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ORIGINAL PAPER

# Urban climate modifies tree growth in Berlin

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## Abstract

Climate, e.g., air temperature and precipitation, differs strongly between urban and peripheral areas, which causes diverse life conditions for trees. In order to compare tree growth, we sampled in total 252 small-leaved lime trees (*Tilia cordata* Mill) in the city of Berlin along a gradient from the city center to the surroundings. By means of increment cores, we are able to trace back their growth for the last 50 to 100 years. A general growth trend can be shown by comparing recent basal area growth with estimates from extrapolating a growth function that had been fitted with growth data from earlier years. Estimating a linear model, we show that air temperature and precipitation significantly influence tree growth within the last 20 years. Under consideration of housing density, the results reveal that higher air temperature and less precipitation led to higher growth rates in high-dense areas, but not in low-dense areas. In addition, our data reveal a significantly higher variance of the ring width index in areas with medium housing density compared to low housing density, but no temporal trend. Transferring the results to forest stands, climate change is expected to lead to higher tree growth rates.

**Keywords** Urban heat island effect · Growth trend · Urban trees · Lime trees

## Introduction

At present, about three quarters of Europe's inhabitants live in urban or peri-urban areas and their share continues to increase (United Nations 2012). Ongoing urbanization entails changes in the local climate and other environmental conditions: (i) a stronger absorption of short-wave radiation due to a lower albedo and multiple reflection due to buildings, (ii) lower evapotranspiration values due to higher degrees of sealed surface, (iii) a higher atmospheric counter-radiation due to horizontal super elevation and a higher degree of air pollution, and (iv) a lower wind speed.

As a consequence, the average annual air temperature in major cities can be 1 to 3 °C warmer than in the neighboring rural areas (e.g., Rötzer 2007; United States Environmental Protection Agency 2014). Maximum differences occur at night with up to 12 °C found for US cities (United States Environmental Protection Agency 2014). Thereby, air temperature difference between the city center and its rural areas rises with the size of the urban population. For the city of London, Graves et al. (2001) found that air temperature decreased by 0.09 °C per mile with increasing distance from the city center. This gradient, however, differs strongly between cities. On average of 419 big cities, Peng et al. (2012) found a mean annual daytime surface urban heat island effect of 1.5 ± 1.2 °C, while the air temperature difference between urban and rural areas may be 2°–10 °C (Shepherd 2005). Besides resulting from different geographical locations, these differences can be attributed to country-specific styles of construction and architecture as well as to country-specific economic systems (Kuttler 2004).

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Along with air temperature, precipitation is higher in cities by 5 to 10% compared to their rural surroundings (Rötzer 2007). These long-term averages, as well as extreme events like heat waves, have negative consequences for the urban environment and human health. For Berlin, the largest German city, Scherer et al. (2014) observed that between 2001 and 2010, 5% of all deaths were directly related to increased air temperature. Dugord et al. (2014) state that the potential heat-stress-related risk is highest in the center of cities.

In many ways, urban trees play an important role for urban ecology and life quality in a city. Green areas, e.g., parks, gardens, or street trees, within cities improve the thermal conditions for human well-being by reducing the air temperature, especially in summer (e.g., Gill et al. 2007). Thereby, trees improve the microclimate through air cooling better than grass, which dries out quicker. Meier and Scherer (2012) studied the role of leaves and investigated the urban tree canopy temperature for different species in Berlin. They found that the small-leaved lime tree (*Tilia cordata* Mill.) is a suitable tree species for reducing air temperature due to lower crown temperature. Related studies by Leuzinger et al. (2010) show that the main factors for urban tree temperature are leaf size, location, stomatal conductance, and canopy architecture. They conclude that the cooling effect of urban trees is species-specific, and small-leaved trees, such as lime trees, show a lower leaf-to-air temperature difference at very high ambient air temperature (> 35 °C) and thus have a higher potential to cool down the immediate environment. Along with esthetic and cultural values, trees provide further environmental services such as filtering particulate matter ($PM_{10}$, $PM_{2.5}$) from the air, increasing biodiversity, or fixing carbon (McPherson et al. 1997; Nowak et al. 2013).

However, there are also several stress influences on urban trees, particularly in the view of climate change. Pauleit et al. (2002) summarize the main challenges for tree life in urban areas of European countries. For Germany soil, de-icing salt, elevated summer temperature, and frost damage are the main influencing factors for stress on trees. Further, water supply plays a fundamental role for tree growth. In cities, it is often impaired by sealed surfaces hampering water infiltration into the rooting zone (Gillner et al. 2013, Randrup et al. 2001). In addition, urban soil compaction might lead to a reduction of soil oxygen and water exchange, resulting in immediate as well as long-term effects on tree health and growth (Randrup et al. 2001). Furthermore, stress can emerge from subsurface pollution and mechanical disturbances (Quigley 2004). Despite the fact that a lot of factors influencing urban tree growth are well known, knowledge on their specific contribution to trees' growth and vitality is still limited. While structural changes of trees caused by changing climate conditions are already reported (Pretzsch et al. 2015; Moser et al. 2015), these studies do not consider differences in the housing density within a city.

Projections for the future development of the abovementioned changing conditions are predicted as becoming more extreme, especially in urban areas (McCarthy et al. 2010). Thus, when compared to forest-stands, urban trees are already more affected by changing climate conditions, which may result in both positive or negative effects on tree growth. Due to this, the urban areas give us the opportunity to investigate the response of urban species to climate change (Farrell et al. 2015). These unique possibilities have been little noticed until now but enable us to already study today the changes of our ecosystems due to climate change (Youngsteadt et al. 2015). Thereby, the differences in environmental conditions between high- and low-dense areas in cities can be large, while the spatial distances are small.

Time series of tree stem growth provides valuable information about growth trends and environmental changes (Schweingruber 1996). Forest science has been using the indicative potential of time series of tree size growth for a long time to quantify the site quality by site-indexing (Skovsgaard and Vanclay 2008), to measure various effects of silvicultural treatment such as pruning, thinning, or fertilization (Assmann 1970), to provide pieces of evidence and claim for compensation in cases of damage of forest by e.g., building operations, and increasingly to eco-monitor human impact on forest ecosystems (Cherubini et al. 2004; Pretzsch 1989) or climate change (Briffa et al. 2004; Pretzsch et al. 2014; Uhl et al. 2013). With just a few exceptions mainly dealing with tree damage or dieback (Eckstein et al. 1981; Gillner et al. 2014, Helama et al. 2012), urban trees so far were hardly used for revealing growth trends and environmental changes (Cook and Kairiukstis 1992). The main reason may be a higher reluctance against sampling urban trees, as any damage or even drop out caused by increment coring is easily compensated by neighboring trees in forests but not in the case of solitarily growing trees in streets or parks. In this study, tree-ring patterns from the center and peripheries of a metropolis were analyzed with regard to the long-term trends in growth.

For a better understanding of urban tree growth influenced by the small-scale environmental conditions, we investigate the long-term growth of *T. cordata* and the growth response on the changing climate conditions in an urban environment. To do so, we use time series analyses of tree stem growth. Measuring and analyzing more than 200 small-leaved lime trees (*Tilia cordata* MILL.) starting from a gradient in the center of the city of Berlin to the surrounding forest, we look at tree-ring patterns and their dependencies on the environmental conditions. Analyzing these data, we focus on the following research questions:

1. How do lime trees generally grow in the city of Berlin and its surroundings?

2. Is there a relation between the growth behavior of lime trees and environmental conditions, e.g., climate variables or housing density?
3. Does the sensitivity differ depending on housing density?

## Materials and methods

### Site description

Berlin is situated within the North-German young moraine landscape. The Warsaw-Berlin glacial valley crosses the city from South-East to North-West. South and North-East of Berlin is bordered by the Teltow-Barnim highlands. Topography varies moderately between 34 m to 115 m asl. Berlin covers an area of 892 km$^2$, with a maximum expansion of 45 km in East-West direction and 38 km in North-South direction. With 3.5 Mio inhabitants, Berlin is the most populated city of Germany. Berlin is subdivided in 12 districts (Fig. 1), from which 9 were selected for sampling. The share of green areas in the city amounts to more than 30% which is exceptionally high in comparison with other European metropolises (Kabisch and Haase 2014).

The region of Berlin belongs to the temperate climate zone with continental influence. Annual mean air temperature is 9.5 °C; the mean precipitation amounts to 578 mm with a typical peak between April and September (1961–1990).

From the climate station in Berlin-Dahlem (52.41° N; 13.31° E), which is situated in the surrounding area of Berlin referring to a low housing density and from a second station at Berlin-Alexanderplatz (52.52° N; 13.41° E), which is located in the highly dense city center of Berlin, monthly climate data since 1961 are available. Climate data from the station Alexanderplatz were not available between 1961 and 1980 and between 1992 and 1999. Missing values were calculated by fitting a linear least squares regression for each of the two periods on the base of the two measured periods 1981–1991 and 2000–2011 (see appendix Table 5). Temperature respectively precipitation data of the site Berlin-Dahlem form the independent parameter data while the data of Berlin-Alexanderplatz are the dependent values. The regression equations of the first period (1981–1991) were used to estimate the data of the period 1961–1980; the regression equations of the period 2000–2010 were used for the calculation of the period 1992–1999 (see appendix Table 5).

### Data acquisition

In total, 252 lime trees were measured in the city of Berlin and its periphery. Sampling campaign was conducted in three periods, in October 2010, in April 2012, and in October 2013. *Tilia cordata* was chosen as it is the most frequent street and park tree in Berlin. *Tilia cordata* is known as a shade tolerant and more or less drought-sensitive tree species (Köcher et al. 2009, Gillner 2012, De Jaegere et al. 2016). This species is able to absorb heavy metals (Gworek et al. 2011) but is more sensitive to emissions and road salt compared to other species like *Platanus* (Schütt et al. 2013).

For the sampling, only healthy trees were considered in order to exclude confounding effects caused by tree diseases. Trees were required to have a diameter at breast height (dbh) above

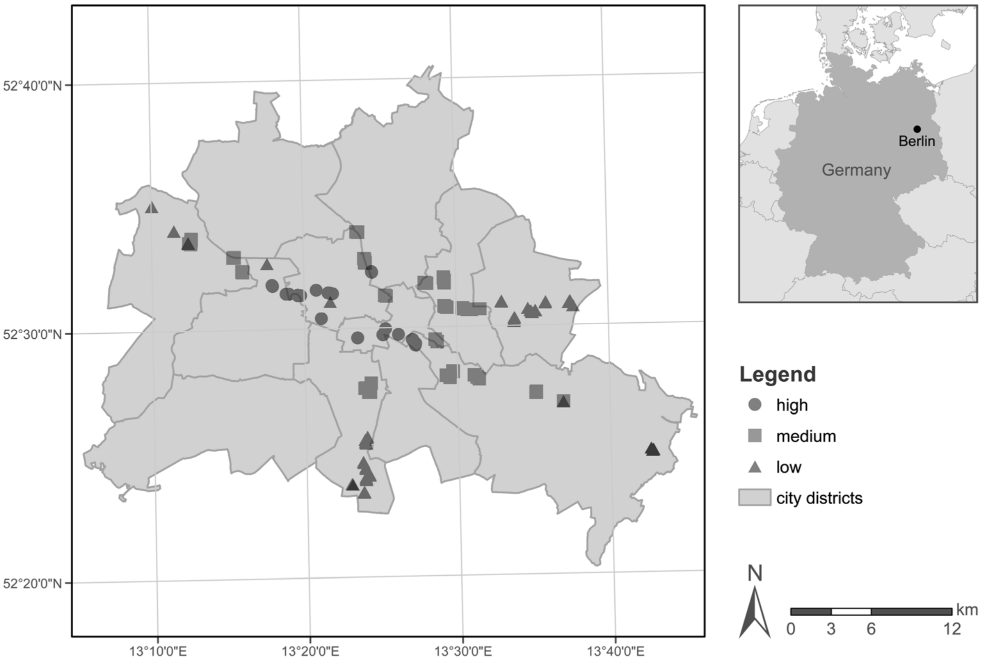


**Fig. 1** Map of the sampling locations of this study, by housing density types: high (circle), medium (rectangle), and low (triangle) within the city of Berlin; the gray borderlines visualize the administrative city districts

40 cm, because otherwise the resulting tree-ring time series would not date back far enough for the purpose of this study. A full list of the selected trees and their parameters is shown in the supplement table. For each tree, the surrounding housing density was classified as “high” (hd), “medium” (md), or “low” (ld), based on the housing density map of Berlin (Urban Observatory, ESRI, 2014). This map displays land use data, with the three categories being classified based on square meters of land area per dwelling.

For all investigated trees, dbh was measured with a diameter tape, the crown radii in eight cardinal and sub-cardinal directions, and crown projection via the vertical sighting method (Preuhsler 1979). Tree height and height to crown base were recorded by using the Vertex IV ultrasonic hypsometer.

For the time series analysis, two increment cores were taken from each tree using a 5 mm increment borer. Where possible, the coring was done from north and east direction. At least two cores at an angle of 90° were taken for minimizing the error rate due to a non-concentric growth. The 504 cores were polished on a sanding machine with 320 grade sandpaper. After preparation, the tree-ring widths were measured with a Digital Positiometer after Johann (Johann 1977) using the software Lignometer. Radius was derived by backwards calculation using the year ring width values. Out of this, the basal area was calculated by means of quadratic mean radius of the two cores per tree. Current annual increment was examined by the difference between the basal areas of two consecutive years of basal area. Cross-dating was conducted firstly visually and then by using the dplR library in R (Bunn 2008). Dimensionless ring-width indices (RWI) were calculated by fitting a smoothing spline of 0.67 of series length with a 50% frequency cutoff. Strength of the common signal is expressed by the EPS (Expressed Population Signal) value using a 50-year moving window. A resulting EPS value above 0.84 (Wigley et al. 1984) indicates an adequate strength of the common signal for the time series and confirms further use of the data.

### Quantifying general growth trends

For analyzing the general growth trend of *T. cordata*, the data set was split into the two periods, 1961–1990 and the period after 1990. The general growth trend is analyzed in a first step for trees in low-dense areas, to exclude the urban impacts, and thereafter for trees in high-dense areas. Doing so, the influence of the urban environment on the general growth trend is considered. A detailed description can be found in the digital appendix.

### Sensitivity of the annual tree increment

For analyzing the sensitivity, which means in our case the oscillation of RWI along the mean value, we used the variance of the RWI (see digital appendix).

### Analysis of the relationship between growth and climate parameters

By using a fitted mixed linear model the relationship between the growth of high- and low-dense urban trees and climate conditions was tested (see digital appendix).

## Results

Air temperature in the city of Berlin was continuously higher over the last 50 years in comparison to the rural site (see Fig. 2 and Table 2). Differences of the 10-year means range from 1.1 °C in the first decade (1961–1970) to 1.4 °C in the last decade (2001–2010). Based on the decadal means (Table 1), the annual air temperature of both sites increased during the 50-year period, in the city center from 9.7 to 11.1 °C and in the periphery from 8.6 to 9.7 °C. The differences of the precipitation amounts of the two sites are largest in the last 20 years, showing higher precipitation sums in the periphery (Table 1).

Most of the sampled trees (107) are situated in a low housing density environment (Table 2), scarcely less (102) in the medium dense area, and the fewest (43) in the city center. Based on the mean values of the measured tree parameters, slight differences among the different housing density classes can be reported. Average tree height and mean growth are largest in the low-density zone, the trees in the medium-density zone show the highest age range, and the trees in the high-density zone have the greatest crown projection area. For the low-dense and high-dense sites, the average growth rate is on a very similar level, but on the medium dense site, it is remarkably lower. Same findings can be stated for the related standard deviation.

The mean courses of the annual radial increment (Fig. 3) show a typical age-related growth trend. This is the case for

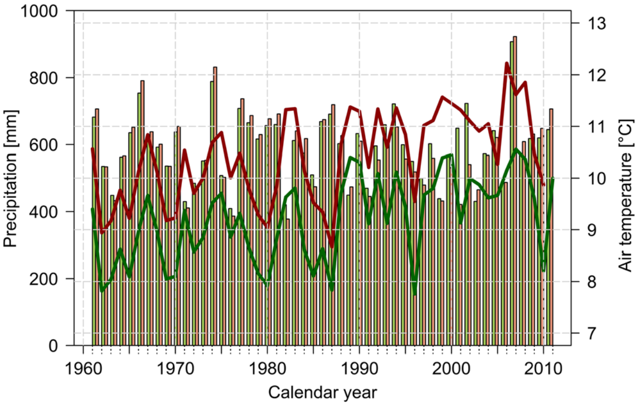


**Fig. 2** Air temperature (annual mean; solid line) and precipitation (annual sum; bars) from the climate station “Alexanderplatz” in the city center (red) and from the peripheral station “Dahlem” (green) in Berlin for the period 1961–2011

**Table 1** Climatic parameters (air temperature and precipitation) for the "Alexanderplatz" climate station in the city center (CC) and for the station "Dahlem" in the periphery (PP) of Berlin are shown as decadal means. Δ indicates the difference between CC and PP.

| | City center | Periphery | Δ |
|---|---|---|---|
| Air temperature [°C] | | | |
| 1961–1970 | 9.7 | 8.6 | 1.1*** |
| 1971–1980 | 10.0 | 8.9 | 1.1*** |
| 1981–1990 | 10.4 | 9.2 | 1.2*** |
| 1991–2000 | 10.9 | 9.6 | 1.3*** |
| 2001–2010 | 11.1 | 9.7 | 1.4*** |
| Precipitation [mm] | | | |
| 1961–1970 | 611 | 601 | 10 |
| 1971–1980 | 589 | 582 | 7 |
| 1981–1990 | 591 | 582 | 9 |
| 1991–2000 | 533 | 570 | − 37*** |
| 2001–2010 | 591 | 622 | − 31 |

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

the complete data set, as well as for the single housing density classes. Standard deviation is lowest for the younger years of the course.

## General growth trends

The overall growth trends of lime trees in the low-dense areas of Berlin are illustrated in Fig. 4 in form of the Delta values of the mean basal area increment ($\Delta ig$). Data are calculated for three age classes (below 40 years, 41 to 80 years, and above 81 years) and depicted over the time period from 1991 to 2011. The reference line symbolizes the growth of all low-dense lime trees estimated from the applied Bertalanffy model (Eq. 1–3 in digital appendix). The fact that the growth course of the younger trees steadily remains above the reference line shows that the growth rate is at a higher level than the average growth. The mean $\Delta ig$ of young trees, aged < 40 years, shows that during the last 20 years, these young trees have grown on average 10 $cm^2\ yr^{-1}$ more (linear regression slope = 0.893 $cm^2\ yr.^{-1}$; $r^2 = 0.62$). Trees of higher age indicate a slow increasing trend which exceeds the reference line by the mid or end of the 90's. For trees, aged between 41 and 80 years, the $\Delta ig$ increases by 0.234 $cm^2\ yr.^{-1}$ ($r^2 = 0.19$), when considering the complete period. Thereby, the course is not consistently increasing and shows two lows for the drought years 1997 and 2004. The oldest trees have the slightest increase (slope = 0.210 $cm^2\ yr^{-1}$; $r^2 = 0.21$) over the considered period, but still show a higher growth than the reference after the year 2004.

For investigating the influence of housing density on tree growth, Fig. 5 displays the difference in growth between high- and low-dense areas. For doing so, two age groups (trees aged younger 60 years or older 60 years) are defined. This division was based on previous analysis of the growth data in 10-year intervals (see appendix Figs. 7, 8, 9, and 10). The data is presented as Delta values and thus directly relates the growth values from high- to low-dense areas. In difference to the before shown results (Fig. 4), the following analysis takes only the measured data into account.

For the younger trees, it can be said that on average positive values, representing a better growth in the high-dense areas, are found between 1981 and 2000, with a first short decline around 1990, 1995, and 1997. Before the year 1981, as well as after 2000, the younger trees grew better in low-dense environments. In difference, before 2002, the older trees grew on average better in the low-dense areas. Before 1976, as well as after 2002, the growth of trees older than 61 years was higher in the high-dense areas, except the year 2007. Interestingly, the comparison of the two age classes shows that the growth reactions to housing density, between younger and older trees, are always opposing. These differences illustrated in Fig. 5 might be related to the ambient climate conditions which vary due to housing density.

**Table 2** Mean values of the measured tree parameters for the complete dataset (all) and the different housing density classes referring to the time period 1900–2011 (growth parameters) and 2011 (tree parameters)

| | All | Low | Medium | High |
|---|---|---|---|---|
| Number of trees | 252 | 107 | 102 | 43 |
| dbh (cm) | 44 (16.5–80.4) | 44 (16.5–80.4) | 45 (25.2–76.8) | 42 (32.8–54.7) |
| Tree height (m) | 17 (8–29) | 18 (10–29) | 16 (8–26) | 16 (12–22) |
| Age range (year) | 32–192 | 33–192 | 32–182 | 48–118 |
| Crown projection area ($m^2$) | 82 (20–286) | 83 (21–286) | 78 (20–199) | 92 (33–148) |
| Avg. radial growth rate ($mm\ yr^{-1}$) | 2.26 | 2.44 | 2.06 | 2.38 |
| Standard deviation of growth rate | 1.00 | 1.16 | 0.82 | 0.89 |
| Expressed Population Signal (EPS) | 0.93 | 0.82 | 0.86 | 0.82 |

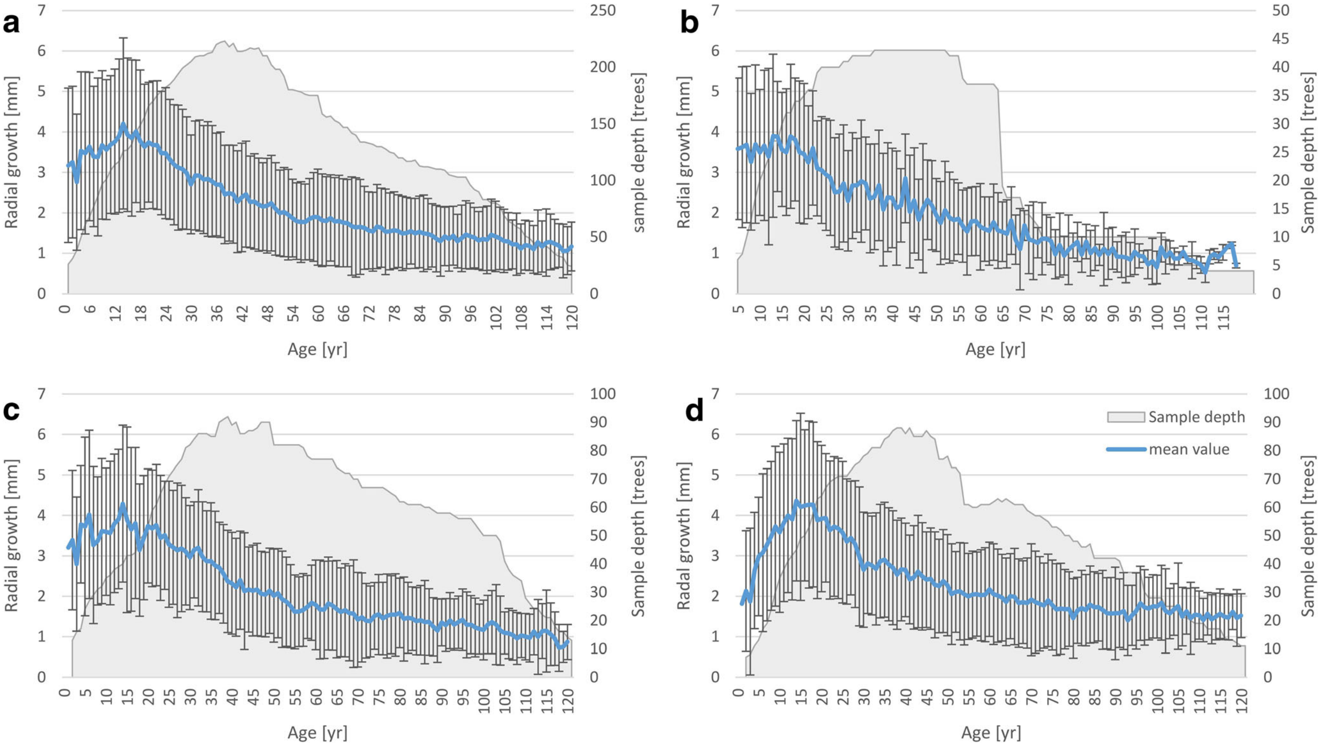


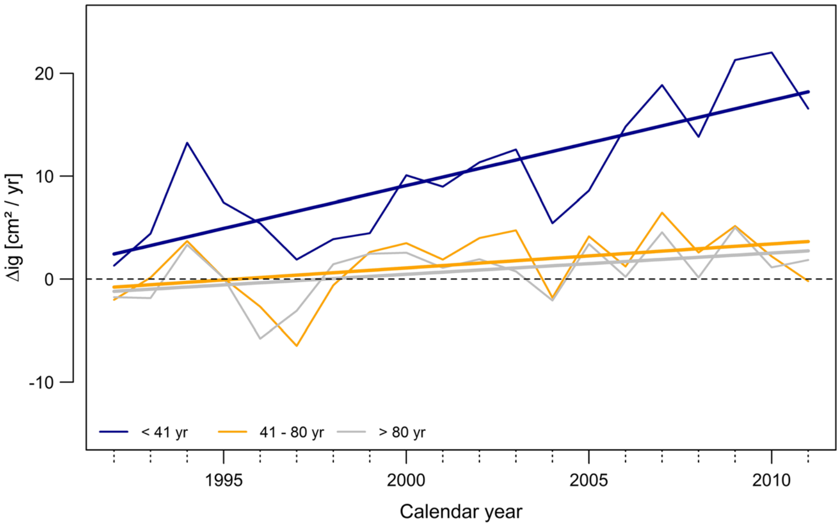
**Fig. 3** Mean value (blue line) of radial growth average, sample depth (gray line), and standard deviation (bars) over age for all (**a**), "high-dense" (**b**), "medium-dense" (**c**), "low-dense" trees (**d**) referring to the period 1900–2011

## Sensitivity of growth course

For investigating the growth sensitivity, the variances of RWI per housing density for the two observation periods were calculated and are depicted in Fig. 6. The variances are lowest in the ld (low-dense) areas and highest in the md (medium-dense) areas. Comparing the two periods, the variances for these two housing density classes decrease from the first to the second period, while the variances of the hd (high-dense) trees increase.

In a next step, the variances of the different trees were analyzed by using a Linear Mixed Effect model (Eq. 5 in digital appendix). Results summarized in Table 3 reveal significant differences between the classes ld and md, having higher variances in md areas. Variances of the hd areas were not significantly different from the ld areas. Further, the model reveals that the differences between the two observation periods reported above (Fig. 6) are not significant, neither in general nor for one of the housing density classes. In difference, the tree age at the time of coring (variable *end.age*) is

**Fig. 4** Delta values of mean basal area increment (Δig) of the "low-dense" trees for the age classes < 41 years (blue), 41–80 years (yellow), and > 80 years (gray); bold graph indicates the linear trend



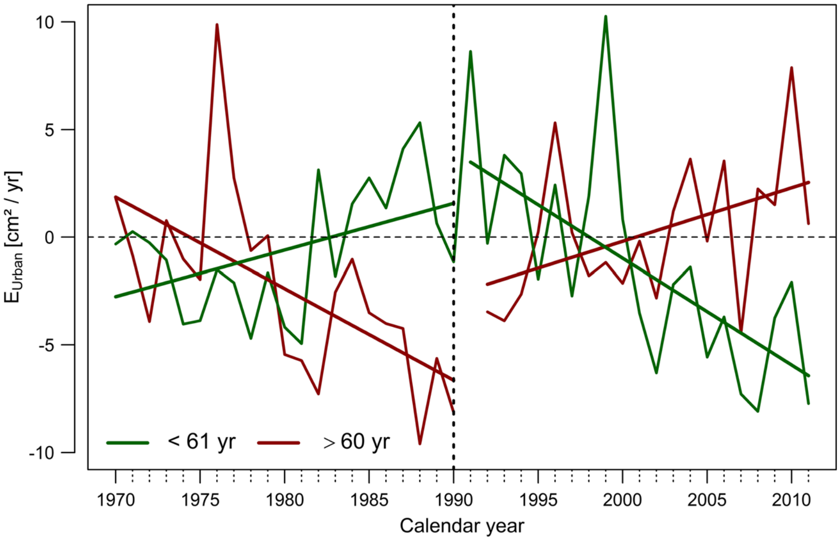


**Fig. 5** Effect of urban climate on tree growth ($E_{Urban} = \overline{ig}_{hd} - \overline{ig}_{ld}$) shown for two age classes < 61 years (green) and ≥ 61 years (red), with the bold lines indicating the linear trend for the respective age classes and observation periods

highly significant which means that older trees have a higher variance than younger ones.

## Relationship between growth and climate

For analyzing the relationship of growth patterns and climate parameters, a linear mixed effect model (Eq. 6 in digital appendix) was applied. Influence of the parameters air temperature, precipitation, and DMI on RWI were tested in combination with varying coefficients like time period (*period1* (before 1990) and *period2* (after 1990)) as well as housing density. The results (Table 4) show significant effects of air temperature, precipitation, and DMI on RWI for the second period and high housing density. Precipitation and DMI further show a significant effect on RWI for the first period and high housing density. In difference, no significant effects of air temperature, precipitation, and DMI on RWI can be found in low-dense areas.

Thereby, air temperature has a positive effect on RWI, while the effect of precipitation is negative. Thus, the growth of trees in high dense areas seems to be benefitted by rising air temperature, while higher precipitation rates seem to stress the trees.

## Discussion

Our findings regarding general growth trends show opposite growth trends before and after 1990. An explanation for these differences might be the increased urban development measures in Berlin starting after 1990 (Schmelcher 2011).

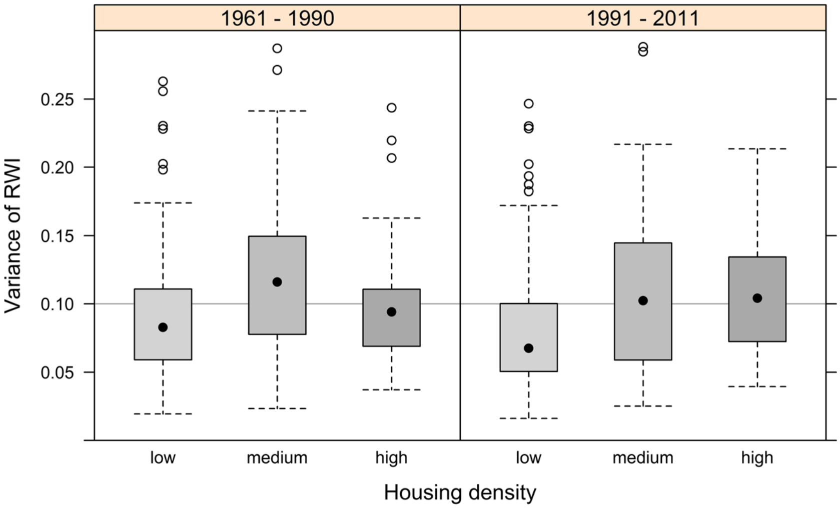


**Fig. 6** Variances of RWI separated by housing density classes and growth periods illustrated as boxplots. The point within the box indicates the median

Correspondingly, we find a zonal effect, showing that during the last ten observed years, the trees in high-dense areas, younger than 60 years, are stressed by increased building density resulting in more extreme climate conditions. While air temperature varies only marginal between the two climate stations, precipitation shows a remarkable decrease during the last two decades for the city center, but not for the periphery. This reduction in water availability might be one reason for the growth decline of the young trees in highly dense areas during this period, whereas the older trees respond with higher growth to this change. Older trees might cope better with the reduced water supply, as they might generally be better adapted to limited resource supply than the younger trees. This finding contradicts with findings from Quigley (2004), who investigated forest and urban trees distributed in three different successional categories. For early successional trees, he finds that young trees are more tolerant to urban conditions, as they have faster growth rates in urban areas. However, this finding is not directly related to precipitation, but to urban conditions in general.

Looking deeper into the relationship between air temperature and housing density, Fenner et al. (2014) investigated different classes of both highly and less densely built-up areas within the city of Berlin. Looking at the period 2001 to 2010, they observed higher air temperature within the urban areas compared to the rural areas. These data confirm the data underlying the analyis of the current article, which also show higher air temperature for the climate station in the city center. These higher air temperatures in urban areas, in turn, were shown to prolong the vegetation period. In this context, Rötzer et al. (2000) reported an early flowering in urban areas.

Sensitivity can be understood as a kind of indicator for the vulnerability of tree growth to climate conditions (Gillner et al. 2013, Gillner et al. 2014, Schweingruber, 1996). As reported by Schweingruber (1996) for natural habitats, the trees with extreme environmental conditions show highest sensitivity. In the present study, the highest sensitivity was found in the medium-dense areas, before as well as after 1990. When transferring the finding from Schweingruber (1996) to the present finding, this would mean that the medium-dense sites are expected to have the most extreme environmental conditions. This cannot be proven with the climate data available for this study. However, the finding appears reasonable, considering that medium-dense areas have undergone the biggest change in recent years, as urban development mostly takes place in these areas.

While we already nowadays observe differences in climate conditions between urban and rural sites, future projections predict especially for the urban areas intensified climate conditions causing thermal stress and vulnerability to heat waves (McCarthy et al. 2010). In line with this, Bowler et al. (2010) point out that confounding variables such as ground cover, distance to sea, and height-to-widths-ratio of street canyons vary between different investigation sites and affect the local air temperature conditions. However, according to Jones (2004) and Parker (2004), no influence of urbanization on the large-scale warming is found.

Still, as aforementioned, the differences in tree growth found between different housing density sites are expected to be moderated by climate parameters. For example, Gregg et al. (2003) report for New York that ozone has a strong influence on tree growth. In this article, however, we focused on the climate parameters precipitation and air temperature. Like the results from our last model (see Table 4) show, air temperature and precipitation have strong influences on tree growth. Thereby, in high dense areas higher air temperature led to higher growth rates, whereas the opposite was the case in low-dense areas. These diverse findings can be confirmed by previous studies, which show that growth reactions on increased air temperature depend on several factors, e.g., tree species, latitude, or altitude (Carrer and Urbinati 2006, Way and Oren 2010). Regarding precipitation, our findings show that after 1990, higher precipitation led to lower growth in high dense areas, but higher growth in low-dense areas. In line with this, previous findings regarding the effect of precipitation on tree growth are confounding. David et al. (2015) confirm the availability of water as being one of the main limiting factors for urban tree growth in Paris. On contrary, De Jaegere et al. (2016) report in their review on *T. cordata* in European forest stands that above the precipitation threshold of 550–600 mm per year, water supply becomes secondary. The annual precipitation sum of Berlin is similar to the abovementioned value, but it has to be considered that in an urban environment due to the impervious runoff, a considerable amount of precipitation does not reach the tree roots. In line with this assumption, Dahlhausen et al. (2016) find a limitation in tree growth for different tree species in urban environments due to a restriction in non-paved area. Still, with the presented results, the statement of De Jaegere et al. (2016) can be confirmed for older trees, but not for trees younger 60 years.

Specific for *T. cordata*, De Jaegere et al. (2016) further state that this species is highly tolerant against heat waves and drought events, wherefor it has an important advantage to other species when adapting to the warming climate conditions. Correspondigly, the effects of climate parameters on tree growth are even higher for other tree species as reported by Friedrichs et al. (2009). In their study, they investigated the growth response of *Fagus*, *Pinus*, and *Quercus* in two German low mountain forest sites and found water availability as the main impact factor of tree growth. Further, they stated an increasing impact during

**Table 3** $VRWI_{ij}$ estimates from LME model (Eq. 5 in digital appendix)

| | Estimate | std. error |
|---|---|---|
| Intercept | 0.0412 *** | 0.009928 |
| Medium-dense | 0.0303 ** | 0.009209 |
| High-dense | 0.0285 | 0.011929 |
| Medium dense: High dense | − 0.0018 | 0.012148 |
| Period1 | 0.0075 | 0.008599 |
| End age | 0.0005 *** | 0.000097 |
| Medium-dense × period1 | 0.0052 | 0.012310 |
| High-dense × period1 | − 0.0122 | 0.016061 |
| Medium-dense × period1: High dense × period1 | − 0.0174 | 0.016174 |

Period1 denotes the timespan 1961 to 1990. The reference level was set to period2 (1991 to 2011) and to low housing density

** $p < 0.01$, *** $p < 0.001$

the last decades. These findings are similar to those presented in the study at hand. Moser et al. (2016) investigated the annual growth and drought tolerance of *T. cordata* in two German cities and classified the species as moderate drought tolerant and found out that the growth reductions of *T. cordata* after a drought event were delayed compared to other species as *Robinia pseudoacacia* which was also investigated in their study. These findings confirm the species-specific reaction patterns as well as the drought tolerance.

**Table 4** Results of selected linear combinations and coefficients based on model (6). *HD* high dense, *LD* low-dense

| Independent variables | Estimate | std. error |
|---|---|---|
| Temp HD period1 | − 0.166 ** | 0.056 |
| Temp HD period2 | 0.487 *** | 0.097 |
| Temp HD period2: period1 | 0.653 *** | 0.112 |
| Prec HD period1 | 0.005 ** | 0.002 |
| Prec HD period2 | − 0.019 ** | 0.003 |
| Prec HD period2: period1 | − 0.024 *** | 0.004 |
| DMI HD period1 | − 0.099 ** | 0.037 |
| DMI HD period2 | 0.409 *** | 0.074 |
| DMI HD period2: period1 | 0.508 *** | 0.083 |
| Temp LD period1 | − 0.007 | 0.047 |
| Temp LD period2 | − 0.028 | 0.079 |
| Temp LD period2: period1 | − 0.022 | 0.092 |
| Prec LD period1 | 0.0009 | 0.002 |
| Prec LD period2 | 0.002 | 0.002 |
| Prec LD period2: period1 | 0.001 | 0.003 |
| DMI LD period1 | − 0.014 | 0.029 |
| DMI LD period2 | − 0.039 | 0.049 |
| DMI LD period2: period1 | − 0.025 | 0.057 |

Period1 denotes the timespan 1961 to 1990 and period2 denotes 1991 to 2011

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

## Conclusion

Summing up, the study at hand represents a comprehensive data set on *T. cordata* growth patterns within the city of Berlin. The results reveal that through local climate, especially in terms of precipitation, housing density impacts urban tree growth.

The urban environment setting gives the opportunity to already today investigate possible effects of climate change on tree growth. While the growth patterns of forest stands cannot be transferred to urban trees, the analysis of urban trees might serve as a possibility to predict future growth behavior of forest stands. Thus, especially the results of the high-dense area are of high interest. These show stronger growth rates with rising air temperature and with decreasing precipitation, indicating that climate change could lead to higher growth rates.

However, when drawing such a conclusion, the following methodological considerations should be regarded. First, the sample size in the high dense area was relatively low. Differences between the urbanization zones might be explained by differences in the tree parameters (dbh, tree height, age range, crown projection area). Further, for the interpretation of the comparison of the different urbanization zones, other factors besides housing density, e.g., building development, might be important. Second, different soil water conditions in urban areas might have an influence on tree growth (Günther 2014). In the present article, it was considered whether the individual tree is situated within the glacial-valley (*gv*). However, as the parameter did not show a significant effect, it was not reported within the results. Third, climate change has further influences in specific in urban areas, e.g., higher atmospheric $CO_2$-concentrations, lower $O_3$-concentration, or fertilization through N-deposition. These changes in air quality parameters are expected to have a positive influence on tree growth (Churkina et al. 2010, George et al. 2007, George et al. 2009, Gregg et al. 2003, IPCC 2014, Kaye et al. 2006, Searle et al. 2012). On the downside, climate change also goes along with negative effects, e.g., drought events, which lead to reduced tree growth (Rötzer et al. 2013, Hartmann 2011, Pretzsch and Dieler 2011) or even tree death (Griess and Knoke 2011, McDowell et al. 2008, Allen et al. 2010). For the present article, it was not possible to relate air quality data to the tree growth data, because air quality data were not available in higher spatial resolution and over a longer period.

Last but not least, the review of De Jaegere et al. (2016) reveals that, due to the lack of observations, the expected impacts of climate change on the vitality of *T. cordata* is generally based on its biology and model calculations. Thus, further investigation on the impact of climate change on *T. cordata*, as well as on other tree species in urban environments, is needed.

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## Appendix

**Table 5** Statistical variables for the gap filling regressions for air temperature and precipitation

| Parameter | Gap filling period | a | b | $R^2$ |
|---|---|---|---|---|
| Air temperature | 1961–1980 | 1.0263 | 0.9168 | 0.879 |
| | 1992–1999 | 0.7665 | 3.602 | 0.543 |
| Precipitation | 1961–1980 | 1.1735 | 93.664 | 0.947 |
| | 1992–1999 | 0.8541 | 26.039 | 0.4382 |

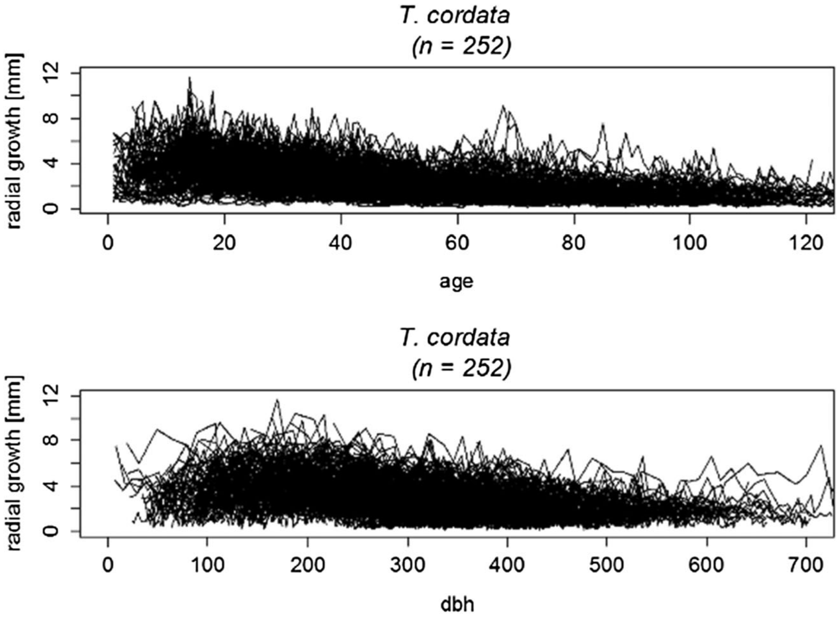

**Fig. 7** Radial growth of all sampled lime trees in Berlin over age (upper) and over diameter at breast height (lower)

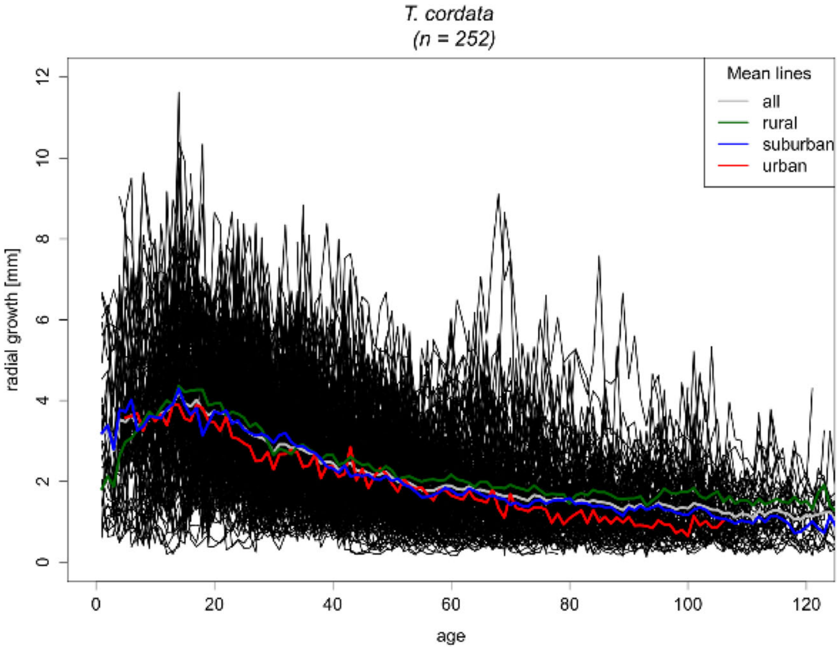

**Fig. 8** Radial growth of all sample lime trees in Berlin and the mean lines for the different data subsets; low-dense (green), medium-dense (blue), high-dense (red), and for the total data set (gray)

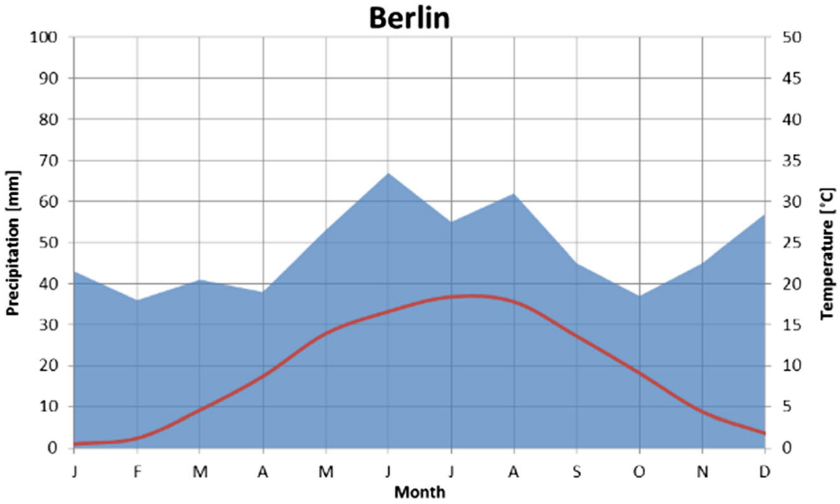

**Fig. 9** Climate diagram for the city of Berlin (climate station Berlin-Dahlem) referring to the period 1961–1990

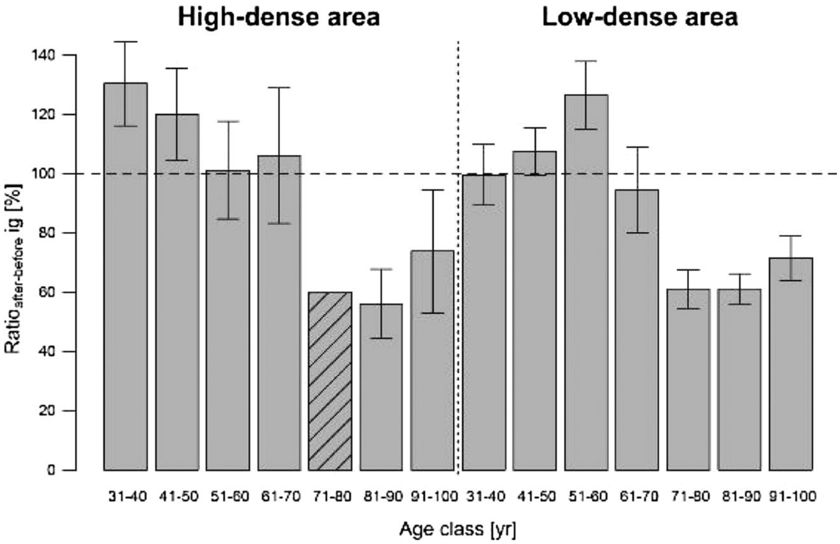

**Fig. 10** Ratio$_{after\text{-}before}$ ig (ig$_{1991–2011}$/ig$_{1961–1990}$) for 10-year age classes (including the confidence intervals) comparing "high-dense" versus "low-dense" area. The crosshatched bar indicates that the sample size for this age class and area is below 50 trees

## References

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshear DD et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259(4):660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Assmann E (1970) The principles of forest yield study. Pergamon Press, Oxford, New York, 506 p

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010) Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landsc Urban Plan 97(3):147–155. https://doi.org/10.1016/j.landurbplan.2010.05.006

Briffa KR, Osborn TJ, Schweingruber FH (2004) Large-scale temperature inferences from tree rings: a review. Glob Planet Chang 40(1-2): 11–26. https://doi.org/10.1016/S0921-8181(03)00095-X

Bunn AG (2008) A dendrochronology program library in R (dplR). Dendrochronologia 26(2):115–124. https://doi.org/10.1016/j.dendro.2008.01.002

Carrer M, Urbinati C (2006) Long-term change in the sensitivity of tree-ring growth to climate forcing in Larix decidua. New Phytol 170(4): 861–872. https://doi.org/10.1111/j.1469-8137.2006.01703.x

Cherubini P, Gärtner H, Esper J, Dobbertin MK, Kaiser KF, Rigling A, Treydte K, Zimmermann NE, Bräker OU (2004) Jahrringe als Archive für interdisziplinäre Umweltforschung| Annual rings as an archive for interdisciplinary environmental research. Schweiz Z Forstwes 155(6):162–168. https://doi.org/10.3188/szf.2004.0162

Churkina G, Zaehle S, Hughes J, Viovy N, Chen Y, Jung M, Heumann BW, Ramankutty N, Heiman M, Jones C (2010) Interactions between nitrogen deposition, land cover conversion, and climate change determine the contemporary carbon balance of Europe. Biogeosciences 7(9):2749–2764. https://doi.org/10.5194/bg-7-2749-2010

Cook ER, Kairiukstis LA (eds) (1992) Methods of dendrochronology: applications in the enviromental sciences. Kluwer Academic Publishers, Dordrecht, 394 p

David A, Boura A, Kraepiel Y, Lata J-C, Barot S, Abbadie L, Ngao J. (2015) Long term impact of climate on tree-growth patterns in Paris street trees and its consequences on tree cooling potential: a dendroclimatic approach. Conference paper, ICUC9.

Dahlhausen J, Biber P, Rötzer T, Uhl E, Pretzsch H (2016) Tree species and their space requirements in six urban environments worldwide. Forests 7(6):111. https://doi.org/10.3390/f7060111

De Jaegere T, Hein S, Claessens H (2016) A review of the characteristics of small-leaved lime (Tilia cordata Mill.) and their implications for silviculture in a changing climate. Forests 7(3):56. https://doi.org/10.3390/f7030056

Dugord P-A, Lauf S, Schuster C, Kleinschmit B (2014) Land use patterns, temperature distribution, and potential heat stress risk—the case study Berlin, Germany. Comput Environ Urban Syst 48:86–98. https://doi.org/10.1016/j.compenvurbsys.2014.07.005

Eckstein D, Breyne A, Aniol RW, Liese W (1981) Dendroklimatologische Untersuchungen zur Entwicklung von Straßenbäumen. Forstw Cbl 100(1):381–396. https://doi.org/10.1007/BF02640656

Esri (2014) Urban Observatory. Environmental Systems Research Institute, CA

Farrell C, Szota C, Arndt SK (2015) Urban plantings: 'living laboratories' for climate change response. Trends Plant Sci 20:597–599. https://doi.org/10.1016/j.tplants.2015.08.006

Fenner D, Meier F, Scherer D, Polze A (2014) Spatial and temporal air temperature variability in Berlin, Germany, during the years 2001–2010. Urban Climate 10:308–331. https://doi.org/10.1016/j.uclim.2014.02.004

Friedrichs DA, Trouet V, Büntgen U, Frank DC, Esper J, Neuwirth B, Löffler J (2009) Species-specific climate sensitivity of tree growth in Central-West Germany. Trees 23(4):729–739. https://doi.org/10.1007/s00468-009-0315-2

George K, Ziska LH, Bunce JA, Quebedeaux B (2007) Elevated atmospheric CO2 concentration and temperature across an urban–rural transect. Atmos Environ 41(35):7654–7665. https://doi.org/10.1016/j.atmosenv.2007.08.018

George K, Ziska LH, Bunce JA, Quebedeaux B, Hom JL, Wolf J, Teasdale JR (2009) Macroclimate associated with urbanization increases the rate of secondary succession from fallow soil. Oecologia 159(3):637–647. https://doi.org/10.1007/s00442-008-1238-0

Gill SE, Handley JF, Ennos AR, Pauleit S (2007) Adapting cities for climate change: the role of the green infrastructure. Built Environment:115–133

Gillner S (2012) Stadtbäume im Klimawandel - Dendrochronologische und physiologische Untersuchungen zur Identifikation der Trockenstressempfindlichkeit häufig verwendeter Stadtbaumarten in Dresden. Diss TU Dresden. http://www.qucosa.de/fileadmin/data/qucosa/documents/9367/Dissertation_Gillner.pdf. Accessed 29 Nov 2017

Gillner S, Vogt J, Roloff A (2013) Climatic response and impacts of drought on oaks at urban and forest sites. Urban For Urban Green 12(4):597–605. https://doi.org/10.1016/j.ufug.2013.05.003

Gillner S, Bräuning A, Roloff A (2014) Dendrochronological analysis of urban trees: climatic response and impact of drought on frequently used tree species. Trees 28(4):1079–1093. https://doi.org/10.1007/s00468-014-1019-9

Graves HM, Watkins R,Westbury P, Littlefair P (2001) Cooling buildings in London: overcoming the heat island. CRC Ltd, London, 311 S.

Gregg JW, Jones CG, Dawson TE (2003) Urbanization effects on tree growth in the vicinity of New York City. Nature 424(6945):183–187. https://doi.org/10.1038/nature01728

Griess VC, Knoke T (2011) Growth performance, windthrow, and insects: meta-analyses of parameters influencing performance of mixed-species stands in boreal and northern temperate biomes. Canadian. J For Res 41:1141–1158

Günther R (2014) The role of soil water content for microclimatic effects of green roofs and urban trees—a case study from Berlin, Germany. J Heat Island Institute Int 9:2

Gworek B, Déckowska A, Pierścieniak M (2011) Traffic pollutant indicators: common dandelion (Teraxacum officinale), scots pine (Pinus Silvestris), small-leaved lime (Tilia Cordata). Polish J Environ Stud 20:87–92

Hartmann H (2011) Will a 385 million year-struggle for light become a struggle for water and for carbon?—How trees may cope with more frequent climate change-type drought events: WILL TREES STRUGGLE FOR WATER AND/OR CARBON? Glob Chang Biol 17(1):642–655. https://doi.org/10.1111/j.1365-2486.2010.02248.x

Helama S, Läänelaid A, Raisio J, Tuomenvirta H (2012) Mortality of urban pines in Helsinki explored using tree rings and climate records. Trees 26(2):353–362. https://doi.org/10.1007/s00468-011-0597-z

Johann K (1977) Eine neue Jahrringmeßanlage für Bohrkerne und Stammscheiben. Forstarchiv 48(10):204–206

Jones PD (2004) Climate over past millennia. Rev Geophys 42(2). https://doi.org/10.1029/2003RG000143

Kabisch N, Haase D (2014) Green justice or just green? Provision of urban green spaces in Berlin, Germany. Landsc Urban Plan 122:129–139. https://doi.org/10.1016/j.landurbplan.2013.11.016

Kaye JP, Groffman PM, Grimm NB, Baker LA, Pouyat RV (2006) A distinct urban biogeochemistry? Trends Ecol. Evolution 21:192–199

Köcher P, Gebauer T, Horna V, Leuschner C (2009) Leaf water status and stem xylem flux in relation to soil drought in five temperate broad-leaved tree species with contrasting water use strategies. Ann For Sci 66(1):101–101. https://doi.org/10.1051/forest/2008076

Kuttler W (2004) Stadtklima – Teil 1: Grundzüge und Ursachen. UWSF - Z Umweltchemie Ökotox 16(3):187–199. https://doi.org/10.1065/uwsf2004.03.078

Leuzinger S, Vogt R, Körner C (2010) Tree surface temperature in an urban environment. Agric For Meteorol 150(1):56–62. https://doi.org/10.1016/j.agrformet.2009.08.006

McCarthy MP, Best MJ, Betts RA (2010) Climate change in cities due to global warming and urban effects: CLIMATE CHANGE IN CITIES. Geophysical Research Letters 37:n/a–n/a. doi: https://doi.org/10.1029/2010GL042845

McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG, Yepez EA (2008) Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytol 178:719–739. https://doi.org/10.1111/j.1469-8137.2008.02436.x

McPherson EG, Nowak D, Heisler G, Grimmond S, Souch C, Grant R, Rowntree R (1997) Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. Urban Ecosystems 1:49–61

Meier F, Scherer D (2012) Spatial and temporal variability of urban tree canopy temperature during summer 2010 in Berlin, Germany. Theor Appl Climatol 110(3):373–384. https://doi.org/10.1007/s00704-012-0631-0

Moser A, Rötzer T, Pauleit S, Pretzsch H (2015) Structure and ecosystem services of small-leaved lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) in urban environments. Urban For Urban Green 14(4):1110–1121. https://doi.org/10.1016/j.ufug.2015.10.005

Moser A, Rötzer T, Pauleit S, Pretzsch H (2016) The urban environment can modify drought stress of small-leaved lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) Forests 7(3):71. https://doi.org/10.3390/f7030071

Nowak DJ, Greenfield EJ, Hoehn RE, Lapoint E (2013) Carbon storage and sequestration by trees in urban and community areas of the United States. Environ Pollut 178:229–236. https://doi.org/10.1016/j.envpol.2013.03.019

Parker DE (2004) Climate: large-scale warming is not urban. Nature 432(7015):290. https://doi.org/10.1038/432290a

Pauleit S, Jones N, Garcia-Martin G, Garcia-Valdecantos JL, Rivière LM, Vidal-Beaudet L, Bodson M, Randrup TB (2002) Tree establishment practice in towns and cities–results from a European survey. Urban For Urban Green 1(2):83–96. https://doi.org/10.1078/1618-8667-00009

Peng S, Piao S, Ciais P, Friedlingstein P, Ottle C, Bréon F-M, Nan H, Zhou L, Myneni RB (2012) Surface urban heat island across 419 global big cities. Environmental Science & Technology 46(2):696–703. https://doi.org/10.1021/es2030438

Pretzsch H (1989) Zur Zuwachsreaktionskinetik der Waldbestände im Bereich des Braunkohlekraftwerkes Schwandorf in der Oberpfalz. Allg Forst- und Jagdzeitung 160(2/3):43–54

Pretzsch H, Dieler J (2011) The dependency of the size-growth relationship of Norway spruce (Picea abies [L.] Karst.) and European beech (Fagus sylvatica [L.]) in forest stands on long-term site conditions, drought events, and ozone stress. Trees-Struct Funct 25(3):355–369. https://doi.org/10.1007/s00468-010-0510-1

Pretzsch H, Biber P, Schütze G, Uhl E, Rötzer T (2014) Forest stand growth dynamics in Central Europe have accelerated since 1870. Nat Commun 5:4967. https://doi.org/10.1038/ncomms5967

Pretzsch H, Biber P, Uhl E, Dahlhausen J, Rötzer T, Caldentey J, Koike T, van Con T, Chavanne A, Seifert T, Toit B, Farnden C, Pauleit S (2015) Crown size and growing space requirement of common tree species in urban centres, parks, and forests. Urban For Urban Green 14(3):466–479. https://doi.org/10.1016/j.ufug.2015.04.006

Preuhsler T (1979) Ertragskundliche Merkmale oberbayerischer Bergmischwald-Verjüngungsbestände auf kalkalpinen Standorten im Forstamt Kreuth. Forstl Forschungsber München 45:372p

Quigley MF (2004) Street trees and rural conspecifics: will long-lived trees reach full size in urban conditions? Urban Ecosystems 7(1):29–39. https://doi.org/10.1023/B:UECO.0000020170.58404.e9

Randrup TB, McPherson EG, Costello LR (2001) A review of tree root conflicts with sidewalks, curbs, and roads. Urban Ecosystems 5(3):209–225. https://doi.org/10.1023/A:1024046004731

Rötzer T, Wittenzeller M, Haeckel H, Nekovar J (2000) Phenology in central Europe–differences and trends of spring phenophases in urban and rural areas. Int J Biometeorol 44(2):60–66. https://doi.org/10.1007/s004840000062

Rötzer T (2007) Auswirkungen des Stadtklimas auf die Vegetation. Promet 33(1/2):40–45

Rötzer T, Liao Y, Görgen K, Schüler G, Pretzsch H (2013) Modelling the impact of climate change on the productivity and water-use efficiency of a central European beech forest. Clim Res 58(1):81–95. https://doi.org/10.3354/cr01179

Searle SY, Turnbull MH, Boelman NT, Schuster WSF, Yakir D, Griffin KL (2012) Urban environment of New York City promotes growth in northern red oak seedlings. Tree Physiol 32:389–400. https://doi.org/10.1093/treephys/tps027

Scherer D, Fehrenbach U, Lakes T, Lauf S, Meier F, Schuster C (2014) Quantification of heat-stress related mortality hazard, vulnerability and risk in Berlin, Germany. DIE ERDE 144:238–259

Schmelcher R (2011) Flächenentwicklung in Berlin: 1991–2010-2030. Senate Department for Urban Development and the Environment, Berlin http://opus.kobv.de/zlb/volltexte/2012/14650/. Accessed 11 December 2015

Schütt P, Schuck HJ, Stimm B (2013) Lexikon der Baum- und Straucharten – Das Standardwerk der Forstbotanik. Nikol Verlag, Hamburg

Schweingruber FH, Eidgenössische Forschungsanstalt für Wald S und L (1996) Tree rings and environment dendroecology. Paul Haupt

Shepherd JM (2005) A review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interactions 9:1–27

Skovsgaard JP, Vanclay JK (2008) Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. Forestry 81:13–31

Uhl E, Ammer C, Spellmann H, Schölch M, Pretzsch H (2013) Zuwachstrend und Stressresilienz von Tanne und Fichte im Vergleich. Allg Forst-und Jagdzeitung 184:278–292

UN (2012) World urbanisation prospects the 2011 revision. United Nations, World Urbanisation Prospects, Department of Economic and Social Affairs

US-EPA (2014) United States. Environmental Protection Agency. Heat Island Effect. http://www.epa.gov/hiri/ from November 11th, 2014

Way DA, Oren R (2010) Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. Tree Physiology 30:669–688. https://doi.org/10.1093/treephys/tpq015

Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. J Clim Appl Meteorol 23(2):201–213. https://doi.org/10.1175/1520-0450(1984)023<C0201:OTAVOC>2.0.CO;2

Youngsteadt E, Dale AG, Terando AJ, Dunn RR, Frank SD (2015) Do cities simulate climate change? A comparison of herbivore response to urban and global warming. Glob Chang Biol 21(1):97–105. https://doi.org/10.1111/gcb.12692