outer bark, and distinct water shortage over several weeks and months, such as during the summer of 2018 in Mainz (Figure 1), causes widespread exfoliation across urban sites (Schmidt 2018; Stadt Mainz 2022).

The underlying reason for such an event is of physical nature as the inflexible lignin-rich outer bark loses connection with the flexible inner bark (phloem) that shrinks in line with the water-conducting stem sapwood. Drought induced stem shrinkage can become particularly pronounced during warm growing season months, when high atmospheric demand and transpiration rates at the leaf level meet water shortage at the root level so that tree stems contract and slim by several centimeter circumference (Zweifel



**Figure 1.** 2018 summer drought in Mainz within the context of the past 30 years. (A) Annual (black) and summer (grey) temperatures, and (B) summer precipitation totals recorded since 1992 at the Mainz-Lerchenberg meteo station. Top map shows the location of Mainz in Germany.

and Häsler 2001; Deslauriers et al. 2007; Oberhuber and Gruber 2010). In 2018, these conditions were met in Mainz when exceptionally warm conditions accompanied the driest summer recorded over the past 30 years (Figure 1B), a covariance pattern characteristic for central European climates (Büntgen et al. 2010; Ljungqvist et al. 2019).

Whereas the basic mechanisms between stem shrinkage and exfoliation are well understood (Kozłowski and Pallardy 1997), little is known about the environmental conditions affecting bark peeling and potentially varying spatial patterns across the diverse sites within a city. We here address these issues by comparing exfoliation rates of several hundred planes, recorded after the summer drought of 2018 in Mainz, with impervious cover, circumference, tree-ring width (TRW), and phloem width (PHW) data to establish a basic understanding of the variability of this characteristic feature across urban structures. This comparison is conducted considering a ranking of sites into different categories integrating the environmental conditions in the nearby surroundings of

sampled trees, and the same categories are employed to analyze the climatic drivers of urban plane growth using TRW data since 2006.

Using this setup, we address the following hypothesis:

1. The 2018 drought caused varying spatial patterns of plane bark exfoliation in Mainz and these patterns can be related to changing microsite conditions as indicated by impervious cover, building heights, and vegetation cover.
2. Additional factors such as tree size, growth rate, and phloem width influence bark exfoliation and override the potential association between exfoliation and tree microsite conditions.
3. Plane ring width data can be used to assess the importance of the 2018 drought and other climatic drivers of plane growth in an urban environment.

By addressing these hypotheses, we provide the first systematic assessment of bark exfoliation patterns and climate drivers of plane growth across a mid-sized city in central Europe.



Figure 2. Plane stem exfoliation estimates ranging from 0% to 100% remaining bark.

## MATERIALS AND METHODS

### Meta Information and Ranking

Three hundred forty-nine London planes were randomly selected throughout the city of Mainz and the percentage of remaining bark estimated based on standardized photographs (Figure 2). Stem circumference measured at breast height ranged from 91 to 340 cm and included a modest tendency towards smaller specimens from the city center near the Rhine to the outskirts (Figure S1). Photographs were used to document the degree of impervious cover within and beyond a radius of 20 m of each tree (Figure S2). These data were combined in Table 1 with estimates of surrounding building heights and vegetation cover to rank all plane sites into 4 categories here characterized as city avenues (site rank [SR] 1), residential and parking lots (SR2), urban plazas and grass strips (SR3), and parks and playgrounds (SR4). Site ranks 1 to 4 correlate at  $r = -0.78$  with the impervious cover estimates. However, contrary to the impervious cover data that only contain a minor drift towards more paved sites in downtown Mainz, site ranks 1 to 4 show distinct spatial clusters including city avenues (SR1) being concentrated in the city center and parks and playgrounds (SR4) mostly occurring in the outskirts (Figures S1B and S1C). The numbers of trees and mean circumferences are relatively even among the site ranks, ranging from 81 to 94 cm and 164 to 197 cm, respectively (Table 1).

### Tree-ring and Phloem Width

Microcores (1.8 mm diameter) 15- to 30-mm long were sampled at stem breast height to measure TRW and (if contained on the sample) PHW at a precision of 0.01 mm using a LinTab device (RinnTech, Heidelberg, Germany). Contrary to classical dendrochronological core samples that typically extend towards the stem pith, and thereby include all rings at breast height, microcore samples only contain the few outermost rings of a trunk. Microcore samples therefore include fewer rings if the growth rate of a particular tree was high, and vice versa, more rings if the recent growth rate was low. The number of rings thus varies considerably among the 349 plane samples ranging from 2 to 41 with a mean around 9. The TRW series were detrended by calculating residuals from linear fits, and chronologies were produced using the arithmetic mean of all 349 planes (ALL) as well as the site rank sub-samples. All plane trees in Mainz were likely irrigated in the first few years after planting, but this period of juvenile growth is not covered by the short microcores that only include the most recent tree-rings.

### Data Analysis

The relationship between remaining bark, impervious cover, site ranks, circumference, TRW and PHW were evaluated using box plots and Spearman correlations. Linear regression was used to add detail to

**Table 1. Site rank characteristics and metrics. TRW is the mean tree-ring width of the years 2016 to 2019. Rbar is the inter-series correlation among detrended TRW series including  $\geq 3$  years.**

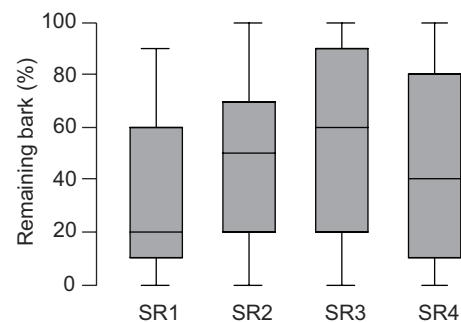
Site	Description	Impervious cover		Building height		Vegetation cover		No. of trees	Circumference	TRW	Rbar
		< 20 m	> 20 m	< 20 m	> 20 m	< 20 m	> 20 m				
SR1	City avenues	High	High	High	High	None	None	87	178 cm	0.23 cm	0.12
SR2	Residential and parking lots	Medium	Low	Medium	Low	Low	Medium	87	170 cm	0.25 cm	0.22
SR3	Urban plazas and grass strips	Low	Medium	Low	Medium	Medium	Low	94	197 cm	0.21 cm	0.15
SR4	Parks and playgrounds	None	None	None	None	High	High	81	164 cm	0.27 cm	0.39

the association between TRW and PHW, as such a comparison appeared fairly fundamental and widespread PHW data has not been conducted yet. The TRW data were analyzed to evaluate varying covariances among the site rank sub-samples and the resulting chronologies compared to highlight differences between the microsites. The SR1 to SR4 TRW chronologies, as well as the chronology integrating all plane TRW data (ALL), were calibrated from 2006 to 2019 against meteorological data recorded at Mainz Lerchenberg (German Weather Service 2021a, 2021b) using Spearman correlations to discover the climatic drivers of plane growth across the city.

## RESULTS AND DISCUSSION

### Micro-Site Effects on Plane Bark Exfoliation

We found no correlation between bark exfoliation and impervious cover estimates at 349 plane sites in Mainz ( $r = -0.03$ ). This result did not meet expectations as the site conditions changed dramatically within the city fundamentally affecting infiltration, runoff, and evaporation. The substantially altered paving of sites, however, did not modify plant water access, conduction, and losses to stimulate spatially varying stem shrinkage and bark exfoliation rates. Since these conditions were not met during the exceptionally warm and dry summer of 2018, it appears likely that no other period of high atmospheric demand caused spatially varying bark exfoliation associated with urban soil sealing patterns.



**Figure 3. Association between remaining bark (in %) and site rank. With SR1 = city avenues, SR2 = residential and parking lots, SR3 = urban plazas and grass strips, and SR4 = parks and playgrounds.**

When considering the surrounding vegetation and building heights in addition to the impervious cover, a weak association between site rank and exfoliation is observed (Figure 3). The median estimates of remaining bark increase from SR1 (20%) to SR3 (60%) indicate that fissuring and flaking off is accelerated along city avenues (SR1) compared to residential and parking lots (SR2), and to urban plazas and grass strips (SR3)(Table 1). However, this tendency is not continued into the least urban rank (SR4: parks and playgrounds) where the remaining bark drops to only 40%. This reversal also affects the Spearman rank correlation ( $r = 0.14$ ), which appears additionally biased by ill-defined site ranks (particularly for residential and parking lots [SR2] and urban plazas

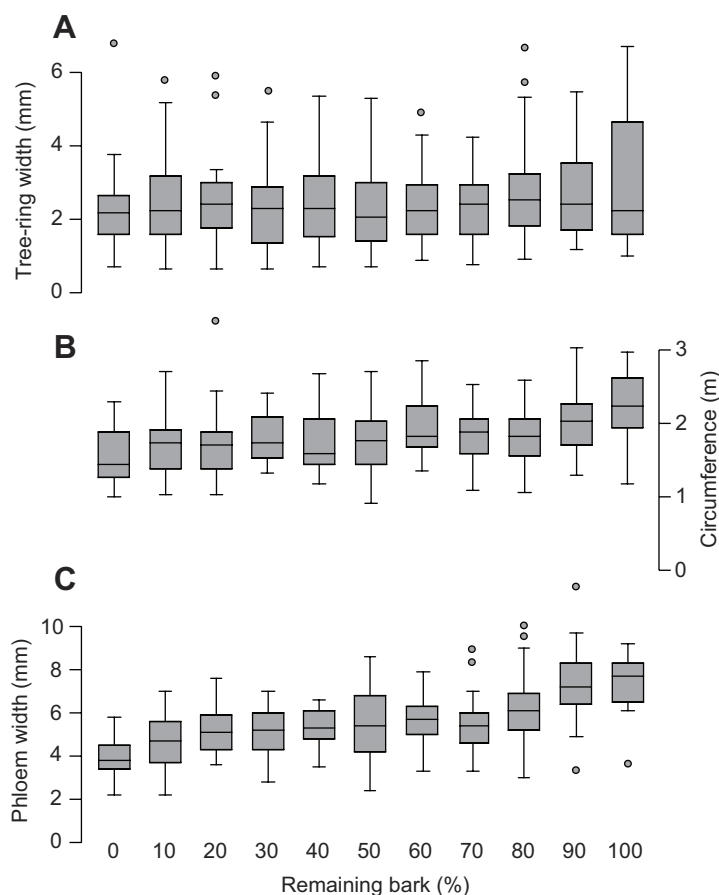
and grass strips [SR3]). Accompanying variables that could potentially bias this calculation, such as circumference changes from SR1 to SR4, appear to be orthogonal and do not affect these estimates. Given these varying results for the different site ranks and the insignificant result when comparing with percent impervious cover, hypothesis (1) on the importance of changing micro-site conditions on post-drought plane bark exfoliation is essentially disproven.

### Other Drivers of Plane Bark Exfoliation

Further tests using tree size and growth rate data reveal a weak relationship between remaining bark and TRW ( $r = 0.11$ ,  $p < 0.05$ ) and stronger relationships with circumference ( $r = 0.33$ ,  $p < 0.001$ ) and PHW ( $r = 0.58$ ,  $p < 0.001$ ). The closer association with circumference, and even more so with PHW, are also reflected by the increasing box plots and medians of remaining bark categories from 0% to 100% (Figure 4). Whereas the relationship between bark exfoliation

and tree size has been detailed before (Kozłowski and Pallardy 1997), the link with PHW is a new finding suggesting that the shrinking of the sugar-conducting inner bark during severe drought conditions affects bark exfoliation and that a wider PHW is amplifying this process.

The limited correlation between exfoliation rates and TRW appeared surprising as we expected TRW to be closely coupled with PHW (which again correlates well with bark peeling). This is not the case, however, as a linear fit explains < 25% of TRW/PHW covariance (Figure S3). The scatter of the XY-plot demonstrates that particularly the data points > 5 mm TRW and > 9 mm PHW deviate substantially from the linear regression indicating a decoupling between these variables in fast-growing planes, which in turn constrained the link between TRW and drought-accelerated exfoliation rates. This conclusion is, however, restricted by the limited number of outermost tree rings used in this calculation (mean = 9 years),



**Figure 4.** Association between remaining bark and (A) tree-ring width, (B) circumference, and (C) phloem width of 349 London planes within Mainz.

which might not well represent the overall growth rates of many of the large and much older trees sampled within the urban areas of Mainz (Figure S1A). The average length of the microcore samples used in this study (17.4 mm) represents < 10% of the estimated stem radii at breast height.

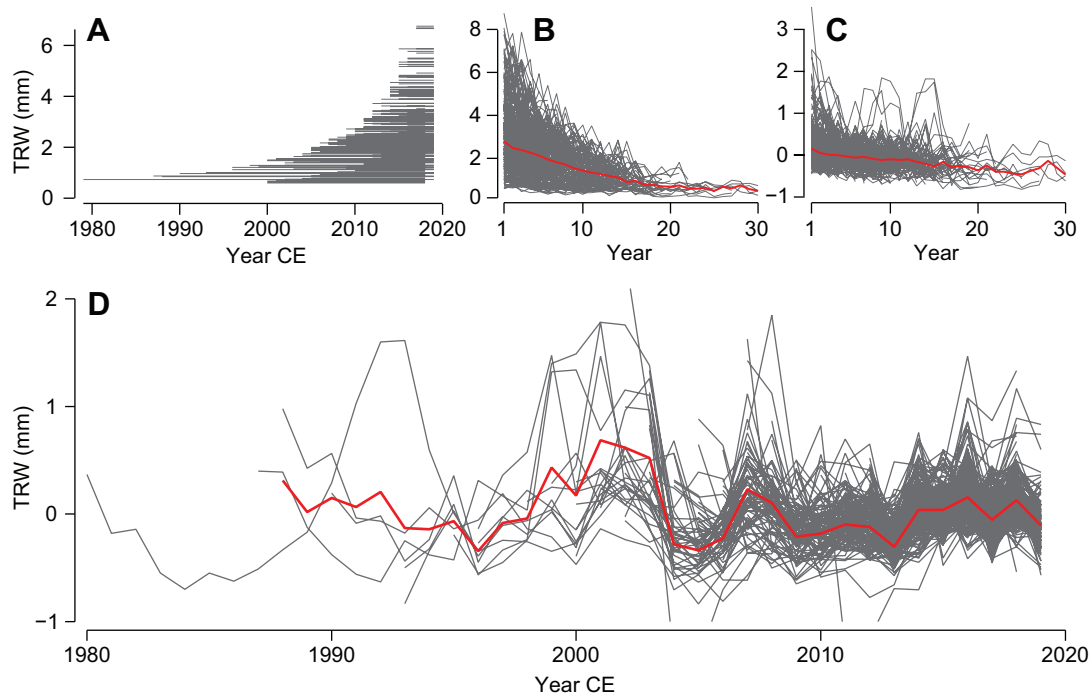
The gradually increasing correlation from TRW-to-circumference-to-PHW with percent remaining bark partly supports hypothesis (2) on the importance of other factors (beyond microsite effects) controlling plane bark exfoliation. This conclusion also underlines the limited practical control of bark exfoliation as these variables are largely beyond the influence of urban foresters.

### Plane Ring Width Characteristics in Different Micro-Sites

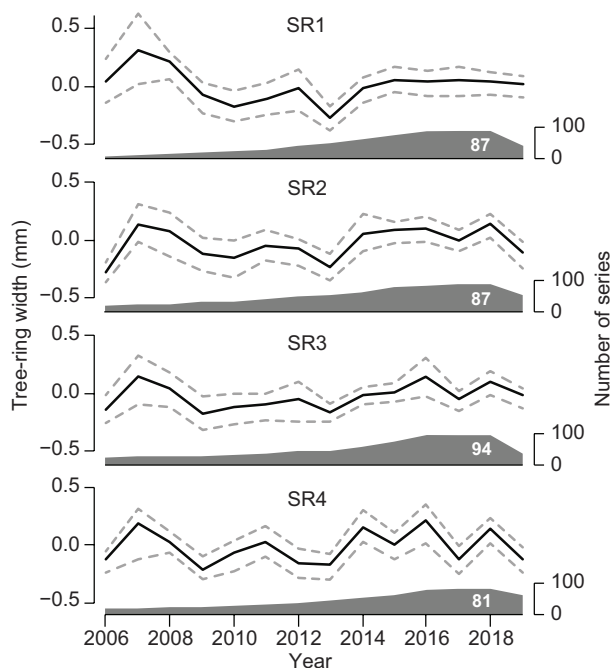
Mainz planes grew relatively fast at a rate of 2.5 mm per year considering the average width of the outermost rings derived from 15- to 30-mm long microcores. While this rate changes dramatically among single trees, ranging from < 0.6 mm to > 6 mm per year, we did not find any systematic difference related

to changing impervious cover and site conditions (Table 1), as would be expected from experiments considering varying pavements (Morgenroth 2011; Morgenroth and Visser 2011) and soil compaction (Smith et al. 2001). This finding underlines the resilience of London planes to cope with varying urban site conditions, which is potentially larger than in other tree species.

The single TRW series reveals a distinct order from slow-growing trees containing many rings to fast-growing trees containing few rings (Figure 5a). This sampling bias is expressed in a sharp TRW decline from 3 mm in the first year to 0.7 mm 20 years after aligning the data by the first year on each core sample (red curve in Figure 5b), though the latter value represents the mean of much fewer trees ( $n = 14$ ). A smaller but still obvious trend remains after removing the mean growth rates from the timeseries, indicating that the outermost rings of the Mainz planes contain a decadal scale declining trend that is likely related the ever-increasing stem girth (i.e., a classic dendrochronological age trend)(Esper et al. 2003). This trend is here estimated to equal  $-0.23$  mm per



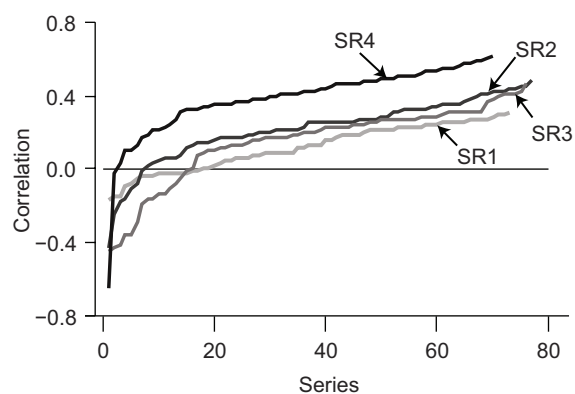
**Figure 5.** Plane tree ring data. (A) Bar plot showing the period and mean tree-ring width (TRW) of all 349 plane trees. Each bar represents one tree. (B) TRW series aligned by first year and their mean (red curve). (C) TRW anomaly series derived from calculating residuals between the original measurements and the means shown in A, aligned by first year. (D) The Mainz plane chronology (red curve) from detrended TRW anomaly series (grey).



**Figure 6.** SR chronologies (black curves) and their 25th to 75th quartile ranges (dashed curves) including city avenues (SR1), residential and parking lots (SR2), urban plazas and grass strips (SR3), and parks and playgrounds (SR4). Grey areas at the panel bottoms indicate the changing number of series averaged in the chronologies and values in white the maximum replication.

decade over the most recent tree rings (red curve in Figure 5c). The age trend complicates comparisons between tree size and growth rate as larger (and older) trees tend to produce smaller outermost rings, and thereby constrains the correlation between TRW and circumference to only  $r = 0.15$  for all 349 plane trees included in this study.

Removal of the age trend by calculating residuals from linear fits produces a dataset of coherent growth variability without any long-term trend since the early 2000s. The detrended mean chronology (red curve in Figure 5d) appears reliable after 2005 CE when  $> 50$  trees are available and the single TRW series indicate some common interannual variability ( $R_{bar} = 0.17$ ). However, this value is still much smaller than  $R_{bar}$  scores from tree-line environments that typically exceed 0.5 (Esper et al. 2010; Hellmann et al. 2016; Büntgen et al. 2017) forming the basis for long climate reconstructions beyond the instrumental period (Esper et al. 2016; Tejedor et al. 2016; Esper et al. 2018; Ljungqvist et al. 2020). The mean chronology

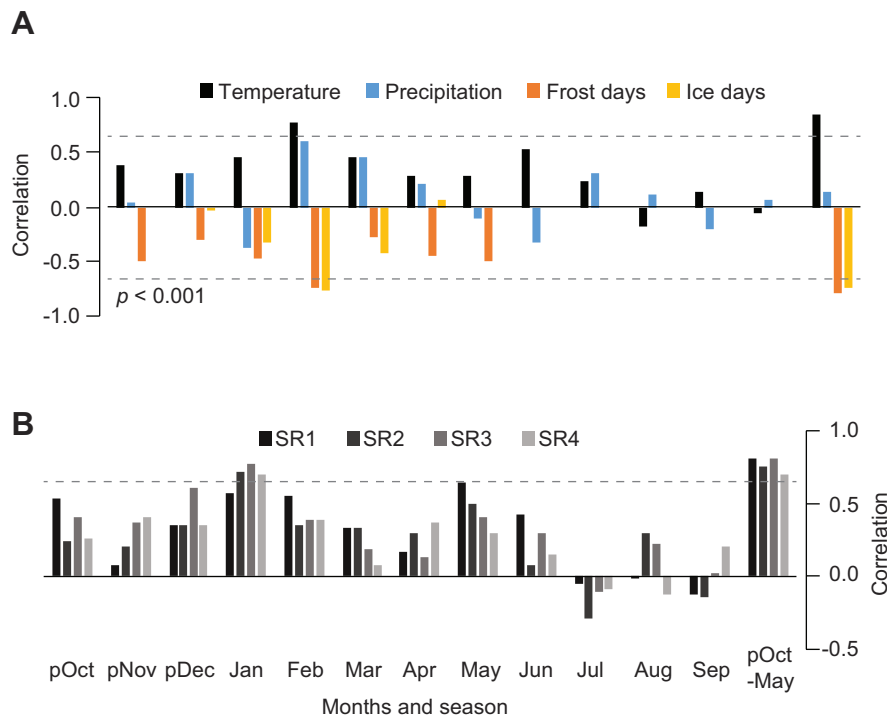


**Figure 7.** SR inter-series correlations. Mean  $R_{bar}$  values of the SR1 (city avenues), SR2 (residential and parking lots), SR3 (urban plazas and grass strips), and SR4 (parks and playgrounds) TRW series, ordered from left-to-right. Only series  $> 3$  years were used (i.e., 56 series of the total of 349 series were excluded). Table 1 shows the mean  $R_{bar}$  scores of each site rank.

illustrated here shows substantially wider rings from 1999 to 2003, but this period appears less reliable as only few series extend back that far and the spread among series is substantially increased. After 2 years of faster growth in 2007 and 2008, plane TRW was particularly small in 2009 and 2013, followed by a period of wider rings and chronology maxima in 2016 and 2018.

This pattern of narrow and wide rings since 2006 is not coherent among the site rank chronologies which suggests that the varying site conditions within Mainz altered the covariance structure among urban London planes (Figure 6). Whereas SR1 (city avenues) shows wide rings in 2007 and 2008, followed by a decline until 2013, the post-2013 data are effectively free of interannual variability. These patterns change somewhat gradually from SR1 to SR4 (i.e., the early decline diminishes), and the post-2013 data show more interannual variability. The latter is particularly striking in parks and playgrounds (SR4) that show a clear up-and-down from year-to-year since 2013 indicating that growth of planes in these sites might be controlled by deviating forcings.

Reductions and increases of interannual variability are at least partly driven by varying inter-series correlations among the single trees ( $R_{bar}$  in Table 1). A detailed analysis of the varying  $R_{bar}$  scores shows that particularly the SR4 park and playground trees deviate from the other SRs in which covariance is



**Figure 8.** Plane tree-ring climate signals. (A) Monthly and seasonal correlations between the Mainz plane chronology (ALL) and instrumental temperatures (black), precipitation (blue), frost days (orange), and ice days (yellow) from previous-year October (pOct) to current-year September, as well as a cold season average ranging from pOct to May. (B) Same as in A, but for the ranked site chronologies (SR1: city avenues, SR2: residential and parking lots, SR3: urban plazas and grass strips, SR4: parks and playgrounds) and monthly and seasonal temperatures. Dashed lines indicate  $p < 0.001$  significance estimates.

systematically lower—except for one tree in SR4 that anticorrelates with all others at  $r = -0.65$  (left data point in black curve in Figure 7). While the varying Rbar values and SR chronologies point to distinct differences between urban sites, it appears important to recall that the intersite correlation among the site rank chronologies is substantial ( $r_{2006-2019} = 0.75$ ), which indicates that the factors synchronizing growth variability across the urban structures of Mainz are surpassing the locally varying site conditions. The high intersite covariance thereby limits expectations about potentially varying climatic forcings among the plane site categories in Mainz.

### Climate Drivers of Plane Tree-Ring Growth

The ALL chronology integrating 349 detrended plane TRW series correlates significantly with cold season temperatures and covarying frost and ice days recorded at Mainz-Lerchenberg (Figure 8). The signal is strongest during (current-year) January and shows a secondary peak again in May, yet the underlying physiological

mechanisms controlling this correlation remain unclear as plant growth is dormant during much of the cold season from previous-year October to current-year April in Mainz (Linden et al. 2016). Previous-year temperature signals in plane TRW data have already been reported (Cedro and Nowak 2006) and seem to be related to the storage of carbohydrates throughout winter and remobilization during spring and summer to support earlywood development (Sala et al. 2012; Gessler et al. 2014; Jacquet et al. 2014). It is important to emphasize, however, that the calibration results shown in Figure 8 are based on rather short TRW chronologies extending over only 14 years from 2006 to 2019 and are therefore much less reliable than scores typically reported in the dendroclimatic literature based on calibration/verification periods over 100 years and more (Esper et al. 2005; Esper et al. 2008; Konter et al. 2016; Römer et al. 2021).

Compared to the temperature and associated frost and ice day signals, which exceed  $p < 0.001$ , the correlations with monthly and seasonal precipitation data remain insignificant. This comparison demonstrates



that rainfall and drought conditions, even during the currently dry-hot springs and summers, had no measurable impact on plane growth in Mainz. Instead, the urban trees appear to benefit from warmer cold-season temperatures, which are projected to increase in upcoming decades (Cheung et al. 2022). Whether the decoupling from growing season drought conditions might additionally be forced by access to (likely highly variable) groundwater levels across the city remains unclear, as the plane root systems are not accessible and spatially resolved water table and root barrier data unavailable (Gilman 2006).

While the climate-growth comparisons support hypothesis 3 on the suitability of tree-ring data to assess potential drought and temperature signals, the expected forcing differences between SR1 through SR3 and SR4 (parks and playgrounds), based on varying chronology and Rbar results (Figures 6 and 7), are not validated by the calibration statistics that appear highly uniform among the sites (Figure 8b). This finding, together with the spatially invariable exfoliation data, led us to conclude that a common climate forcing synchronizes growth variability across the urban structures of Mainz, and that the highly variable site characteristics within the city have no detectable impact on both plane growth and bark exfoliation.

## CONCLUSIONS

An unprecedented network of monitoring and TRW data from 349 plane trees has been established to evaluate spatial patterns of drought-induced bark exfoliation across the urban structures of a central European city. Unlike highly variable site conditions including changes in impervious cover, vegetation cover, and building heights, no systematic differences in plane bark exfoliation are detected. This conclusion is in line with supplementary TRW analyses revealing largely coherent growth variations among urban plane sites forced by cold season temperatures. The significant and spatially invariable temperature signal as well as the consistent exfoliation rates support the conclusion that climate rather than local site conditions control London plane stem growth and drought-induced bark peeling, limiting potential efforts to practically influence these variables in urban environments.

The conclusions from this pioneering study could be substantiated by including classic 40+ cm core

samples to support assessments of growth variability and climate signals over the past 50 to 100 years, instead of only the past 1 to 2 decades covered by  $\leq 3$  cm microcores. Additional information about locally varying groundwater access and root barriers would be beneficial, though we acknowledge that such data are difficult to generate in urban environments. It appears instructive to replicate this study in another, perhaps Mediterranean, climate zone, and to differentiate between *Platanus orientalis*, *Platanus occidentalis*, and their hybrid, *Platanus*  $\times$  *acerifolia*, using genetic analyses. Projects considering these approaches will demonstrate whether the conclusion established here on the dominance of climate forcing over site differences on plane growth and bark exfoliation will remain.

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## ACKNOWLEDGEMENTS

Supported the German Science Foundation (Grant No. ES 161/12-1), SustES (CZ.02.1.01/0.0/0.0/16\_019/0000797), ERC Advanced Grant Monostar (AdG 882727), and Gutenberg Research College. We are thankful to the Mainz Grünamt and city authorities for advice and collaboration.

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## Conflicts of Interest:

The authors reported no conflicts of interest.

Appendix on next page.