Assessing urban climate effects on *Pinus sylvestris* with point dendrometers: a case study from Stockholm, Sweden

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Abstract

Key message Extreme drought conditions, in addition to the urban heat island effect, modify the growth response and water storage dynamics of urban Scots pine trees in the Stockholm region.

Abstract Changes in surface properties of the urban environments significantly impact the local microclimate. While urban trees are known for providing important thermal regulation, the impact of urban climate on tree growth remains relatively unexplored. The present study focuses on the climate response and growth dynamics of urban Scots pine trees (*P. sylvestris*) in comparison to their rural counterparts. High-resolution monitoring of stem-radius variations using automatic point dendrometers was performed during the growing seasons (April–October) of 2017 and 2018 in Stockholm, Sweden. In 2018, the region experienced a severe and long-lasting summer drought. In May and July, temperatures were up to 5 °C higher relative to the reference period (1981–2010), and precipitation sums were below the reference period for the entire growing season. Our results show that the urban climate primarily impacts the daily water storage dynamics by decreasing the radius change amplitudes and delaying the time of maximum stem-water replenishment and depletion. Under standard climatic conditions, the warmer climate (1.3 °C) at the urban sites had a positive impact on radial growth increment. Drought periods significantly impact the climate–growth relationships. Stem shrinkage intensifies during the day, and lower growth rates were registered, resulting in reduced annual growth. The high-resolution monitoring provided valuable insights into daily and seasonal patterns of Scots pine stem-radius variations, showing that growth responses to increasing temperature are mainly controlled by moisture availability and site-specific conditions.

Keywords *Pinus sylvestris* · Point dendrometers · Urban climate · Daily fluctuations · Seasonal patterns · Stem radial increment

Introduction

Trees and green areas, in general, play an essential role in urban environments not only by mitigating the urban heat and health problems related to heatwaves and air pollution but also by maintaining the ecological sustainability of the remaining habitats (Bowler et al. 2010; Escobedo et al. 2011; Roeland et al. 2019). However, tree growth and vitality in

urban environments face several challenges, in particular high temperatures and water deficits that may result in positive or negative growth reactions. On the one hand, increased temperature may lead to enhanced growth and an extended vegetation period compared to a natural temperate forest stand (Pretzsch et al. 2017). On the other hand, water-deficit may limit tree growth, lifespan and overall vitality by affecting daily and seasonal water storage dynamics influencing nutrients uptake and transport within the stem (Clark and Kjelgren 1990; Kreuzwieser and Gessler 2010; McCarthy and Pataki 2010). Research investigating the potential impacts of such challenges in urban trees is still limited and mostly based on tree-ring data (annual radial growth) often collected from street-trees and climatic variables at monthly resolution (Dahlhausen et al. 2018; Gillner et al. 2014; Helama et al. 2012).

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Detailed measurements of trees' instantaneous reaction to environmental changes, monitored simultaneously with climatic parameters are often used in the context of climate change effects on tree growth in forest ecosystems. Automatic dendrometers enable continuous high-resolution measurements of stem radial variation at sub-hourly resolution providing valuable insights into the main climatic variables affecting the stem radial increment (SRI) (Deslauriers et al. 2003a; Drew and Downes 2009; King et al. 2013; Klippel et al. 2017; Kocher et al. 2012; van der Maaten et al. 2013).

Benefiting from urban planning practices focused on ecological preservation since the early 1900s, several patches of indigenous forests can still be found in many urban areas across Sweden. With an urban heat island (UHI) effect of 1.2 °C (Richter et al. 2013), an increasing trend for urban expansion, and the location in a drought-sensitive region (Linderholm et al. 2004; Seftigen et al. 2013), Stockholm's urban area provides a good research opportunity on native trees' growth response to the ongoing climatic changes in addition to the urban climate effects. We hypothesize that in urban environments, increased temperatures may lead to enhanced growth relative to the natural forest stands, but that tree growth might be more sensitive to drought periods and heatwaves. In this paper, we present the first study assessing *P. sylvestris* instantaneous tree-growth control using automatic point dendrometers at urban environments in comparison with a natural forest stand. With the present monitoring set-up of high-resolution dendrometer data and climatic information, we aim to: (1) identify the sensitivity of *P. sylvestris* radial increment to climatic parameters in rural and urban environments and (2) comprehend in which way radial growth, including daily and seasonal patterns of stem-radius variation, differs between rural and urban trees.

Materials and methods

Study area and climatic conditions

Stockholm is located at the east coast of Sweden (59° 20' N, 18° 00' E) (Fig. 1a), where the Gulf of Bothnia meets the Baltic Sea. The climate is humid, with an annual mean temperature of 6.6 °C and 549 mm annual precipitation (SMHI, period 1981–2010). July is the warmest month with a mean temperature of 17.2 °C and February is the coldest, with a mean temperature of −3.0 °C. On average, precipitation is highest during July and August, and snowfall occurs mainly from December to March. The vegetation belongs to the boreonemoral zone, with the occurrence of mixed forests, including *P. sylvestris*, *Picea abies*, *Quercus robur*, *Betula pendula* and *Populus tremula* (Rydin et al. 1999).

Over the monitoring period, the study region experienced strong contrasting weather conditions (Fig. 2). During the growing season (i.e. April–October) of 2017, temperature values and precipitation sums were very close to the reference period 1981–2010. In 2018, the region experienced an extreme summer drought, with May and July temperatures up to 5 °C higher than the reference period (1981–2010) and precipitation sums below the reference period for the entire growing season.

Monitoring set-up and measurements

Beforehand, the spatial distribution of Stockholm's UHI was estimated based on Land-surface temperature (LST) data acquired with the Landsat-8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS). Based on those results, three sites were selected to monitor *P. sylvestris* stem-radius variation during two growing seasons (Fig. 1). One site is characterized by rural conditions, located at the Tyresta National Park, south of Stockholm. The other two sites are located in urban parks (remnant patches of previous indigenous forest), within the Stockholm UHI and at a linear distance of approximately 1.2 km from each other (Solna Råsunda and Solna Juvenalen), and nearly 23 km from the rural site. No signs of human influence, such as irrigation, plantations or soil management or sealing, are visible in the vicinity (25 m radius) of the monitored trees. Automatic point dendrometers (model DR, Ecomatik, Munich, Germany; accuracy < 2 µm, temperature coefficient 0.1 lm/K) were used to monitor seasonal and daily stem-radius changes since summer 2016. At each site, two healthy and dominant trees of *P. sylvestris*, without apparent injuries or morphological anomalies, and within the age range of 60–80 years, were selected and equipped with a dendrometer at a logging interval of 30 min. The instruments were placed at the same height in all the trees, to reduce potential impacts on the time of stem radius daily maxima and minima (Zweifel and Hasler 2001). The height was set to 2.5 m to avoid vandalism. Before installing the equipment, the outermost part of the bark was removed from the trees to minimize the noise in the measurements from the bark swelling and shrinking. The raw data output is given in volts (V) and conversion to microns (µm) was done according to the manufacturer's specifications.

Site descriptions

Rural (59° 21' 37" N, 17° 59' 12" E)—The site is located about 20 km south from central Stockholm and within the Tyresta nature reserve that surrounds Tyresta National Park (Fig. 1). The reserve covers an area of approximately 2730 hectares and has a high stand density of mixed forest. The terrain is characterized by bare bedrock outcrops, steep

Fig. 1 Sites location and specific conditions. **a** Land-surface temperature (LST) estimation for the region with the location of the Urban (black) and rural (green) sites; **b** Urban sites location: Urban₍₁₎ (blue); Urban₍₂₎ (red). Maps modified from ©Lantmäteriet

Fig. 2 Stockholm monthly precipitation (bars) and air temperature (line) anomalies for the years 2017–2018 relative to the normal period 1981–2010

joints and smaller flat areas with dense forest vegetation; the soil type is podsol, mostly shallow and stony, and covered by blueberry shrubs (*Vaccinium myrtillus*) and various moss species. The monitored trees are located in the forest interior.

Urban₍₁₎ (59° 10' 18 N, 18° 13' 07 E)—Located in central Stockholm, this site presents a green area of approximately

3 hectares (Fig. 1). The vegetation is mainly composed of *P. sylvestris* and *Quercus robur* trees. The terrain is characterized by a gentle slope (ca 4%), the soil is compact and stony with a thin (< 5 cm) layer of litter, covered by grass. The monitored trees are located at an open south-facing slope.

Urban₍₂₎ (59° 22' 06 N, 18° 00' 02 E)—This site is located ca 1.2 km from Urban₍₁₎, and presents a green area

of approximately 5 hectares (Fig. 1). The vegetation is composed of a mixed stand of deciduous and coniferous trees. The terrain is flat, the soil is compact with a slightly more organic-rich upper horizon compared to Urban₍₁₎, and covered by grass. The monitored trees are located at an open north-facing slope.

Meteorological data

Over the study period, direct monitoring of air temperature and relative humidity (RH) was performed in situ for all the sites with data loggers (HOBO U23-001 Pro v2; accuracy for temperature ± 0.21 °C, for relative humidity $\pm 2.5\%$) placed at the height of approximately 2–2.5 m and 30 min resolution. At the site level, consistently throughout the monitoring period, monthly minimum temperatures ($T_{\min}$) were substantially lower (on average 3 °C) at the rural site and monthly maxima ($T_{\max}$) slightly higher (on average 0.5 °C) at the urban environments. Additional data for precipitation were retrieved from Tullinge meteorological station (59° 10.734' N, 17° 54.75' E; Elevation: 2 m; 15 min resolution; located ca. 20 km from all the monitored sites). Sunshine duration was collected from the Stockholm meteorological station (59° 20.52' N, 18° 3.45' E; elevation: 2 m; hourly resolution; location ca. 20 km from Tyresta and 5 km from the urban parks). The vapour pressure deficit (VPD) was calculated from air temperature and RH data, using the Magnus equation (Murray 1967).

Data analysis

All dendrometer and meteorological data were converted into hourly resolution and the analysis performed over the length of the growing seasons, i.e. April–October [Day of the Year (DOY) 91 to 303] 2017 and 2018. The individual time-series of dendrometers were averaged to single time-series per site. Information on stem-radius variation (ΔR) was extracted using two approaches: (1) the circadian cycle,

where diurnal metrics are obtained from the daily radius cycle, i.e. information on stem-radius daily maximum, minimum and amplitude change from radius maximum to radius minimum (King et al. 2013); and (2) the stem cycle, where radius changes are divided into three distinct phases, i.e. contraction, expansion and stem-increment (Deslauriers et al. 2003b; Downes et al. 1999), using the R package DendrometerR (van der Maaten et al. 2016). Information on full cycles (i.e. contraction, expansion, increment) development was assessed to extract the net radius variation. A cycle with a final radius maximum surpassing the previous one was classified as a positive variation ($\Delta R+$), and a final radius maximum lower than the previous one was classified as a negative variation ($\Delta R-$) (Turcotte et al. 2009). Spearman correlations were calculated to describe the relationship between the stem-increment phase and the different climatic parameters. Statistical analyses were conducted using SPSS Version 26.0 (SPSS Inc., Chicago, IL, USA).

Results

Climate sensitivity and stem-increment dynamics

Climate sensitivity analysis between the SRI and the different climatic parameters shows that tree growth in the region is driven by a combined response to temperature and moisture availability (Fig. 3). At the site level, rural Scots pine trees presented a rather consistent response to temperature ($p < 0.01$; $r_T = 0.7$) and RH ($p < 0.01$; $r_{RH} = 0.4$), in both years. Urban trees showed a higher dependency on site-specific conditions in response to climate: under the cooler and wetter conditions of 2017 trees at both urban sites (U₍₁₎; U₍₂₎) presented a similar response to temperature ($p < 0.01$; $r_T = 0.5$) and RH ($p < 0.01$; $r_{RH} = 0.4$) as their rural counterparts. Under the influence of the extremely warm and dry conditions of 2018, no consistent pattern was observed in their

Fig. 3 Correlation between the SRI time-series and the different climatic variables for the monitoring period (April–October). The dotted lines indicate the 0.01 significance level

climate–growth response. Trees at $U_{(1)}$ show a significant ($p < 0.01$) though low response to both temperature and RH ($r_T = 0.2$ and $r_{RH} = 0.3$), whereas in $U_{(2)}$, SRI was mainly controlled by temperature ($p < 0.01$; $r_T = 0.5$). In addition, at $U_{(2)}$, the influence of the RH is inexistent, and a significant ($p < 0.01$) and positive response to sunshine and VPD ($r_{\text{Sunshine}} = 0.3$ and $r_{\text{VPD}} = 0.2$) is observed.

A closer look into the SRI dynamics and growth rates shows that microclimatic differences between urban and rural environments influence not only the trees' climatic response but also their vegetative period (Fig. 4). In 2017, under climatic conditions close to the reference period (i.e., 1981–2010), urban and rural trees presented a similar vegetative period with maximum growth rates occurring in May and June. Urban trees exhibited higher daily growth rates and total annual growth (Fig. 4a, b). In contrast, the heat stress and water deficits experienced in 2018 lead to higher growth variability among the sites. While maximum growth rates still occurred in May and June for urban trees, rural ones presented a more dispersed growth throughout the season with higher daily growth rates and cumulative growth (Fig. 4c, d).

Daily and seasonal rhythms of water storage

Comparison of monthly mean diurnal cycles between urban and rural Scots pine trees shows that regardless of the prevailing weather conditions, urban trees experience lower radius amplitudes than their rural counterparts (Fig. 5). Urban–rural differences in the daily rhythm of water storage are higher under the influence of cooler and wetter climatic conditions, with a temporal delay between the occurrence of the local R_{max} and R_{min} (T_{max} 07:30 and T_{min} 16:30 CET) observed at the urban sites in comparison with the rural ones (T_{max} 06:00 and T_{min} 14:30 CET) (Fig. 6). Under drought-stress conditions, our results point to a more converged response of the daily water storage cycle with marginal differences in the daily radius maximum (R_{max}) and minimum (R_{min}) among the sites.

On the seasonal scale, daily radius time-series and frequency distribution of net variation ($\Delta R+$ and $\Delta R-$) suggest that mid-April marks the beginning of the growing season for urban and rural trees in the region (Fig. 7). Relatively little increment occurs at all the sites with a slightly higher percentage of $\Delta R+$ at the urban environments. Continuous growth increment occurs throughout May, with an $\Delta R+$ frequency $> 80\%$ at all the sites. It is mainly from June until the end of July that radial growth differs the

Fig. 4 SRI daily growth rates (μm) and annual totals (μm) for the monitoring period 2017–2018

Fig. 5 Monthly mean circadian cycle for the growing season (April–October) during the monitoring period 2017–2018

Fig. 6 Annual mean (April–October) of stem-radius diurnal cycle for rural (dash line) and urban (solid line) environments with time of day when the local maximum and minimum radius ($R_{\max}$ and $R_{\min}$) occur

most between urban and rural trees. From August to the end of September, the proportion of $\Delta R+$ and $\Delta R-$ distribution varies between the environments with varying weather conditions. With temperatures close to the reference period (i.e. 2017), $\Delta R+$ frequency is higher at the urban environments, whereas under extremely warm and dry conditions (i.e. 2018), the opposite pattern is observed. In October, stem-radius variation stabilized among all sites with the occurrence of small daily fluctuations. A frequency of $\Delta R-$ close to 100% at all the sites suggests cessation of growth for the trees in the region.

Discussion

Over the whole monitoring period, urban sites are characterized by an average temperature difference of 1.3 °C and a 10% lower air humidity compared to the rural location, capturing the magnitude of the UHI in the region (Richter et al. 2013). Our analysis confirms that these microclimatic differences affect urban trees radial growth as well as their climatic response, especially under drought-stress conditions. However, our results also show that even under the

Fig. 7 Time series of *P. sylvestris* daily radius variation at the different environments (Rural—green line; Urban₍₁₎—black line and Urban₍₂₎—grey line) with precipitation data for the region in the bot-

tom panel. Frequency distribution of full cycles with positive radius change ($\Delta R+$) and negative radius change ($\Delta R-$) over the growth period (April–October)

same local urban climate, Scots pine radial growth is modified by site-specific conditions (Oberhuber 2017; Oberhuber et al. 2014; Oberhuber and Kofler 2000; Zweifel et al. 2005) with mean growth rates differing among the two urban sites. At site Urban₍₁₎, trees show higher sensitivity to water availability, which might be related to the gentle slope of approximately 4% and differences in the overall forest structure (mainly composed of *P. sylvestris* and *Quercus robur* trees). At site Urban₍₂₎, where the terrain is flat and with a higher percentage of grass-coverage, growth is somewhat complacent (i.e. low degree of annual variation) even during extreme climatic years and is thus less sensitive to drought conditions. We assume that these differences in site-specific conditions may explain the growth rates differences between the urban sites.

Regarding SRI dynamics (Fig. 4), a quite homogeneous response amongst the urban trees is observed; regardless of the climate conditions prevailing in 2017 and 2018,

more than 70% of the annual stem increment occurred during May and June. Radial increment is assumed to occur mainly during the night when stem–water refilling reaches its maximum and air temperatures are lower (Deslauriers and Morin 2005; Richardson and Dinwoodie 1960). However, large differences between day- and night-time temperatures may reduce cell expansion (Begum et al. 2012; Dünisch 2010). Due to the night-time effect of the UHI, minimum temperatures are higher at the urban sites (Fig. 8), especially during May and June, the main period of early wood formation for conifers at high northern latitudes (Deslauriers et al. 2003a), resulting in higher daily growth rates. In contrast, July was the peak of the severe drought period of 2018 (Fig. 2); therefore, we hypothesize that in response to the soil–water-deficit, urban trees reduced their metabolism, and minimal radial increment occurred (Fig. 4c). The increase in $T_{\min}$ experienced at the rural environment during this period together with the

Fig. 8 Monthly maximum and minimum temperatures for the three sites over the growth period (April–October) of 2017–2018

overall forest structure (i.e. dense forest vegetation; higher relative air humidity) triggered the stem radial increment for rural trees.

The differences between urban and rural environments are distinct in terms of magnitude and duration of the stem-radius diurnal cycles. Daily radius variations represent the water movement (i.e. depletion and replenishment) within the stem (Deslauriers et al. 2007; Offenthaler et al. 2001). During the day, water loss through the canopy due to transpiration causes stem contraction. At night, the transpiration process ends, and absorption of soil water occurs, leading to stem expansion (Zweifel et al. 2005). Although sharing a similar seasonal variation (Fig. 5), our results suggest that in comparison with the rural environment, urban climates may cause lower stem ΔR variation and affect the timing of maximum replenishment and depletion ($R_{\max}$ and $R_{\min}$) (Fig. 6). Urban environments are often characterized by high water runoff and low infiltration rates (Clark and Kjelgren 1990), decreasing the moisture content of the soil. Although compaction or sealing of surfaces does not play a role for our study sites U(1) and U(2), the gentle slope may cause similar effects. As a response to the low water availability, urban trees may exhibit reduced transpiration rates explaining the lower radius amplitudes for the urban Scots pine trees in our study. The observed delay of the time of maximum replenishment and depletion may be a direct result of the typical temporal variation of urban and rural air temperatures (i.e. urban areas are characterized by a reduced cooling in the late afternoon and a slow warm-up after sunrise) (Oke 1987).

Additionally, our results suggest that under severe drought conditions, urban trees may experience increased stress. Daily mean amplitudes are intensified and an early occurrence of the time of the local $R_{\max}$ is observed suggesting limited stem replenishment overnight. To fulfil the transpiration demands during the day, trees will use the internal reserves having a negative consequence for radial increment (Steppe et al. 2015).

Comparison of seasonal growth patterns highlights the importance of site-specific conditions on *P. sylvestris* stem-radius dynamics, and the assessment of the $\Delta R+$ and $\Delta R-$ frequency distribution reveals how these patterns changed under the influence of extreme climate conditions.

At the rural environment, temperature changes drive the shifts in *P. sylvestris* seasonal dynamics, whereas moisture availability is more critical at the site Urban₍₁₎. For site Urban₍₂₎, no shift or alteration was identified on the radius dynamics between the two growing seasons, indicating a larger drought tolerance compared to site Urban₍₁₎. Overall, temperature controls growth onset and cessation, and precipitation is an essential driver for increment during summer. However, to exact pinpoint, these crucial periods solely based on dendrometer measurements is a challenge (Deslauriers et al. 2007; Mäkinen et al. 2003). Therefore, complementary cellular analysis through micro-coring or/and pinning (Deslauriers et al. 2003b; Mäkinen et al. 2008; Schmitt et al. 2004) are a requirement to test the hypothesis of expected extended growing seasons through an earlier start and a delayed cessation under forthcoming climatic changes.

Conclusion

Our results suggest that an increase in temperature will likely lead to increased radial growth and changes in the seasonal dynamics. Drought-sensitive sites are more exposed to heat stress conditions, and growth may be reduced. Since temperatures are expected to continue to increase, and heat waves are likely getting more severe and frequent, our results may serve as examples for future reactions of *P. sylvestris* to climate change in the study region.

Comparison of growth responses at different environments (i.e. urban vs rural) provided valuable insights into local growth variability and highlighted the importance of

site-specific conditions as a key factor to trees' response under environmental stress. It is important to increase the knowledge regarding the remaining green ecosystems within the urban limits to avoid ecological degradation and to provide tools for strategic urban planning to mitigate the effects of the climate change in these densely populated areas.

Author contribution statement SH conceived the idea and together with ER designed the study. ER performed the data analysis and wrote the manuscript. SH supported the interpretation and revised the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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