

Article

Complex Study of the Physiological and Microclimatic Attributes of Street Trees in Microenvironments with Small-Scale Heterogeneity

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Abstract

Rapid urban growth leads to an extension of artificial surfaces and inefficient energy management, an increase in urban heat islands, and local climate change. This has increased the need for green infrastructure and urban trees are playing an important role. It is important to ensure that tree groups can withstand climate warming and disturbances. This study investigated the physiological parameters of *Tilia tomentosa* ‘Seleste’ trees situated in a medium-sized Hungarian city, examining their relationship with microclimatic differences observed on opposing sides of a street. Instruments placed on 10 trees recorded air temperature and humidity, revealing a significant difference in total insolation, which resulted in higher maximum daily temperatures on the sunny side. These microclimatic variations were found to significantly affect physiological attributes, particularly pigment content. Trees on the sunny side exhibited a higher relative water content and a higher ratio of chlorophyll *a/b*, indicative of light acclimatisation. Trees on the sunny side exhibited a higher relative water content and a higher ratio of chlorophyll *a/b*, indicating an acclimatisation to light. Furthermore, a positive correlation was observed between pigment content, total insolation, and growing degree days. The findings demonstrate how fine-scale microclimate differences influence tree physiology, providing crucial physiological indicators that inform the capacity of urban trees to provide vital ecosystem services, such as local climate regulation. This emphasises the importance of climate-conscious urban planning, as even small-scale climate change can have a broader impact.

Keywords: climate change; urban trees; microclimate; physiological factors; insolation; chlorophyll; Szeged; Hungary



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1. Introduction

It is estimated that 68% of the world’s population will live in cities by 2050 [1]. The intensive expansion of cities leads to an increase in built-up areas, and the unfavourable energy management of these surfaces further modifies the climate of the urbanised regions. The increasingly frequent periods of heatwaves and droughts in cities contributed to

increased stress on the urban population, which requires immediate action. Developing urban green infrastructure can provide a solution, as plants, particularly trees can effectively reduce excess heat caused by built-up areas and climate change through evapotranspiration and shading [2–6]. These mechanisms are fundamental to the ecosystem service of local climate regulation (belonging to the class of “Regulation of temperature and humidity, including ventilation and transpiration at local scales” in the Common International Classification of Ecosystem Services [7–14], in which trees have a privileged role within the elements of green infrastructure due to their size and physiological properties [15,16]. The level of services increases every year with the age and size of the plants, so tree vegetation is a significant and valuable element of urban planning [17,18].

Numerous studies address the local-scale urban heat island mitigating effect of urban trees [19,20]. However, the interaction between urban climate and tree physiology is a two-way process: dry air and high temperatures act as stress factors on plant growth and physiological processes [21,22], for which climate-aware urban green space planning could be a solution [23,24]. This highlights the necessity for climate-aware urban green space planning. Recent reports also underscore limiting factors related to the urban environment, such as tree degradation caused by various pollutants [25–27]. While studies have revealed the effect of certain factors (e.g., urban heat island, surface temperature, air pollution) on the growth and ring structure of trees [28–31], the relationship between the extent of the urban heat island effect and plant phenology [32], and the general impact of climate change on urban tree growth [33]. A significant gap persists in understanding how small-scale climate differences affect trees within highly heterogeneous urban environments. Existing research, such as a general review by Jang and Leung [34] on tree responses to water deficit (changes in growth, morphological, physiological and biochemical parameters, as an effect of urban circumstances and climate change). Studies by Martínez-Villa et al. [35] studied the changes in morphological and physiological traits as affected by the temperature differences within the city. Konarska et al. [36] investigated the effect of different degrees of surface paving on physiological attributes and ecosystem service provision of trees. Gebert et al. [37] provided useful results about the microclimatic and physiological characteristics of trees on different sides of a street. But the number of samples (trees) was very limited, and the focus of the investigation was the effects of water-sensitive urban design (biofiltration). This is important because it can influence how well trees survive, grow, and provide benefits to residents [37,38]. Localised microclimatic conditions, particularly excessive solar radiation in urban areas, can contribute to human thermal discomfort and induce physiological stress in urban vegetation, even for tree species with high heat tolerance. This is a self-reinforcing process: the stress of trees has reduced their ability to shield and cool the environment due to a decrease in photosynthesis activity and a deterioration of the canopy, which further increases the human heat load and worsens the comfort of the urban microclimate. One of the key ecosystem services provided by trees is microclimate regulation through their shading effect. When it comes to human thermal comfort, micro-scale variations in radiation and shading within a small area can have a more significant impact than the large-scale urban heat island effect, which is primarily related to air temperature [39]. This indicates a need for more detailed, fine-scale analyses.

The present study addresses this critical knowledge gap by focusing on the fine-grained heterogeneity of urban microclimates and their specific physiological impacts on individual trees within a street canyon. While macro-scale urban heat island effects are well-documented, the detailed, multi-parameter, spatio-temporal analysis within a single, highly heterogeneous street canyon, as conducted here, offers a unique contribution. This level of granular investigation is often absent in broader urban studies and is crucial for understanding the nuanced responses of trees to their immediate surroundings. The

physiological attributes of the trees can be considered as indicators of ecosystem condition, playing an important role in biodiversity policy. Therefore, the knowledge of their spatio-temporal patterns within the urban environment can aid relevant mapping and indicator development efforts as well.

In a previous study, newly planted trees on both sides of a reconstructed street were examined over eight years, and significant differences in growth between the two sides were identified [40]. This study aimed to provide a better understanding OF the spatio-temporal patterns of structural or physiological attributes of the vegetation, as well as microclimatic factors, which can serve as indicators of ecosystem service provision [41]. The relevant physiological processes of the vegetation are strongly influenced by various factors (e.g., the height and building materials of surrounding buildings, macroclimatic conditions, etc.) [28,29,36,42]. There is a clear need to further investigate how these indicators change over time in different climates, enabling their application in ecosystem service computer models or satellite-based methods.

To this end, the following research questions were addressed: (i) How do microclimatic variations within a heterogeneous urban street canyon influence the physiological responses of urban trees, and how can these physiological indicators serve as proxies for assessing tree health and informing urban green infrastructure management for enhanced ecosystem service provision? (ii) What type of relationship can be observed between plant physiological indicators and microclimatic conditions?

2. Materials and Methods

2.1. Study Area and Tree Selection

The study was conducted in Szeged, one of the largest cities in Hungary, located in the Lower Tisza region of the Southern Great Plain, with a population of about 160,000. Its climate is warm and dry, classified as the “Dfb” subtype (warm summer, continental climate) of Köppen’s classification [43]. Szeged lies on the flat alluvial plain of the Tisza River at an altitude 76 m surrounded by agricultural land with limited topographic variation, which allows unobstructed air mass movement and contributes to high summer temperatures: average temperature between 1991 and 2020 May: 16.9 °C June: 20.6 °C July: 22.3 °C August: 22.4 °C September: 17.2 °C October: 11.7 °C and one of the lowest annual precipitation in Hungary (534 mm/year).

Our study area was located in the densely built-up city centre of Szeged, in a narrow street canyon oriented NW-SE (Figure 1). The tree row is located in a narrow inner-city street canyon, bordered by 2–3-storey (10–12 m) 19th-century buildings, with a distance of 2.5 m from the building façades. Trees are planted in a continuous green strip of variable width between 1.5 and 2.5 m, generally covered with shrubs and at least 10 cm of mulch. The roadway between the two rows of trees is covered with small-element paving blocks (partly permeable). 117 pre-cultivated (4–5-year-old) nursery-grown *Tilia tomentosa* ‘Seleste’ trees were planted during the 2014 street reconstruction project, making them 13–14 years old at the time of the study. We selected five trees from each side of the street (Northern/sunny and Southern/shaded), to ensure a controlled comparison of physiological responses under similar structural and environmental conditions. During the selection, we considered the structural diversity of the street. The chosen trees were surrounded by uniform conditions, ensuring similar growth factors (e.g., ground cover, tree pit size, disturbances, etc.) on both sides of the street. Mean values and coefficients of variation (CV) were determined for tree total height, crown height, and crown diameter on the northern/sunny and southern/shaded sides (sunny: 11.1 m, CV = 7.4%; 8.6 m, CV = 9.6%; 4.7 m, CV = 10.4%; shaded: 12.4 m, CV = 11.5%; 9.4 m, CV = 15.2%; 5.3 m,

CV = 8.2%). This sample allowed for high-resolution microclimatic and physiological monitoring throughout the study period.

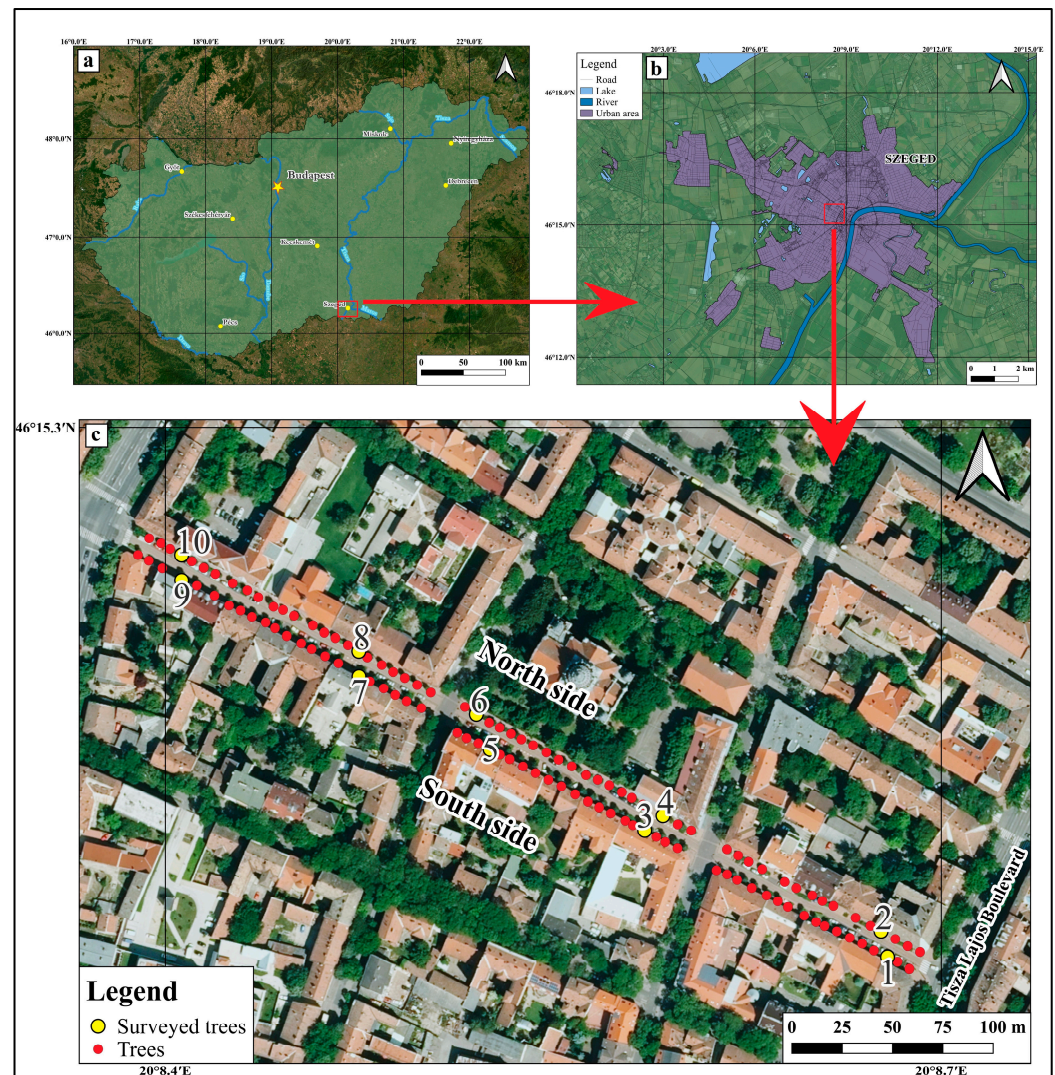


Figure 1. (a) Location of Szeged in Hungary; (b) Location of surveyed area in Szeged; (c) Trees, involved in this study (number 1–10) are located in the same street in the densely built-up city centre (Gutenberg Street).

2.2. Microclimate and Insolation Conditions

We placed Optin Ambient Data Loggers (ADLs) (Optin Ltd., Szeged, Hungary), each equipped with a weather and radiation shield, in the canopy of the selected trees at a height of approximately 4 m and recorded the air temperature and relative humidity in every 10 min from 1 May to 31 October 2022 (Figure 2a).

For each day we calculated the average daily temperature. The accuracy of the built-in temperature sensor is ± 0.2 °C, and the accuracy of the relative humidity sensor is ± 1.8 RH%. To prepare our data for statistical analysis, we calculated the growing degree days (GDD) from the temperature values for 1, 2, 7 and 30 days before the sampling, using 5 °C as the base temperature, as recommended in the literature [44]. The base temperature represents the threshold below which vegetation growth processes slow down to a point where significant changes become undetectable. We calculated the average of relative humidity for 1 and 2 days before sampling. We also modelled potential incoming solar radiation, which has a significant effect on the microclimate, for 1, 2 and 7 days before

sampling, using the Terrain Analysis tool of the SAGA GIS 7.8.2 software. We used daily and hourly resolutions to model a more extended period (April–October), and calculated the total insolation values for trees from the output raster of the SAGA GIS modelling using the QGIS 3.20 software. Using the Zonal Statistics tool, we calculated the mean value of the pixels in the area covered by the canopy, and modelled total insolation for 1, 2 and 7 days before the sampling. These values were then used in the correlation tests.

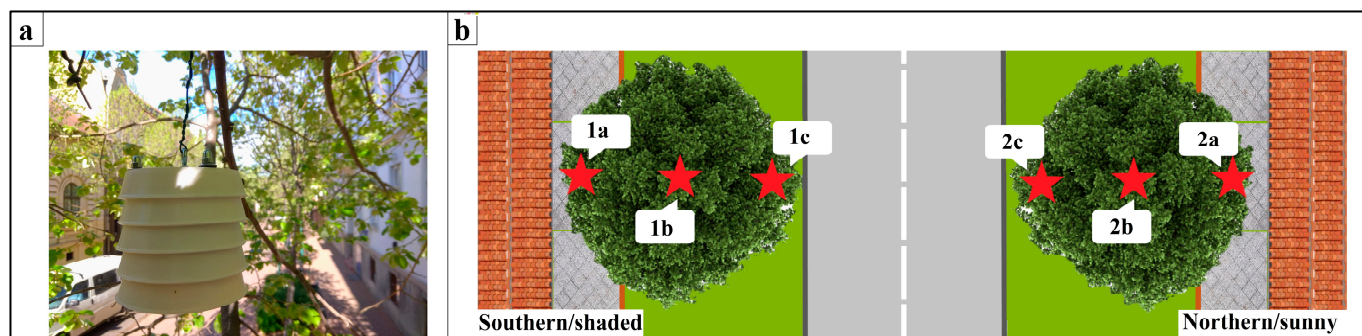


Figure 2. (a) Optin Ambient Data Logger equipped with radiation shield is placed in the tree crown; (b) Positions of the collected leaves, in the shaded and the sunny side of the street a: along the walls, b: in the middle of the tree crown, c: along the middle of the street.

2.3. Sample Collection and Determination of Leaf Relative Water Content

We collected 3 leaves from 3 points on the canopy of each selected tree from May to October (9 leaves per tree per month, with sampling conducted in the middle of each month (resulting in a total of 540 samples during the active vegetation period in 2022) (Figure 2b). The leaves were carefully selected to avoid variation in size, age or other parameters. They were immediately placed in labelled polythene bags to minimise evaporation and transported to the laboratory, where the fresh weight (FW) of each leaf was measured on a four-decimal analytical scale. The leaves were then placed between filter papers and soaked in distilled water for 24 h to obtain turgid weight (TW). For dry weight (DW), leaves were dried in a drying oven (Binder ED-115, BINDER GmbH, Tuttlingen, Germany) at 80 °C for 24 h. We calculated the percentage value of the relative water content (RWC) (1) of the leaves using the following formula:

$$\text{RWC}(\%) = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times 100 \quad (1)$$

2.4. Pigment Content of Leaves

We simultaneously collected leaf samples from the same place of the selected trees (where we collected leaves for RWC) to determine the pigment content. The leaves were placed in labelled polythene bags and placed in a −20 °C freezer as quickly as possible. We cut 20 mg of plant material from the same part of each leaf. The samples were placed in a 2 mL microcentrifuge tube with a 5 mm glass bead and then frozen in liquid nitrogen. The samples were shaken in a Retsch MM 301 mixer (Retsch, Haan, Germany) for 2 min at a frequency of 30 Hz, then 1 mL of 95% ethanol was added, and the samples were shaken again for 2 min. Afterwards, we centrifuged the samples at 16,800× *g* for 10 min. The supernatants were diluted 3 times with 95% ethanol and determined their optical density (OD) at 470, 648 and 664 nm with a Multiskan GO spectrophotometer (Thermo Scientific, Waltham, MA, USA). We calculated the chlorophyll *a* (Chl *a*) (2), chlorophyll *b* (Chl *b*) (3)

and carotenoid (Car) (4) pigment content of the extracts based on the measured absorbance values using the following equations [45]:

$$\text{Chl } a = (13.36 \times A_{664 \text{ nm}}) - (5.19 \times A_{648 \text{ nm}}) \quad (2)$$

$$\text{Chl } b = (27.43 \times A_{648 \text{ nm}}) - (8.12 \times A_{664 \text{ nm}}) \quad (3)$$

$$\text{Car} = \frac{(1000 \times A_{470 \text{ nm}}) - (2.13 \times \text{Chl } a) - (97.64 \times \text{Chl } b)}{209} \quad (4)$$

$$\text{ChlSum} = \text{Chl } a + \text{Chl } b \quad (5)$$

The total chlorophyll (ChlSum) (5) content was obtained as the sum of the chlorophyll *a* and chlorophyll *b* values.

2.5. Statistical Analyses

Microclimate and insolation parameters were collected from 540 sampling elements. Outliers were removed, then 511 and 466 of these were also characterised for RWC and pigment contents, respectively. Sampling elements represented two sites: Northern/sunny ($n = 251$; $n = 236$) and Southern/shady ($n = 260$; $n = 230$). First, statistical analyses examined the null hypothesis that means characterising samples from the two sites were equal. Normality and scedasticity were checked using Shapiro–Wilk and F-probes, respectively, and means were compared using Student's *t*-test. The null hypothesis was rejected for $p < 0.05$, and the two means were considered different. A second analysis was aimed at identifying correlations between parameters. The null hypothesis for this analysis was that two parameters were not correlated in the statistical population, and it was rejected (and correlation was established) when *p*-values calculated from Pearson's correlation coefficient (*r*) were < 0.05 . We analysed three cases, evaluating correlations for the entire vegetation period: (i) using the entire dataset (without separating the two sides, $n = 511$ of RWC; $n = 466$ for pigment contents), (ii) using data from the Northern/sunny side only ($n = 251$ of RWC; $n = 236$ of pigment contents), or (iii) using data from the Southern/shaded side only ($n = 260$ of RWC; $n = 230$ of pigment contents). These analyses were carried out using the PAST 4.03 software [46].

During the study, we also considered the modelled data of the total insolation reaching the tree canopies for each tree. Permutational Multivariate Analysis of Variance (PERMANOVA), based on Bray–Curtis dissimilarity and 999 permutations, was used to test the effects of street sides (shaded/sunny) on physiological characteristics. We used the strata argument to constrain permutations to months accounting for the different sampling times. We then calculated pairwise PERMANOVAs between the street sides for each month separately. To visually illustrate the compositional differences between the street sides, we performed a non-metric multidimensional scaling (NMDS) ordination with Bray–Curtis dissimilarity using the square-root-transformed leaf characteristics. We fitted environmental vectors onto the ordination and calculated correlations between ordination values and fitted vectors to assess the relationships between environmental variables and compositional differences. Model analyses were performed in R using the *adonis2*, *metaMDS* and *envfit* functions of the *vegan* package [47,48].

3. Results

3.1. Difference in the Insolation and the Microclimate

The total insolation values between the two sides of the street showed significant differences in the sample area, although the extent varied. On average, we obtained 1.45 times higher values during the modelling in the selected trees on the northern/sunny side. De-

pending on the position within the street, the ratio varied between 1.26 and 1.74 times for each pair of trees (Figure 3).



Figure 3. Total (direct and indirect) insolation raster for the entire vegetation period (April–October). Average of the total insolation per trees and ratio of tree pairs.

Average daily temperatures were calculated, and after subtracting the values of the southern/shady side from the values of the northern/sunny side, a heat surplus emerged in favour of the northern side, which was most pronounced in summer. Starting with a 0.2 °C difference at the beginning of May, the average for May reached 0.36 °C, and then increased to over 0.4 °C in all three summer months. After the summer season, the difference decreased rapidly, and by the end of the study period, it was nearly absent (Figure S1).

Average maximum temperatures were calculated from values measured on the two street sides. The difference also appeared in the daily maximums, with a difference of up to 3 °C during heatwaves, approaching nearly 4 °C in the second half of July (Figure 4).

The hottest day of 2022 was the 23rd of July in Szeged, a result of a heatwave that was preceded and followed by a significant drought period. On this day, the daily maximum was above 40 °C at all points on the sunny side. Using this day as a sample, we investigated the daily course of the temperature differences calculated from the air temperature values measured on individual pairs of trees ($\Delta T = T_{\text{sunny}} - T_{\text{shaded}}$). The individual differences resulting from the position of tree pairs are well illustrated by comparing the micro-scale temperature differences at the tree pair level, reflecting the environmental mosaicism well (Figure 5). No significant temperature difference was observed between the two sides of the street during the night. The differences began after sunrise. Throughout most of the day, we detected higher temperature values on the sunny side for all tree pairs, except for some hours after sunrise when tree pairs in more open positions at both ends of the street (tree pair 1–2 and 9–10) experienced lower temperatures. The highest ΔT was 5 °C in the early afternoon.

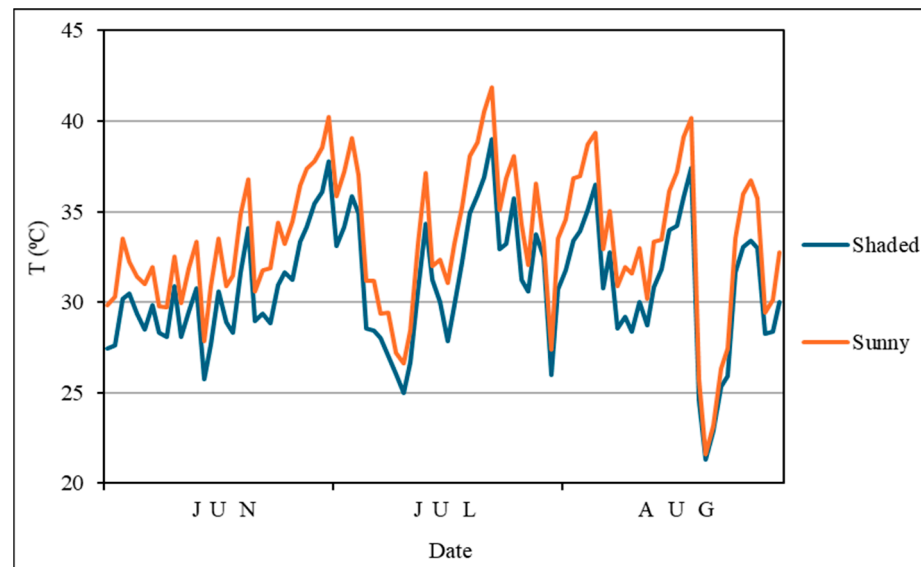


Figure 4. Daily maximum temperature (averaged for the northern/sunny and southern/shaded street sides). (Summer of 2022: June–August).

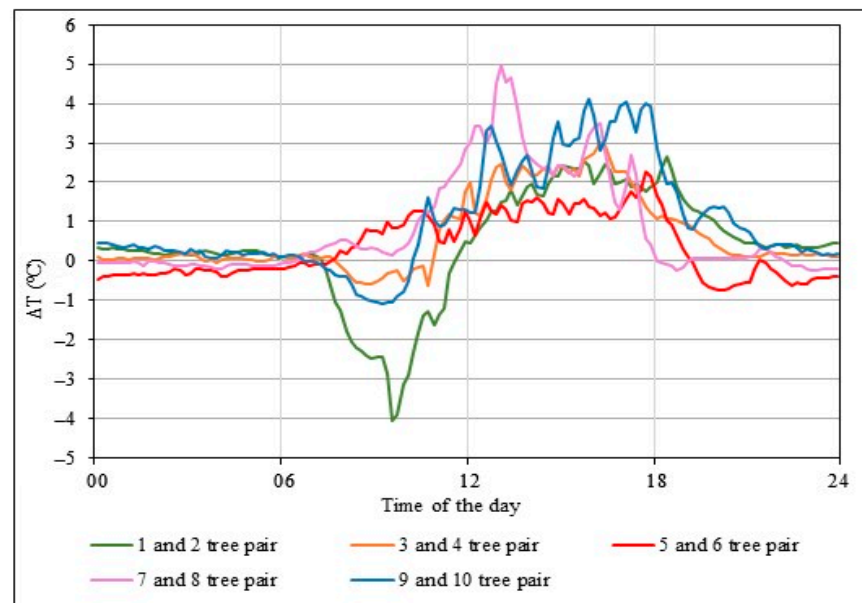


Figure 5. Temperature differences ΔT ($\Delta T = T_{\text{sunny}}^{2;4;6;8;10} - T_{\text{shaded}}^{1;3;5;7;9}$) between pairs of trees on the hottest day of the summer (23 July 2022).

In the case of relative humidity, no significant difference was observed between the two sides from May to the end of August beyond the specified accuracy of the instrument.

3.2. Changes in Leaf Water Content and Pigmentation During the Vegetation Period

Examining the microclimatic conditions, it was clear that the environmental mosaicism in the street is significant. Therefore, we present the variability of physiological parameters through the average values of the samples from the sunny and shady sides. However, it is sometimes necessary to address these phenomena at the individual level as well. Under extreme environmental conditions, for example, early ageing (early onset of senescence) may occur in individual trees, which significantly influences leaf pigmentation (e.g., total chlorophyll content) and may also cause shifts in the averages.

In May, the relative water contents (RWC) of the leaves were similar on both sides, though the average value on the sunny side was slightly higher. RWC values around 85%

were relatively high, indicating good water status in the leaves at the beginning of the summer (Figure 6a). By June, there was a significant drop in the values, but the rate of decrease was greater on the shady side (13%) than on the sunny side (10%). The lowest averages were observed in July, but the values on the sunny side remained higher than those on the shady side until August. This trend reversed during the autumn, as the water status of the trees on the shady side slightly improved (a 3–5% increase was detected), while a slight decrease was observed on the sunny side. It is important to note that a large drop in pigment contents indicated early senescence in two trees on the sunny side, and these low values may have caused a shift in the average (Figure S2).

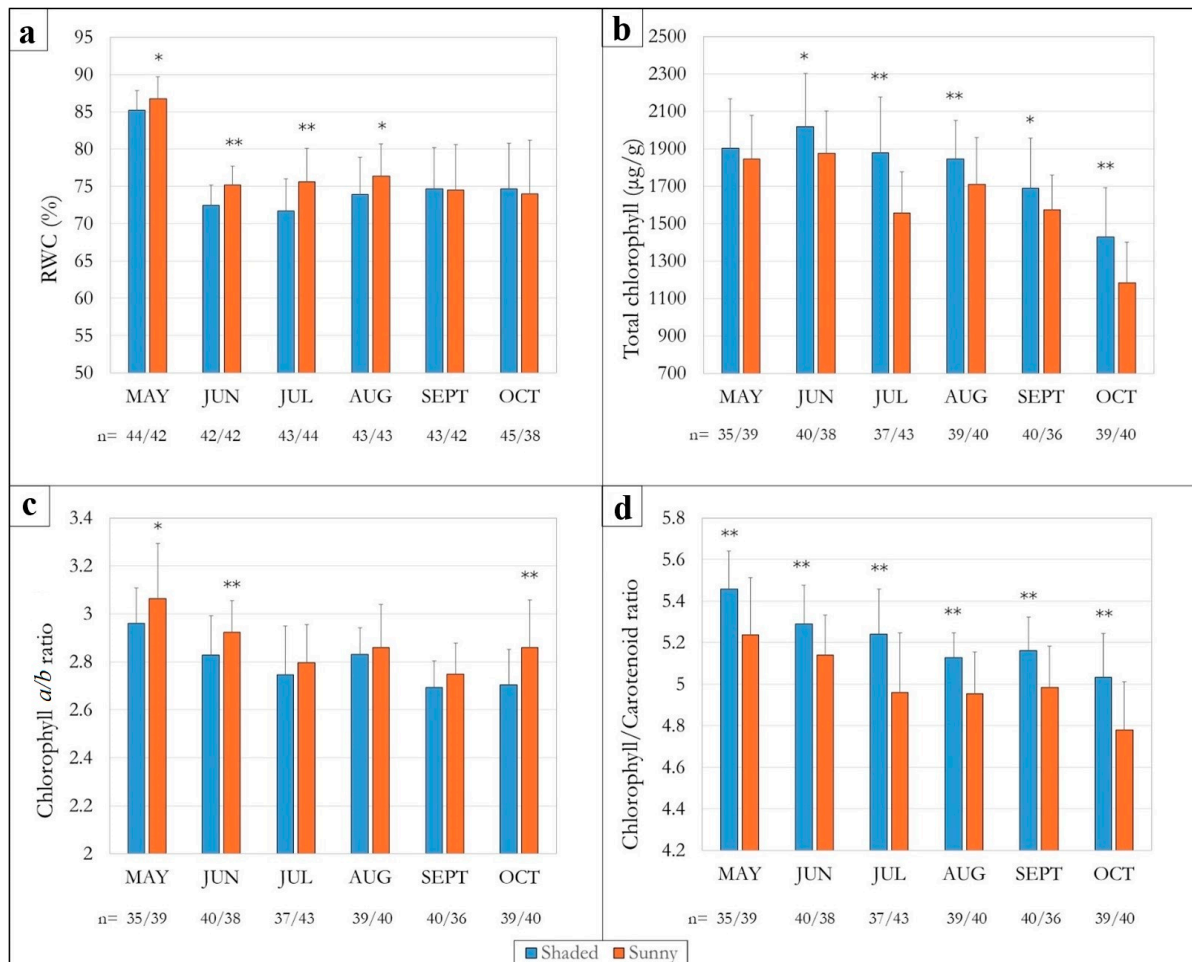


Figure 6. Average of the (a) relative water content, (b) total chlorophyll content, (c) chlorophyll *a/b* ratio, (d) chlorophyll/carotenoid ratio on the shaded (blue) and the sunny (orange) side of the street. Significantly ($p < 0.05$) different means are indicated by * ($p < 0.05$) and ** ($p < 0.01$). (with column heights as means and error bars as standard deviations and n: number of shaded/sunny samples).

3.3. Leaf Chlorophyll and Carotenoid Content Changes During the Vegetation Period

In May, we detected higher chlorophyll content on the shaded side, and this trend persisted throughout the entire study period (Figure 6b). Over the course of the study, the trends of change were similar on both sides: compared to the May values, an increase was observed in June. However, due to the extreme heat and drought in July, a significant decline occurred during that month, with the decrease being much greater on the sunny side. After a slight increase in August, the autumn period brought a significant decrease in chlorophyll content on both sides.

Unlike the total chlorophyll content, the ratios of chlorophyll *a/b* were generally higher on the sunny side (Figure 6c). The highest values on both street sides were recorded in

May, after which they decreased over time. The difference in the ratio remained throughout the entire study period, favouring the sunny side, although the trends followed similar patterns: a continuous decrease until July, followed by a slight increase in August. During the autumn months, the difference between the two sides increased again. We note that on the shaded side, high chlorophyll content was measured alongside increased chlorophyll *a* and *b*, but a lower ratio due to the high chlorophyll *b* content.

The chlorophyll/carotenoid ratio was also calculated as a generally accepted indicator of plant physiological status [49]. It reached its highest values at the beginning of the active vegetation period on both sides of the street, remaining lower on the sunny side throughout the season (Figure 6d). After a substantial decline in July, the ratio stagnated, but we observed a significant reduction in October.

In summary, among the physiological parameters examined, we observed a clear positive difference in chlorophyll content and the chlorophyll/carotenoid ratio in the shady side, whereas the chlorophyll *a/b* ratio remained higher on the sunny side throughout the entire period. Additionally, except for the autumn period, the RWC values were higher on the sunny side during all other periods.

3.4. Relationships Between Physiological and Environmental Parameters

To study the differences between physiological characteristics, we performed various statistical analyses. RWC was significantly higher on the sunny side, whereas the pigment amounts were higher on the shaded side throughout the examined period (Table S1). Regarding the ratios, the chlorophyll *a/b* ratio was significantly higher on the sunny side, whereas the chlorophyll/carotenoid ratio was significantly higher on the shaded side.

During the preparation of the statistical analysis, we examined several environmental factors. The following three factors that were found to be the most relevant based on preliminary investigations are included in the current analysis: the average relative humidity 2 days prior to sampling (RH% 2D), Growing Degree Days value from 7 days before sampling (7GDD), and the summarised total insolation during the day before sampling (Insol1D). The relative water content showed no significant (or only a weak) linear relationship with most of the investigated environmental factors (Table S2). A strong positive correlation was found between the total insolation and the 7GDD values for most of the parameters. The correlation coefficient (*r*) was close to or above 0.5, with corresponding *p*-values indicating strong positive correlations between 7GDD and various pigment indicators (total chlorophyll, chlorophyll *a*, chlorophyll *b*, and carotenoid contents). This suggests that accumulated heat, indicative of the growing season's progression, is a significant driver of pigment synthesis and accumulation in *Tilia tomentosa*. Relative humidity showed no correlation with RWC and only weak negative correlations with other parameters, with the strongest negative correlations observed for total chlorophyll, chlorophyll *a*, and chlorophyll/carotenoid ratio.

This indicates that lower humidity is generally associated with reduced pigment levels, likely due to increased water stress. In most cases, when the entire dataset was divided into separate groups (sunny and shaded sides), stronger correlation values were observed. This suggests that the sensitivity of physiological responses to environmental drivers (insolation, GDD, RH) differs depending on the microclimatic regime. For instance, the chlorophyll/carotenoid ratio and the chlorophyll *a/b* ratio on the shaded side showed a stronger relationship with total insolation compared to the sunny side. This implies that trees on the shaded side might be more responsive to changes in light availability, while those on the sunny side might be more impacted by heat or water stress. This differential sensitivity points to distinct physiological response mechanisms or adaptations based on the microclimatic exposure. The chlorophyll/carotenoid ratio and the chlorophyll *a/b* ratio

on the shaded side showed a stronger relationship with the total insolation compared to the sunny side (Table S2).

Differences in physiological characteristics between the street sides were significant when considering all months ($R^2 = 0.2169$, $p < 0.001$) and each month separately ($R^2 > 0.14$, $p < 0.041$), except in May ($R^2 = 0.07$, $p = 0.175$), according to the PERMANOVA analysis (Table S3). While the R^2 values, ranging between 0.14 and 0.27 for most months, indicate a moderate explanatory power, the consistent statistical significance across the majority of the growing season supports the robustness of the observed differences. This implies that even if other factors contribute more to the overall variability, the street side effect is a detectable and consistent environmental driver of physiological differentiation.

NMDS ordination of samples showed a relatively clear separation between the sunny and shaded street sides (Figure 7). The low stress factor (0.039) indicates a strong representation of the original data dissimilarities in the reduced-dimensional space, lending high confidence to the visual separation. Points representing individual trees on the sunny side (orange) formed a distinct cluster separated from those on the shaded side (blue), indicating a clear and consistent differentiation in their overall physiological profiles. All environmental variables were significantly related to the ordination ($R^2 = 0.06$ – 0.26 , $p < 0.05$). The environmental vectors (RH% 2D, 7GDD, and Insol1D) are overlaid onto the ordination space, with their direction indicating the gradient of the variable and their length indicating the strength of their correlation with the ordination axes. The RH% 2D vector, pointing predominantly towards the sunny-side samples, highlights that slightly higher relative humidity may shape the physiological responses observed in trees exposed to full sun, and suggesting that lower humidity is associated with certain unfavourable physiological states. This pattern, however, was not observed for 7GDD and Insol1D.

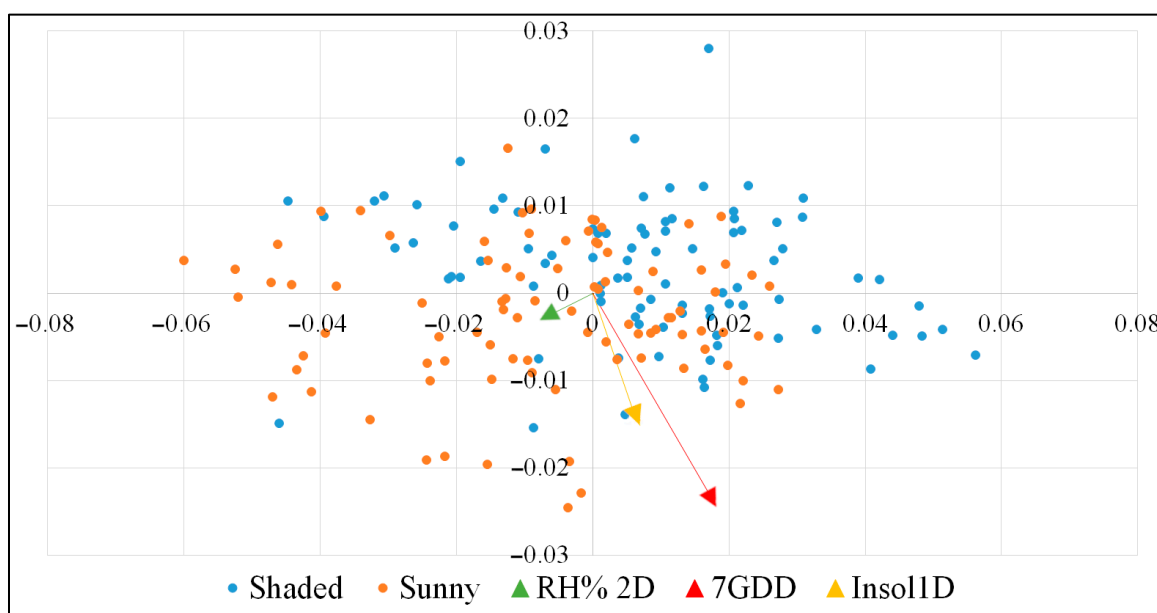


Figure 7. Non-metric multidimensional scaling (NMDS) ordination based on Bray–Curtis dissimilarity matrix of physiological parameters of the surveyed trees. Points represent individual trees with orange indicating sunny sides and blue indicating shaded sides of the street. Environmental vectors, including RH% 2D, 7GDD and Insol1D, represent significant ($p < 0.05$) correlations with the ordination axes. Each point contains all physiological parameters (RWC, pigments) of the tree collected at the sampling site (Figure 2b).

4. Discussion

The aim of our study was to examine the relationship between the physiological state of *Tilia tomentosa* trees and the microclimatic parameters in a narrow urban street canyon throughout a full vegetation period. We selected trees from both the sunny and the shaded side of a narrow street in the middle of a city centre. We chose silver lime trees because they are commonly planted in the streets and squares of Szeged and are also widely used in ecophysiological studies [50,51].

Most likely the position of the Sun is responsible for the variability of the temperature differences shown in Figure 5. Due to the orientation of the street, the sun hits the Southern/shady side in the morning. From about 10 o'clock onwards, the temperature differences reverse, and the northern/sunny side receives more sunlight for the rest of the day. The tree pair 5–6 is unique because Tree 6 is located in a more open section, thus it receives continuous sunlight from the morning. It is probably due to this openness that the long wave radiation at night is less obstructed, resulting in lower nighttime values for Tree 6. On the other hand, for tree pairs located in the more built-up parts of the street, the temperature difference was sometimes higher at night in favour of the sunny/north side. The temperature difference between the two sides of the street, exceeding 2 °C in several instances during the day, is also noteworthy. This is particularly significant considering that no differences in air temperature values exceeding 1–2 °C were observed between measurements taken in the shade of trees and at adjacent sunny reference points under similar climatic conditions [52,53].

The higher RWC values measured on the sunny side, particularly during peak stress periods, may initially appear counter-intuitive. However, this aligns with adaptive strategies observed in other studies where trees respond to high heat and evaporative demand by closing their stomata through increased abscisic acid (ABA) production to conserve water, leading to higher RWC in the samples [54]. This physiological regulation mechanism allows trees to maintain higher tissue water content despite external stress, suggesting a strong, rapid response in *Tilia tomentosa* under high insolation and temperature. The weak linear relationship between relative humidity and RWC may be attributed to the lack of significant humidity differences between the two sides.

Chlorophyll-*a* converts light energy into chemical energy, whereas chlorophyll *b* broadens the absorption spectrum of the plant by capturing light that chlorophyll *a* cannot absorb efficiently. We also determined the chlorophyll *a/b* ratio because it serves as an effective indicator of both the available light conditions and plant health [55,56]. Shade plants generally have larger light harvesting antenna complexes, and thus lower chlorophyll *a/b* ratios than sun plants [57], and the observed low *a/b* ratio of trees on the shaded side reflects an adaptive mechanism to relatively low light conditions. Under weaker light irradiation, the vegetation produces more chlorophyll *b* to capture as much light as possible, thereby ensuring efficient photosynthesis [55]. This type of adaptive behaviour occurs in shade-tolerant plants [58], whose goal is to capture the maximum amount of light possible. On the shaded side, especially during the summer months, the amount of chlorophyll-*a* and *b* were significantly higher than on the sunny side. In contrast, on the sunny side, both pigments decreased sharply during the same period, particularly in the samples collected in the droughty-prone month of July. When light is not a limiting factor, or is even available in excess, plants tend to produce less chlorophyll, with chlorophyll *a* being dominant due to its role in light energy absorption, and there is no need for high amount of chlorophyll *b*. This reduction in chlorophyll content on the sunny side could be attributed to this phenomenon or the chlorophyll degradation under excessive light exposure [59]. We also noticed a decrease in the chlorophyll *a/b* ratio in the autumn, likely due to leaf senescence [60].

Carotenoids contribute to photoprotection [61,62] and the chlorophyll/carotenoid ratio is a good indicator of plant response to abiotic stress [63–65], even though it continuously decreases during the active period until autumn due to the breakdown of chlorophyll. A higher ratio generally indicates healthier vegetation with high chlorophyll content because, with low chlorophyll content, an increase in carotenoid amount (and thus the decrease in the ratio) is a response to intense light and heat stress, helping to protect the photosynthetic apparatus. The low ratio on the sunny side during the entire vegetation period, particularly from July onwards, may be attributed to intense light and heat stress, combined with a significant lack of precipitation, which resulted in continuous stress. We speculate that trees may struggle to reach groundwater in urban soils, which are often partially filled with construction debris, making the drought period even more challenging for them [66]. This environmental background could have contributed to the yellowing of the canopy on the sunny side from mid-summer, a phenomenon we observed consistently each year. In contrast, leaves from trees on the shaded side remained visibly healthier, even in October. The varying environmental conditions may explain the differing correlations between the total and partial (sunny/shaded side) values of the chlorophyll/carotenoid ratio and the insolation values. These conditions can lead to different levels of variability, which in turn may weaken the correlation when examining the entire dataset.

Various data analysis methods indicate that all examined environmental factors (RH% 2D, 7GDD, Insol1D) significantly correlate with the accumulation of various plant pigments (Table S2). Differences between the samples of sunny and shaded street sides were confirmed by the NMDS, although the measured environmental parameters did not fully explain the separation of samples in the ordination space. This observation highlights the sensitivity of these biological markers, suggesting that the physiological state of urban vegetation can be easily monitored using any of these parameters. Therefore, data obtained with limited access to the plants (e.g., remote sensing, satellite images, etc.) are useful not only for assessing the health status of trees but also for understanding surrounding microclimatic conditions. The moderate R^2 values from PERMANOVA (0.14–0.27) 1, despite their statistical significance, underscore that while street side is a significant factor, it is not the sole or overwhelming determinant of physiological variation.

During the analysis of the physiological parameters of the trees, we found significant differences between the sunny and shaded street sides of the street when considering all data from the growing season, as well as when testing each month separately, with the clear exception of May (Table S3). We speculate that during spring, the lower air temperatures and the more available water in the soil results in less overall stress than the hot and dry summer months. After the demanding summer months, the differences persist into autumn, when the leaf senescence limits full plant regeneration [67].

This implies that other unmeasured or unaccounted factors, such as fine-scale variations in soil moisture or nutrients, subsurface infrastructure, localised air pollution, or inherent genetic variability among trees, likely contribute substantially to the remaining variance in physiological responses. This complexity is characteristic of urban ecosystems, where multiple stressors interact to influence tree health. While biological mechanisms (e.g., stomatal closure for RWC, light adaptation for Chl *a/b*) are plausible physiological explanations for the observed correlations, the correlation itself does not constitute proof of causation. This study focuses on physiological indicators (RWC, pigment content) that reflect tree health and condition. These indicators serve as proxies or underpinnings for ecosystem service provision, rather than direct measures of the services themselves. While this study did not directly quantify ecosystem services such as climate regulation, the findings demonstrate that physiological parameters are highly sensitive biological markers of microclimatic stress. These indicators provide valuable insights into the physiological

capacity of urban trees to perform ecosystem services and can serve as crucial inputs for assessing ecosystem condition and informing future ecosystem service models.

The understanding the statistical relationships between impact and ecophysiological factors can also contribute to the development of longer-term growth and ecosystem service models of urban trees [17,68]. These models are already widely used in both for research and practical urban environmental management. With the growing emphasis on ecological green space planning, there will be an even greater need for decision-support tools suitable for scenario evaluation and forecasting. The effect of the stand climate and the surrounding built-up area can add significant value to models that assess growth and ecosystem services.

The sampling protocol and the applied measurement methods proved suitable for detecting microclimatic differences within the street and analysing the ecophysiological effects. Based on monthly sampling and parallel micrometeorological measurements, it was possible to reveal the connections between plant responses and other physiological processes using widely used physiological indicators. As more experience becomes available for measuring pigments and water stress through remote sensing [69–72], these techniques can be considered suitable for characterising the ecosystem state in specific urban green space analyses and can be integrated into ecosystem assessments. Such scientific approaches are supported by our analysis and obtained data that help to understand the connection between climatic parameters and physiological responses under drought and heat stress. Furthermore, our data demonstrate that plant physiological parameters exhibit significant seasonal variability throughout the year, even on a monthly basis. Therefore, the timing of sampling must be integrated into existing models and remote sensing data when analysing the relationships between the vegetation and its environment.

This study provides valuable insights, but certain methodological considerations and limitations should be acknowledged. First, the findings are based on a single tree species, *Tilia tomentosa*, despite its common use in urban environments [73,74]. Physiological responses to microclimatic stress can vary significantly across different species with varying drought tolerance, light requirements, and growth habits. Therefore, the generalizability of these specific physiological thresholds and responses to the broader urban tree population should be considered with caution. Second, the study was conducted within a single street canyon in Szeged. Urban morphology is highly diverse, and microclimatic conditions (e.g., wind patterns, sky view factor, reflected radiation) and their impacts on trees can differ substantially in wider streets, open parks, or areas with different building heights and materials. Third, the data was collected over a single growing season. Physiological responses of trees can exhibit significant inter-annual variability due to fluctuating climatic conditions, such as the severity of heatwaves, drought intensity, and precipitation patterns. Multi-year studies would provide more robust insights into long-term acclimatisation and resilience. Fourth, as indicated by the NMDS ordination where measured environmental parameters did not fully explain the separation of samples, other unmeasured factors likely influence tree physiology. These could include localised soil properties (e.g., compaction, water holding capacity, nutrient availability), specific pollutant loads, or pest/disease pressures, which were not directly quantified in this study. The inherent complexity of urban ecosystems suggests that tree health is a product of multiple interacting stressors, not solely microclimatic variations.

However, the number of studies that attempt to examine the relationship between environmental factors and physiological parameters on a micro scale is extremely limited; therefore, despite its methodological limitations, this study can be a good starting point for later, more extensive by extending our approach across multiple years, and integrate physiological indicators into remote sensing-based monitoring and urban ecosystem service models. Further research will also more extensively examine the entire urban area under

varying built-up types to assess how different urban morphologies influence microclimatic effects on tree physiology.

5. Conclusions

Urban trees provide numerous ecosystem services, including climate regulation, air and water purification, and biodiversity support. They enhance aesthetics, increase property values, and offer recreational opportunities. Understanding the relationship between tree physiology and environmental parameters is crucial for effective urban forestry management. Factors such as temperature, humidity, and irradiation influence tree growth, health, and their ability to provide ecosystem services. By monitoring these parameters, we can optimise tree selection, planting locations, and maintenance practices to maximise their benefits in urban environments. Observed physiological differences, such as lower pigment content and reduced chlorophyll/carotenoid ratio on the sunny side, may manifest as earlier leaf senescence and reduced canopy density. These changes directly impact the ecosystem services noticeable to urban residents. A diminished canopy reduces shading capacity, leading to increased surface and air temperatures and exacerbating human thermal discomfort, especially during heatwaves. Furthermore, early leaf yellowing and shedding detract from the aesthetic appeal of urban green spaces, potentially reducing residents' satisfaction and perceived quality of their immediate environment. This creates a negative feedback loop where stressed trees provide fewer cooling benefits, further increasing heat stress on both trees and people.

Our results highlighted the connection between certain parameters of tree condition and growth and those of the microclimatic conditions. A significant difference in total insolation characterised the two sides of the street that served as a sample area, which resulted in a different microclimate on the two sides of the street. Due to the excess radiation, the air temperature values measured on the trees on the sunny side of the street were higher than those on the shaded side for most of the examined period. Limitations of this study include the single-year observation period, focus on a single species and a single street. However, the uniform growth and environmental conditions enabled highly precise tracking of microclimatic and physiological variations. This setting offers important baseline input for future, larger-scale studies that will encompass a wider range of sites and species.

Investigating the connection between physiological parameters and microclimatic conditions will serve as the basis for analysing the effects of the observed differences in physiological characteristics on ecosystem service provision. The very high maximum temperature values on the sunny side not only indicate extreme microenvironmental conditions for the tree growth but also highlight the significance of the heat stress mitigation service provided by the trees. Investigating how significant these differences in physiological characteristics are compared to those caused by other related factors (e.g., urban heat island, other limiting factors) would be worthwhile. These exploratory analyses of tree condition characteristics aid in the selection of suitable indicators in remote sensing-based analysis and monitoring methods. The sensitivity of pigment contents to microclimatic differences, along with their extensive measurement possibilities, provides a solid foundation for assessing the ecosystem condition and services of urban trees. The long-term goal could also be set to integrate microclimatic effects into growth models for urban trees (since relevant ecosystem service models of urban trees typically rely on quite generic allometric equations), and these results could contribute to the development of methods for analysing the climate-regulating effectiveness of urban trees.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land14091775/s1>, Figure S1: Differences in daily mean temperature between the northern and southern side; Figure S2: Total chlorophyll content values for whole trees on northern and southern side Table S1: Differences between the physiological characteristics of trees on northern and southern side; Table S2: Pearson correlation test between environmental factors and physiological characteristics; Table S3: Pairwise comparisons of leaf characteristics on northern and southern side.

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References

1. Un-Habitat. *World Cities Report 2022: Envisaging the Future of Cities*; Un-Habitat: Nairobi, Kenya, 2022.
2. Wang, J.; Zhou, W.; Jiao, M. Location Matters: Planting Urban Trees in the Right Places Improves Cooling. *Front. Ecol. Environ.* **2022**, *20*, 147–151. [CrossRef]
3. Helletsgruber, C.; Gillner, S.; Gulyás, Á.; Junker, R.R.; Tanács, E.; Hof, A. Identifying Tree Traits for Cooling Urban Heat Islands—A Cross-City Empirical Analysis. *Forests* **2020**, *11*, 1064. [CrossRef]
4. Gillner, S.; Vogt, J.; Tharang, A.; Dettmann, S.; Roloff, A. Role of Street Trees in Mitigating Effects of Heat and Drought at Highly Sealed Urban Sites. *Landsc. Urban Plan.* **2015**, *143*, 33–42. [CrossRef]
5. Oliveira, S.; Andrade, H.; Vaz, T. The Cooling Effect of Green Spaces as a Contribution to the Mitigation of Urban Heat: A Case Study in Lisbon. *Build. Environ.* **2011**, *46*, 2186–2194. [CrossRef]
6. Pauleit, S.; Duhme, F. Assessing the Environmental Performance of Land Cover Types for Urban Planning. *Landsc. Urban Plan.* **2000**, *52*, 1–20. [CrossRef]
7. Haines-Young, R.; Potschin, M.B. *Common International Classification of Ecosystem Services (CICES) V5. 1 and Guidance on the Application of the Revised Structure*; Fabis Consulting Ltd.: Nottingham, UK, 2018.
8. Bolund, P.; Hunhammar, S. Ecosystem Services in Urban Areas. *Ecol. Econ.* **1999**, *29*, 293–301. [CrossRef]
9. Gómez-Baggethun, E.; Gren, Å.; Barton, D.N.; Langemeyer, J.; McPhearson, T.; O’farrell, P.; Andersson, E.; Hamstead, Z.; Kremer, P. Urban Ecosystem Services. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*; Springer: Heidelberg, Germany, 2013; pp. 175–251.
10. Liang, D.; Huang, G. Influence of Urban Tree Traits on Their Ecosystem Services: A Literature Review. *Land* **2023**, *12*, 1699. [CrossRef]
11. La Notte, A.; Czúcz, B.; Vallecillo, S.; Polce, C.; Maes, J. Ecosystem Condition Underpins the Generation of Ecosystem Services: An Accounting Perspective. *One Ecosyst.* **2022**, *7*, e81487. [CrossRef]
12. Nedkov, S.; Zhiyanski, M.; Dimitrov, S.; Borisova, B.; Popov, A.; Ihtimanski, I.; Yaneva, R.; Nikolov, P.; Bratanova-Doncheva, S. Mapping and Assessment of Urban Ecosystem Condition and Services Using Integrated Index of Spatial Structure. *One Ecosyst.* **2017**, *2*, e14499. [CrossRef]
13. Tonyaloğlu, E.E. Spatiotemporal Dynamics of Urban Ecosystem Services in Turkey: The Case of Bornova, Izmir. *Urban For. Urban Green.* **2020**, *49*, 126631. [CrossRef]
14. Hou, Y.; Liu, Y.; Zeng, H. Assessment of Urban Ecosystem Condition and Ecosystem Services in Shenzhen Based on the MAES Analysis Framework. *Ecol. Indic.* **2023**, *155*, 110962. [CrossRef]

15. Salmond, J.A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M.; Dirks, K.N.; Heaviside, C.; Lim, S.; Macintyre, H.; et al. Health and Climate Related Ecosystem Services Provided by Street Trees in the Urban Environment. *Environ. Health* **2016**, *15*, 95–111. [\[CrossRef\]](#)
16. Pretzsch, H.; Moser-Reischl, A.; Rahman, M.; Pauleit, S.; Rötzer, T. Towards Sustainable Management of the Stock and Ecosystem Services of Urban Trees. From Theory to Model and Application. *Trees* **2023**, *37*, 177–196. [\[CrossRef\]](#)
17. Rötzer, T.; Rahman, M.; Moser-Reischl, A.; Pauleit, S.; Pretzsch, H. Process Based Simulation of Tree Growth and Ecosystem Services of Urban Trees under Present and Future Climate Conditions. *Sci. Total Environ.* **2019**, *676*, 651–664. [\[CrossRef\]](#)
18. Rötzer, T.; Moser-Reischl, A.; Rahman, M.; Grote, R.; Pauleit, S.; Pretzsch, H. Modelling Urban Tree Growth and Ecosystem Services: Review and Perspectives. *Prog. Bot.* **2021**, *82*, 405–464.
19. Leal Filho, W.; Wolf, F.; Castro-Díaz, R.; Li, C.; Ojeh, V.N.; Gutiérrez, N.; Nagy, G.J.; Savić, S.; Natenzon, C.E.; Quasem Al-Amin, A.; et al. Addressing the Urban Heat Islands Effect: A Cross-Country Assessment of the Role of Green Infrastructure. *Sustainability* **2021**, *13*, 753. [\[CrossRef\]](#)
20. Cuce, P.M.; Cuce, E.; Santamouris, M. Towards Sustainable and Climate-Resilient Cities: Mitigating Urban Heat Islands through Green Infrastructure. *Sustainability* **2025**, *17*, 1303. [\[CrossRef\]](#)
21. Haase, D.; Hellwig, R. Effects of Heat and Drought Stress on the Health Status of Six Urban Street Tree Species in Leipzig, Germany. *Trees For. People* **2022**, *8*, 100252. [\[CrossRef\]](#)
22. Warner, K.; Sonti, N.F.; Cook, E.M.; Hallett, R.A.; Hutya, L.R.; Reinmann, A.B. Urbanization Exacerbates Climate Sensitivity of Eastern U Nited S Tate Broadleaf Trees. *Ecol. Appl.* **2024**, *34*, e2970. [\[CrossRef\]](#)
23. Sjöman, H.; Nielsen, A.B. Selecting Trees for Urban Paved Sites in Scandinavia—A Review of Information on Stress Tolerance and Its Relation to the Requirements of Tree Planners. *Urban For. Urban Green.* **2010**, *9*, 281–293. [\[CrossRef\]](#)
24. Gill, S.E.; Handley, J.F.; Ennos, A.R.; Pauleit, S. Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environ.* **2007**, *33*, 115–133. [\[CrossRef\]](#)
25. Hirsch, M.; Böddeker, H.; Albrecht, A.; Saha, S. Drought Tolerance Differs between Urban Tree Species but Is Not Affected by the Intensity of Traffic Pollution. *Trees* **2023**, *37*, 111–131. [\[CrossRef\]](#)
26. Molnár, V.É.; Tóthmérész, B.; Szabó, S.; Simon, E. Urban Tree Leaves' Chlorophyll—A Content as a Proxy of Urbanization. *Air Qual. Atmos. Health* **2018**, *11*, 665–671. [\[CrossRef\]](#)
27. Petrova, S.T.; Yurukova, L.D.; Velcheva, I.G. Assessment of the Urban Trees Health Status on the Base of Nutrient and Pigment Content in Their Leaves. *J. Biol. Sci. Biotechnol.* **2014**, *3*, 69–77.
28. Le Saint, T.; Nabucet, J.; Hubert-Moy, L.; Adeline, K. Estimation of Urban Tree Chlorophyll Content and Leaf Area Index Using Sentinel-2 Images and 3D Radiative Transfer Model Inversion. *Remote Sens.* **2024**, *16*, 3867. [\[CrossRef\]](#)
29. Le Saint, T.; Nabucet, J.; Sulmon, C.; Pellen, J.; Adeline, K.; Hubert-Moy, L. A Spatio-Temporal Dataset for Ecophysiological Monitoring of Urban Trees. *Data Brief* **2024**, *57*, 111010. [\[CrossRef\]](#)
30. Locosselli, G.M.; de Camargo, E.P.; Moreira, T.C.L.; Todesco, E.; de Fátima Andrade, M.; de André, C.D.S.; de Andre, P.A.; Singer, J.M.; Ferreira, L.S.; Saldiva, P.H.N.; et al. The Role of Air Pollution and Climate on the Growth of Urban Trees. *Sci. Total Environ.* **2019**, *666*, 652–661. [\[CrossRef\]](#)
31. Lichtenthaler, H.K.; Ač, A.; Marek, M.V.; Kalina, J.; Urban, O. Differences in Pigment Composition, Photosynthetic Rates and Chlorophyll Fluorescence Images of Sun and Shade Leaves of Four Tree Species. *Plant Physiol. Biochem.* **2007**, *45*, 577–588. [\[CrossRef\]](#)
32. Stanley, C.H.; Helletsgruber, C.; Hof, A. Mutual Influences of Urban Microclimate and Urban Trees: An Investigation of Phenology and Cooling Capacity. *Forests* **2019**, *10*, 533. [\[CrossRef\]](#)
33. Pretzsch, H.; Biber, P.; Uhl, E.; Dahlhausen, J.; Schütze, G.; Perkins, D.; Rötzer, T.; Caldentey, J.; Koike, T.; van Con, T.; et al. Climate Change Accelerates Growth of Urban Trees in Metropolises Worldwide. *Sci. Rep.* **2017**, *7*, 15403. [\[CrossRef\]](#)
34. Jang, J.; Leung, D.W. The Morpho-Physio-Biochemical Attributes of Urban Trees for Resilience in Regional Ecosystems in Cities: A Mini-Review. *Urban Sci.* **2022**, *6*, 37. [\[CrossRef\]](#)
35. Martínez-Villa, J.A.; Paquette, A.; Feeley, K.J.; Morales-Morales, P.A.; Messier, C.; Durán, S.M. Changes in Morphological and Physiological Traits of Urban Trees in Response to Elevated Temperatures within an Urban Heat Island. *Tree Physiol.* **2024**, *44*, tpa145. [\[CrossRef\]](#)
36. Konarska, J.; Tarvainen, L.; Bäcklin, O.; Rantfors, M.; Uddling, J. Surface Paving More Important than Species in Determining the Physiology, Growth and Cooling Effects of Urban Trees. *Landsc. Urban Plan.* **2023**, *240*, 104872. [\[CrossRef\]](#)
37. Gebert, L.; Coutts, A.; Tapper, N. The Influence of Urban Canyon Microclimate and Contrasting Photoperiod on the Physiological Response of Street Trees and the Potential Benefits of Water Sensitive Urban Design. *Urban For. Urban Green.* **2019**, *40*, 152–164. [\[CrossRef\]](#)
38. Sanusi, R.; Johnstone, D.; May, P.; Livesley, S.J. Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer. *J. Environ. Qual.* **2016**, *45*, 167–174. [\[CrossRef\]](#)

39. Aleksandrowicz, O.; Pearlmutter, D. The Significance of Shade Provision in Reducing Street-Level Summer Heat Stress in a Hot Mediterranean Climate. *Landsc. Urban Plan.* **2023**, *229*, 104588. [\[CrossRef\]](#)
40. Kacsova, C.; Kiss, M.; Gulyás, Á. Studying The Growth Characteristics of Urban Trees Using An Example From Szeged, Hungary. *Acta Climatol. Et Chorol.* **2021**, *55*, 17–26. [\[CrossRef\]](#)
41. Czúcz, B.; Keith, H.; Maes, J.; Driver, A.; Jackson, B.; Nicholson, E.; Kiss, M.; Obst, C. Selection Criteria for Ecosystem Condition Indicators. *Ecol. Indic.* **2021**, *133*, 108376. [\[CrossRef\]](#)
42. Talebzadeh, F.; Valeo, C. Evaluating the Effects of Environmental Stress on Leaf Chlorophyll Content as an Index for Tree Health. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Bristol, UK, 19 December 2021; IOP Publishing: Bristol, UK, 2022; Volume 1006, p. 012007.
43. Kotttek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. *World Map of the Köppen-Geiger Climate Classification Updated*; Gebrüder Borntraeger: Stuttgart, Germany, 2006; Volume 15.
44. Liu, Y.; El-Kassaby, Y.A. Evapotranspiration and Favorable Growing Degree-Days Are Key to Tree Height Growth and Ecosystem Functioning: Meta-Analyses of Pacific Northwest Historical Data. *Sci. Rep.* **2018**, *8*, 8228. [\[CrossRef\]](#)
45. Lichtenthaler, H.K.; Buschmann, C. Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Curr. Protoc. Food Anal. Chem.* **2001**, *1*, F4-3. [\[CrossRef\]](#)
46. Hammer, Ø.; Harper, D.A. Past: Paleontological Statistics Software Package for Educaton and Data Anlysis. *Palaeontol. Electron.* **2001**, *4*, 1.
47. Oksanen, J.; Blanchet, F.G.; Kindt, R.; Legendre, P.; Minchin, P.R.; O'hara, R.; Simpson, G.L.; Solymos, P.; Stevens, M.H.H.; Wagner, H.; et al. Community Ecology Package. *R Package Version* **2013**, *2*, 321–326.
48. Team, R.C. *A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2022.
49. Merzlyak, M.N.; Gitelson, A.A.; Chivkunova, O.B.; Rakitin, V.Y. Non-Destructive Optical Detection of Pigment Changes during Leaf Senescence and Fruit Ripening. *Physiol. Plant.* **1999**, *106*, 135–141. [\[CrossRef\]](#)
50. Stratópoulos, L.M.F.; Zhang, C.; Duthweiler, S.; Häberle, K.-H.; Rötzer, T.; Xu, C.; Pauleit, S. Tree Species from Two Contrasting Habitats for Use in Harsh Urban Environments Respond Differently to Extreme Drought. *Int. J. Biometeorol.* **2019**, *63*, 197–208. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Zhang, M.; Ni, Y.; Li, M. Evaluation of the Growth, Adaption, and Ecosystem Services of Two Potentially-Introduced Urban Tree Species in Guangzhou under Drought Stress. *Sci. Rep.* **2023**, *13*, 3563. [\[CrossRef\]](#)
52. Takács, Á.; Kiss, M.; Hof, A.; Tanács, E.; Gulyás, Á.; Kántor, N. Microclimate Modification by Urban Shade Trees—an Integrated Approach to Aid Ecosystem Service Based Decision-Making. *Procedia Environ. Sci.* **2016**, *32*, 97–109. [\[CrossRef\]](#)
53. Rahman, M.A.; Moser, A.; Gold, A.; Rötzer, T.; Pauleit, S. Vertical Air Temperature Gradients under the Shade of Two Contrasting Urban Tree Species during Different Types of Summer Days. *Sci. Total Environ.* **2018**, *633*, 100–111. [\[CrossRef\]](#)
54. Muhammad Aslam, M.; Waseem, M.; Jakada, B.H.; Okal, E.J.; Lei, Z.; Saqib, H.S.A.; Yuan, W.; Xu, W.; Zhang, Q. Mechanisms of Absciscic Acid-Mediated Drought Stress Responses in Plants. *Int. J. Mol. Sci.* **2022**, *23*, 1084. [\[CrossRef\]](#)
55. Dale, M.; Causton, D. Use of the Chlorophyll a/b Ratio as a Bioassay for the Light Environment of a Plant. *Funct. Ecol.* **1992**, *6*, 190–196. [\[CrossRef\]](#)
56. Lichtenthaler, H.K.; Babani, F. Light Adaptation and Senescence of the Photosynthetic Apparatus. Changes in Pigment Composition, Chlorophyll Fluorescence Parameters and Photosynthetic Activity. In *Chlorophyll a Fluorescence: A Signature of Photosynthesis*; Springer: Berlin, Germany, 2004; pp. 713–736.
57. Melis, A.; Harvey, G. Regulation of Photosystem Stoichiometry, Chlorophyll a and Chlorophyll b Content and Relation to Chloroplast Ultrastructure. *Biochim. Et Biophys. Acta (BBA) Bioenerg.* **1981**, *637*, 138–145. [\[CrossRef\]](#)
58. Radoglou, K.; Dobrowolska, D.; Spyroglou, G.; Nicolescu, V.-N. A Review on the Ecology and Silviculture of Limes (*Tilia Cordata* Mill., *Tilia Platyphyllos* Scop. and *Tilia Tomentosa* Moench.) in Europe. *Romania* **2008**, *15*, 16.
59. d'Alessandro, S.; Beaugelin, I.; Havaux, M. Tanned or Sunburned: How Excessive Light Triggers Plant Cell Death. *Mol. Plant* **2020**, *13*, 1545–1555. [\[CrossRef\]](#)
60. Nath, K.; Phee, B.-K.; Jeong, S.; Lee, S.Y.; Tateno, Y.; Allakhverdiev, S.I.; Lee, C.-H.; Nam, H.G. Age-Dependent Changes in the Functions and Compositions of Photosynthetic Complexes in the Thylakoid Membranes of *Arabidopsis Thaliana*. *Photosynth. Res.* **2013**, *117*, 547–556. [\[CrossRef\]](#)
61. Demmig-Adams, B.; Gilmore, A.M.; Iii, W.W.A. In Vivo Functions of Carotenoids in Higher Plants. *FASEB J.* **1996**, *10*, 403–412. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Edge, R.; McGarvey, D.; Truscott, T. The Carotenoids as Anti-Oxidants—A Review. *J. Photochem. Photobiol. B Biol.* **1997**, *41*, 189–200. [\[CrossRef\]](#)
63. Biswal, B. Carotenoid Catabolism during Leaf Senescence and Its Control by Light. *J. Photochem. Photobiol. B Biol.* **1995**, *30*, 3–13. [\[CrossRef\]](#)
64. Fang, Z.; Bouwkamp, J.C.; Solomos, T. Chlorophyllase Activities and Chlorophyll Degradation during Leaf Senescence in Non-Yellowing Mutant and Wild Type of *Phaseolus vulgaris* L. *J. Exp. Bot.* **1998**, *49*, 503–510.

65. Zhou, X.; Huang, W.; Zhang, J.; Kong, W.; Casa, R.; Huang, Y. A Novel Combined Spectral Index for Estimating the Ratio of Carotenoid to Chlorophyll Content to Monitor Crop Physiological and Phenological Status. *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *76*, 128–142. [\[CrossRef\]](#)
66. Süßel, F.; Brüggemann, W. Tree Water Relations of Mature Oaks in Southwest Germany under Extreme Drought Stress in Summer 2018. *Plant Stress* **2021**, *1*, 100010. [\[CrossRef\]](#)
67. Zani, D.; Crowther, T.W.; Mo, L.; Renner, S.S.; Zohner, C.M. Increased Growing-Season Productivity Drives Earlier Autumn Leaf Senescence in Temperate Trees. *Science* **2020**, *370*, 1066–1071. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Pace, R.; De Fino, F.; Rahman, M.A.; Pauleit, S.; Nowak, D.J.; Grote, R. A Single Tree Model to Consistently Simulate Cooling, Shading, and Pollution Uptake of Urban Trees. *Int. J. Biometeorol.* **2021**, *65*, 277–289. [\[CrossRef\]](#)
69. Delegido, J.; Van Wittenberghe, S.; Verrelst, J.; Ortiz, V.; Veroustraete, F.; Valcke, R.; Samson, R.; Rivera, J.P.; Tenjo, C.; Moreno, J. Chlorophyll Content Mapping of Urban Vegetation in the City of Valencia Based on the Hyperspectral NAOC Index. *Ecol. Indic.* **2014**, *40*, 34–42. [\[CrossRef\]](#)
70. Degerickx, J.; Roberts, D.A.; McFadden, J.P.; Hermy, M.; Somers, B. Urban Tree Health Assessment Using Airborne Hyperspectral and LiDAR Imagery. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *73*, 26–38. [\[CrossRef\]](#)
71. Fuentes, S.; Tongson, E.; Gonzalez Viejo, C. Urban Green Infrastructure Monitoring Using Remote Sensing from Integrated Visible and Thermal Infrared Cameras Mounted on a Moving Vehicle. *Sensors* **2021**, *21*, 295. [\[CrossRef\]](#)
72. Marques, P.; Pádua, L.; Sousa, J.J.; Fernandes-Silva, A. Assessing the Water Status and Leaf Pigment Content of Olive Trees: Evaluating the Potential and Feasibility of Unmanned Aerial Vehicle Multispectral and Thermal Data for Estimation Purposes. *Remote Sens.* **2023**, *15*, 4777. [\[CrossRef\]](#)
73. Kesić, L.; Vuksanović, V.; Karaklić, V.; Vaštag, E. Variation of Leaf Water Potential and Leaf Gas Exchange Parameters of Seven Silver Linden (*Tilia tomentosa* Moench) Genotypes in Urban Environment. *Topola/Poplar* **2020**, *10*, 15–24. [\[CrossRef\]](#)
74. Petrova, S.; Velcheva, I.; Nikolov, B.; Vasileva, T.; Bivolarski, V. Antioxidant Responses and Adaptation Mechanisms of *Tilia tomentosa* Moench, *Fraxinus excelsior* L. and *Pinus nigra* JF Arnold towards Urban Air Pollution. *Forests* **2022**, *13*, 1689. [\[CrossRef\]](#)

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