

Identifying the Coolest Trees on the Block: Drone-Based Thermal Image Analysis of Tree Crown Temperatures

Paul J. Haverkamp¹, Nicola Notari², Christian Kaindl³, Jasmin Joshi³

¹ILF Institute for Landscape and Open Space, OST, Eastern Switzerland University of Applied Sciences, Rapperswil/Switzerland · paul.haverkamp@ost.ch

²ICE Institute for Computational Engineering, OST, Eastern Switzerland University of Applied Sciences, Buchs/Switzerland

³ILF Institute for Landscape and Open Space, OST, Eastern Switzerland University of Applied Sciences, Rapperswil/Switzerland

Abstract: Human-induced climate change is causing increasing temperatures, changing rainfall regimes, increased frequency of natural disasters and extreme weather, and loss of biodiversity. Mitigating climate change effects in cities, where higher temperatures and the urban heat island (UHI) effect are increasingly impacting citizen health, is becoming more difficult. Varied strategies are needed to alleviate complications due to UHI and climate change. Trees as nature-based solutions are one of the most popular and easiest mitigation measures to implement. This study investigated drone thermal images measuring the surface temperature of tree crowns, open grass, gravel paths, and shadows over grassy areas and gravel paths in the Enea Tree museum, an arboretum in Rapperswil-Jona, Switzerland. We wanted to identify tree species with consistent temperature differences compared to ambient air temperature (always cooler or always warmer than other species) in different weather conditions. In addition, we compared thermal properties of different shaded vs. unshaded surface covers. We found that tree species significantly differed in their crown surface temperatures. *Parrotia persica* and *Acer palmatum* were warmer than air temperature across all dates, while *Platanus x hispanica* was always cooler than air temperature. Surface temperatures of trees were correlated with the specific leaf area (SLA) with trees with higher SLAs and thus thinner leaves having on average a higher crown-surface temperature. The largest cooling effects were measured in tree shadows over grass. Importantly, shadows over gravel paths were found to be only slightly cooler than the ambient air and did therefore not contribute to microclimatic cooling. Our method can help planners identify suitable tree species and ground covers to reduce urban heat and promote cooling, especially in cities and climates where predicted temperature and rainfall changes could affect long-term survival of traditionally used tree species.

Keywords: Drone, thermal, tree crown, grass, shade

1 Introduction

Human-induced climate change is leading to increasing temperatures, rising sea levels, changing rainfall regimes, increasing frequency of natural disasters and extreme weather events, and, ultimately, loss of biodiversity (IPCC 2023). Mitigation of all possible scenarios is becoming more difficult, especially in cities dealing with these pressures as well as with increased population and housing density (GRIMM et al. 2008). Heat related deaths are increasing in recent years, especially in cities affected by the urban heat island (UHI) effect, which is reduced nighttime cooling in urban areas compared to natural or rural surroundings (OKE 1982, JOHNSON & WILSON 2009). While it is important to develop varied strategies to alleviate complications due to intensified UHI effects, trees as nature-based solutions have

become one of the most popular and easiest methods to mitigate heating effects, especially in urban environments with high levels of sealed surfaces (KLEEREKOPER et al. 2012, ETTINGER et al. 2024).

UHI effects can be lessened, and microclimate temperatures reduced with vegetation through removing sealed surfaces and planting ground cover, trees, and shrubs, as well as through green roofs and ground-based green facades. Planting trees can have the largest impacts and have been shown to reduce physiological equivalent temperature (PET) by 10-13% in large cities, representing a stronger effect for pedestrians than green roofs and facades (ZÖLCH et al. 2016). Trees have been found to reduce land surface temperature by 8-12°C on average in Central European cities (SCHWAAB et al. 2021). Cooling from trees is due to shading and evapotranspiration, with shade capable of decreasing the surface temperatures of natural and man-made surfaces by significant amounts (SHARMIN et al. 2023). Recent studies also highlight possible health benefits of larger, connected groupings of trees, especially in cities (CHI et al. 2025). However, the criteria and data to choose the best tree species and combinations of tree species as nature-based solutions for climate change mitigation for a given environmental situation are often not well defined or consistently available.

Adding greenspace in cities is widely accepted by the public (KLEEREKOPER et al. 2012) and thus selection of suitable plant functional types and species becomes important. Research has identified different tree morphologies influencing the cooling effects, including crown shape, canopy size and density, features of the leaves, as well as configurations of plantings (GEORGI & DIMITRIOU 2010, SHAHIDAN 2015). Canopy density, leaf area index (LAI), and leaf area density are regarded as having the greatest influence on surface cooling by trees (ARMSON et al. 2013, RAHMAN et al. 2015, HELLETSGRUBER et al. 2020). Many studies have also found that different species, as well as their locations, can lead to different levels of cooling (RAHMAN et al. 2015, RAHMAN et al. 2019, HELLETSGRUBER et al. 2020, MORAKINYO et al. 2020). It is therefore imperative to choose the correct species to plant in the right geographic location to best improve the local cooling effects (ZÖLCH et al. 2016, MORAKINYO et al. 2020).

This study investigated the effectiveness of an unmanned aerial vehicle (UAV or drone) equipped with a thermal camera to measure the surface temperature of tree crowns, open grass, gravel paths, and tree shadows over grassy areas and gravel paths on three summer days in an arboretum in Rapperswil-Jona, Switzerland. The goal was to determine if – under environmentally similar conditions – certain tree species had consistent temperature differences with ambient air temperature (always cooler or always warmer than other species) on days with different weather conditions. We also investigated how specific leaf area influences these tree crown surface temperatures.

1.1 Study Area

The research was conducted at the Enea Tree Museum (ETM; 47.22°N, 8.87°E) in Rapperswil-Jona, St. Gallen, Switzerland (www.enea.ch/baummuseum/). This arboretum is a 75,000 m² park on the property of the headquarters of Enea, GmbH, near Lake Zurich. Tree species in this arboretum are frequently used in landscape architecture projects. Trees in the park are mostly over 20 years old, with individual trees over 100 years old. This study focused on 192 individual trees from 42 different species (Figure 1). The trees are managed year-round through watering, fertilization, and pruning. Rapperswil-Jona is in eastern Switzerland

with a yearly precipitation of 1381 mm (www.hydrodaten.sg.ch) and average annual temperature of 10.7°C (SCHMUTZ 2024). This location allowed for the study to be conducted in a managed environment with access to many different tree species of similar age in one location, as well as reducing variation in temperature for trees located in different geographic areas, and inherent control over soil, water, and management conditions.

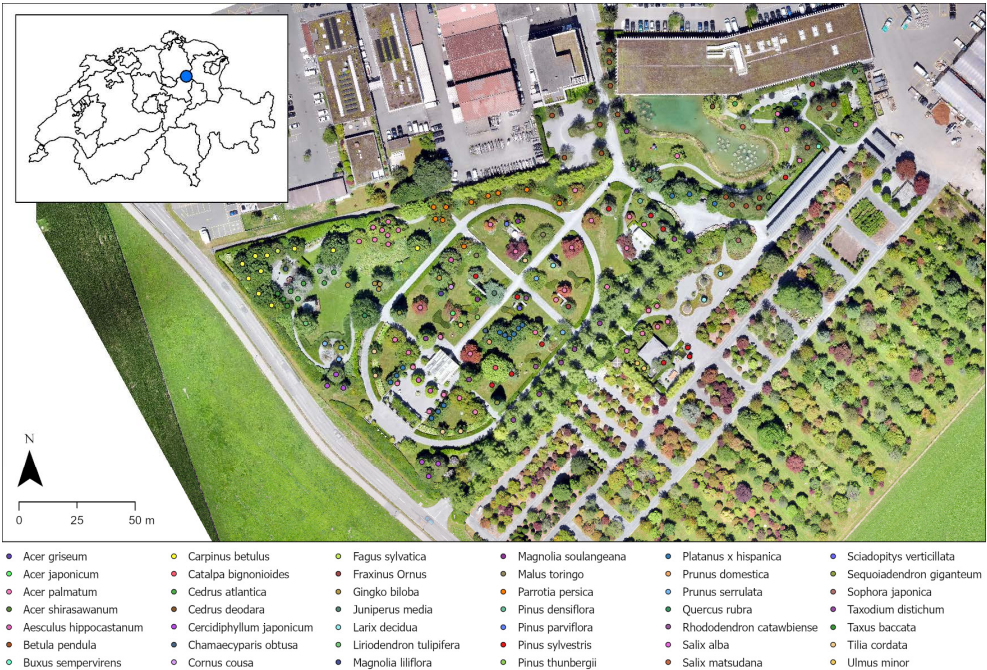
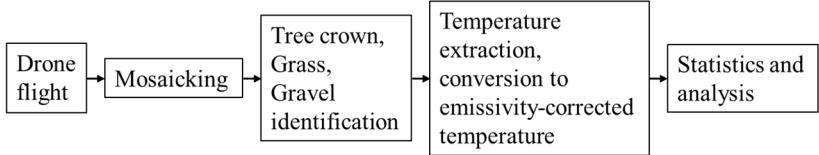


Fig. 1: The Enea Tree Museum (ETM) in Rapperswil-Jona, Switzerland, RGB image from the drone flight on 11 July 2022. All analysed trees are shown in the map. Inset map shows location within Switzerland.

2 Materials and Methods

The data was collected using a drone-mounted thermal camera to record images of surface temperatures. The thermal images were then mosaicked together to create a georeferenced thermal map of the Enea Tree Museum in °C. Using the thermal mosaics, we delineated the tree crowns, grass, and gravel areas to be analysed and compared. We then extracted the temperature data from all areas and calculated emissivity-corrected temperatures. This data was then used in the analysis (Table 1).

Table 1: Summary of the workflow used in this research



2.1 Data Collection

RGB and thermal infrared images were collected with an agEagle (previously senseFly) Duet-T camera mounted on an agEagle eBee X glider UAV flown over the ETM. The Duet-T camera has an RGB and thermal camera mounted and controlled together so images from both cameras overlap and images can be analysed together.

Flights were chosen for two days in summer 2022 and one day in summer 2023 to get a range of temperatures and conditions. Flights were on 11 July and 18 August 2022, and 16 August 2023. The data collection on 11 July 2022 and 16 August 2023 were mostly sunny days, while 18 August 2022 was mostly cloudy.

All flights were planned in agEagle eMotion software version 3.12 to cover the entire grounds of the ETM within one flight. The flights in 2022 were flown at a height of approximately 61 m on 11 July 2022, 71 m on 18 August 2022, and 61 m in 2023. 555 thermal images were taken on 11 July 2022, 532 on 18 August 2022, and 490 on 16 August 2023 (for more information see Appendix, Table A1). The thermal sensor on the Duet-T requires warming up to get accurate detections, and thus the eBee X flew in a circle for at least 10 minutes after launching to give the sensor ample time to warm up. It was only after these 10 minutes that the eBee X was sent a command to begin its mission and data was collected.

Air temperature, relative humidity, wind speed, and solar radiation were recorded at the same time as the flights at the Eastern Switzerland University of Applied Sciences’ Institute of Solar Technology at Rapperswil, approximately 3.6 km from the study site (see Appendix Table A1). Measurements were recorded every 10 seconds and mean values over 30 minutes surrounding the approximate times of the drone flights. Mean air temperature on 11 July 2022 during the flight was 25.2°C and on 18 August 2022 was 22.9°C. The warmest mean temperature was recorded on 16 August 2023 (28.0°C).

2.2 Image Processing

RGB and thermal images were imported into Pix4D Mapper software version 4.9.0 (agEagle) for mosaicking using the template provided by agEagle. RGB and thermal images were co-registered to the same geographic location and stitched together resulting in overlapping mosaics of RGB and thermal images at ground surface distance (GSD) resolutions of 0.03 m in July 2022, 0.05 m in August 2022, and 0.03 m for 2023 (see Appendix, Table A1). While the original GSD were different, we resampled a subset of the imagery and analysed this imagery and found it to have no effect on the results and statistical significance.

2.2.1 Individual Tree Crown Identification in the Imagery

A web map of aerial imagery of the ETM was used by employees of Enea, GmbH to identify the species of individually recognized trees in the images. This served as species validation for the analysis. A total of 192 trees were identified and analysed over the two years.

The locations of the individual trees were imported into ArcGIS Pro (ESRI) and overlaid onto the RGB and thermal image mosaics. A circle polygon layer was created at each location over the most homogeneous thermal area of the sunny side of the tree crown. We chose to focus on homogeneous areas to reduce the influence of shaded areas due to taller sections of trees or neighbouring trees, or due to openings in the trees due to loss of leaves or tree structure. However, in some trees this was not possible due to the highly heterogeneous natures of the tree crown temperatures and we used the most similar areas with the least thermal heterogeneity.

2.2.2 Identification of Grassy Lawns, Gravel Paths, and Shaded Areas in the Imagery

Areas covered with managed grassy lawns were similarly designated in ArcGIS Pro by creating circle polygons in large heterogeneous areas of the lawns at the ETM. Similarly, gravel paths, and shaded areas of lawns and gravel paths were identified with circle polygons created in ArcGIS Pro. The lawn, grassy lawn, gravel paths, and shadowed areas were identified for temperature analysis.

2.2.3 Mapping of Thermal Differences

Thermal difference (recorded surface temperature minus mean air temperature) maps were created for each date by subtracting the mean air temperature at the time of the flight from the surface temperature mosaic. This was done for each date (11 July 2022 shown in Figure 2; 18 August 2022 in Appendix, Figure A1; 16 August 2023 in Appendix Figure A2) to visually assess thermal differences.

2.3 Data Analysis

2.3.1 Tree Crown Temperature Analysis

Thermal mosaics and tree crown, grassy lawn, gravel path, and shaded area shapefile polygons were imported into Python 3.8 and temperature values within the circle polygons of the tree crowns were extracted. Data was organized using the ‘pandas’ Python library for statistical analysis.

We corrected the recorded temperatures based on surface type emissivity by using the Stefan-Boltzmann correction equation (Eq. 1):

$$T_{surface} = \sqrt[4]{\frac{T_{sensor}^4 - (1 - \epsilon) * T_{air}^4}{\epsilon}} \quad (1)$$

Where $T_{surface}$ is the corrected temperature at the surface, T_{sensor} is the corrected measured temperature from the thermal camera, T_{air} is the mean ambient air temperature during the flight, and ϵ is the emissivity of the surface. Temperatures were converted to Kelvin before

the calculation and back to Celsius after the calculation. The extracted pixel values from the circle polygons were emissivity-corrected based on surface type emissivity, using $\epsilon = 0.98$ for tree crowns and grass, and $\epsilon = 0.92$ for the gravel path. A literature review found vegetation emissivity ranges of about 0.95-0.99 and choose 0.98 as a common value for all vegetation in the study. We used $\epsilon = 0.92$ for the gravel path as this is a conservative value for rough stone. The mean surface temperature of each polygon was then calculated based on the emissivity-corrected values.

Mean air temperatures for the flight time were subtracted from median individual emissivity-corrected tree crown temperatures (tree crown temperatures from this point forward) and compared across species. The results indicate how the tree crown temperatures compared to air temperature, with negative values indicating tree crown temperatures below air temperature, positive values indicating tree crown temperatures above air temperature, and zero indicating the same temperature. Analysis was done on all tree species with eight or more individual trees identified in the ETM to reduce the effects of inter-tree variation. This resulted in eight tree species (see Appendix, Table A2) being compared in the final analysis. Box plots were created for the temperature differences for each species and each date. We tested if temperature differences were significantly different between species using a Kruskal-Wallis H-test to determine if there was at least one significant difference per date. We followed this with Dunn's post-hoc test, using a Holm-Bonferroni correction, for pairwise comparisons to identify the significant differences between species. We used the non-parametric tests since the thermal sensor data is not normally distributed.

2.3.2 Open Grass, Gravel Path, and Shaded Area Temperature Analysis

Mean air temperatures for the flight time were subtracted from median grassy lawn, gravel path, and shaded area circle polygons identified in the imagery. The results indicate how the different surface temperatures compared to air temperature, with negative values indicating surface temperatures below air temperature, positive values indicating surface temperatures above air temperature, and zero indicating the same temperature. Box plots were calculated for the temperature distribution of the surfaces and each date. Median temperature differences were considered significantly different between surface types by using a Kruskal-Wallis H-test to determine if there was at least one significant difference per date. We followed this with Dunn's post-hoc test, using a Holm-Bonferroni correction, for pairwise comparisons to identify the significant differences between surfaces. We used the non-parametric tests since the thermal sensor data is not normally distributed. The boxplot also included a category for the median value of the difference with air temperature for a combined tree species group, that included all trees in the study (not just those with more than eight individuals) to highlight the differences in surface temperatures.

2.3.3 Factors Influencing Temperature Differences

Previous studies have indicated the influence of specific leaf area (SLA), leaf area index (LAI), and leaf area density (LAD) on tree drought resistance (e. g. SAKSCHEWSKI et al. 2016) cooling effects (ARMSON et al. 2013, RAHMAN et al. 2015, HELLETSGRUBER et al. 2020). We chose to investigate whether specific leaf area (SLA) is correlated with surface temperature differences in our study species. Specific leaf area is the density of a leaf, measured as the area of a leaf divided by its dry weight. We used a literature review to determine SLA (Appendix 1, Table A1) for all species besides *Parrotia persica*, for which we could not find any

published information on SLA. We, therefore, took five leaves each from two trees at the OST campus in Rapperswil in August 2024 and within the first 10 minutes of clipping them from the tree, scanned the leaves to a jpeg and dried them in a drying oven (80°C for 24 hours). We imported the jpeg images in the R statistical program (R CORE TEAM 2025) and calculated the leaf area using the ‘LeafArea’ package (KATABUCHI 2015). We weighed the dried leaves and calculated the mean SLA for each leaf by dividing the area by the weight for each leaf.

We then examined the influence of SLA on the temperature differences (tree-crown mean temperature minus air temperature). We used a linear mixed-effects (LME) model in Python using ‘pandas’ and ‘statsmodels’ packages with temperature differences as the dependent variable and SLA and date as fixed effects and included their interactions. SLA was mean-centered to help interpretability, since SLA cannot equal zero. We used LME because we had multiple temperature difference measures across three dates from the same individual trees, and this model accounts for non-independence of observations within the same tree. We did not include species and individual tree in the fixed effect to avoid problems with collinearity, since SLA is the same per species and thus across dates for each individual tree. We included individual tree as a random effect, allowing each tree to have its own baseline temperature difference. Model parameters were estimated using Restricted Maximum Likelihood, and significance of the fixed effects were determined using Wald z-tests.

3 Results

3.1 Species Comparisons of Tree-crown Temperatures

The coolest day of the study was 18 August 2022 with a mean air temperature of 22.9°C and all median tree crown temperatures being below air temperature. The warmest day, 16 August 2023 (mean air temperature of 28°C), found all median tree crown temperatures to be above the air temperature except *Platanus x hispanica*. The third day of the study, 11 July 2022, had a mean air temperature near the mid-point between the two other days (25.2°C), but still found most tree species to have median tree-crown temperatures below air temperature. Maps of the thermal differences of surface temperature from the ambient air temperature for all dates (Figure 1, Appendix Figures A1, A2) highlight the impacts of the cooler tree crowns and shaded areas (blue areas). These also show that open grass had a mean of 6.6°C warmer than air temperature over the three measurement dates (red areas).

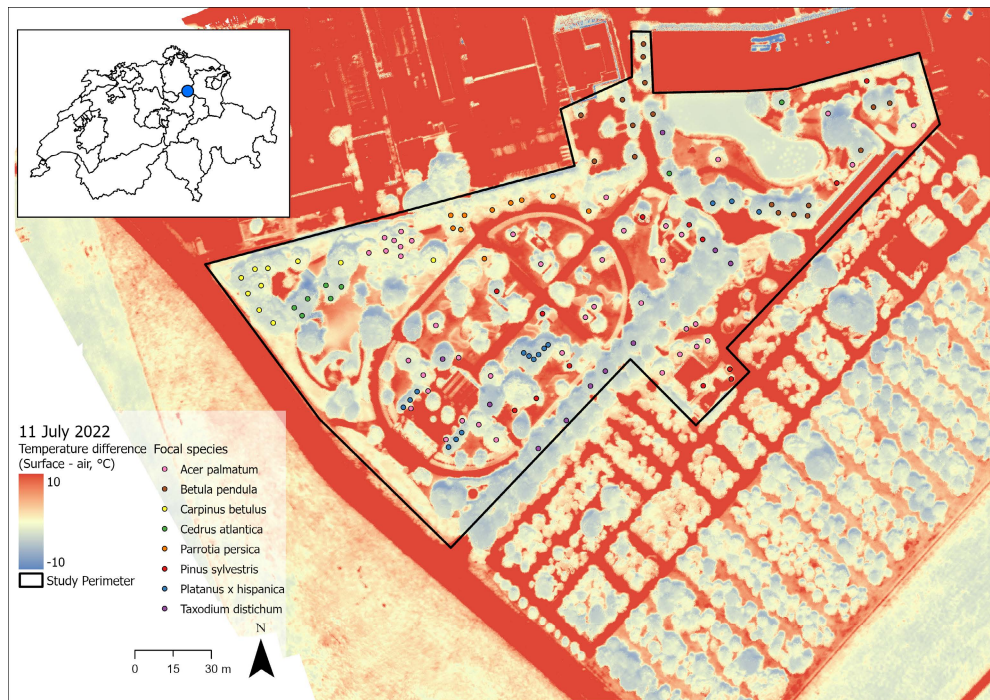


Fig. 2: Surface temperature differences with ambient air temperature on 11 July 2022, which was sunny and warm, but had the second-warmest air temperature of the three study dates. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.

All tree species were found to have cooler median tree canopy temperatures than the air temperature in August 2022, while all but two had cooler median tree canopy temperatures in July 2022 (Figure 3). All but one tree species were found to have warmer median tree canopy temperatures than the air temperature in August 2023, although two others had difference values very close to zero. The tree crown temperature of *Platanus x hispanica* (the London plane, a frequently used species in urban greening) was below the mean air temperature for all dates (Figure 3). This was the only species that was found to be cooler than air temperature for all dates. *Taxodium distichum* (Bald Cypress) had the lowest median species temperature difference for both dates in 2022. *Cedrus atlantica* (Atlas Cedar) also consistently had lower temperature differences than most other species.

In contrast, *Parrotia persica* (Persian Ironwood) had the highest median temperature difference with air temperature for all dates and was one of only two species with higher temperatures than air temperature in July 2022 (Figure 3). *Acer palmatum* (Japanese Maple) had the second highest median temperature difference across all dates.

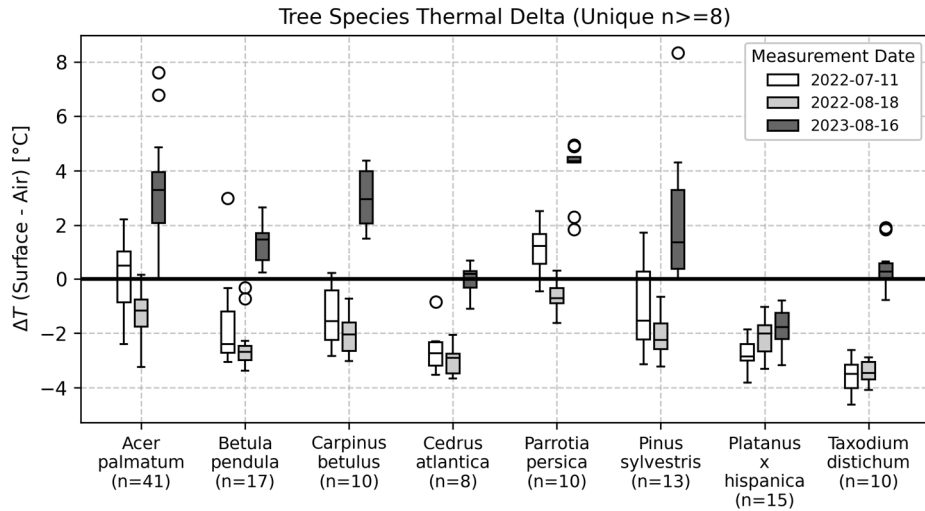


Fig. 3: Boxplot showing differences in temperatures between tree-crown surfaces and air temperature from species with more than eight individuals for all three study dates. Values above zero indicate warmer surface temperatures than air temperature, while values below zero indicate cooler surface temperatures than air temperature.

Species identity had a significant effect on temperature differences for all dates: 11 July 2022, $H(7) = 77.44$, $p < 0.001$; 18 August 2022, $H(7) = 62.92$, $p < 0.001$; 16 August 2023, $H(7) = 83.24$, $p < 0.001$. Post-hoc Dunn's test with Bonferroni correction found both *Parrotia persica* and *Acer palmatum* warmer than *Betula pendula*, *Cedrus atlantica*, *Platanus x hispanica*, and *Taxodium distichum* for all dates (Appendix, Tables A4–A6).

3.2 Open Grass, Gravel Path, and Shaded Area Temperature Analysis

The gravel paths always had the largest difference with air temperature and were thus the warmest surfaces, while the open grass areas consistently had the second highest temperature differences (Figure 4). The median gravel path surface temperature was more than 18 °C warmer than air temperature on the two warmest days of the study and was still more than 6 °C warmer on the coolest day with the most clouds (Figure 4). In contrast, shaded grass had mean temperatures below air temperature on the two sunny days, but not on the cloudy day, while tree crowns were cooler than air temperature except on the hottest day. Open grass and gravel had the warmest mean temperature differences. The mean shaded grass temperature difference across all three dates were 2.9 °C cooler than the air, 2.3 °C cooler than the tree crowns, 2.7 °C cooler than the shaded gravel, 9.5 °C cooler than open grass, and 17.8 °C cooler than open, gravel paths. In contrast, the shaded gravel was on average 0.2 °C cooler than air temperature across all three dates.

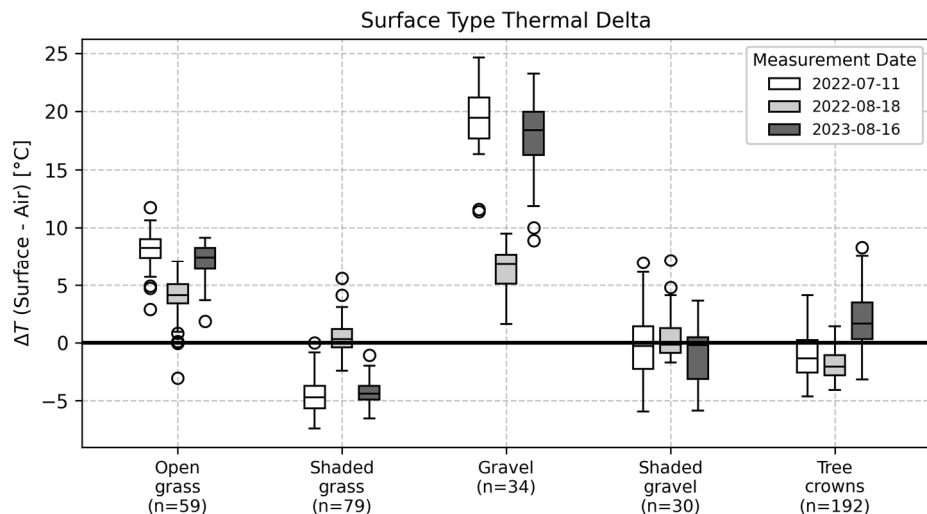


Fig. 4: Boxplot showing differences in temperatures between different surface types and air temperature for all three study dates. Values above zero indicate warmer surface temperatures than air temperature, while values below zero indicate cooler surface temperatures than air temperature.

Surfaces types had a significant effect on temperature differences for all dates: 11 July 2022, $H(4) = 290.55$, $p < 0.001$; 18 August 2022, $H(4) = 280.41$, $p < 0.001$; 16 August 2023, $H(4) = 316.68$, $p < 0.001$. Post-hoc Dunn's test with Holm-Bonferroni correction found no difference in temperature differences between open grass and gravel paths for all dates except August 2023, which was the hottest day, (Appendix, Tables A7-A9) despite the large differences in temperature differences. The Dunn's test is based on distribution of ranks instead of means, and high variance of the gravel measurements, with low sample size, may have led to overlaps in the rank-sum distributions with open grass, thus not identifying a significant difference. Shaded grass was cooler than all other surfaces for all dates, except in August 2022 for shaded gravel, where there was no difference, and being warmer than tree crowns.

3.3 Factors Influencing Temperature Differences

Linear mixed-effects modelling found SLA significantly influenced the temperature difference between mean tree-crown temperature and air temperature, but the strength of interactions varied significantly across dates, with the warmest day (16 August 2023) having the strongest relationship and the coolest day (18 August 2022) having the weakest relationship compared to 11 July 2022 (Appendix, Table A3). Higher SLA values were significantly correlated with slightly higher tree-crown temperatures than air temperature (Figure 5).

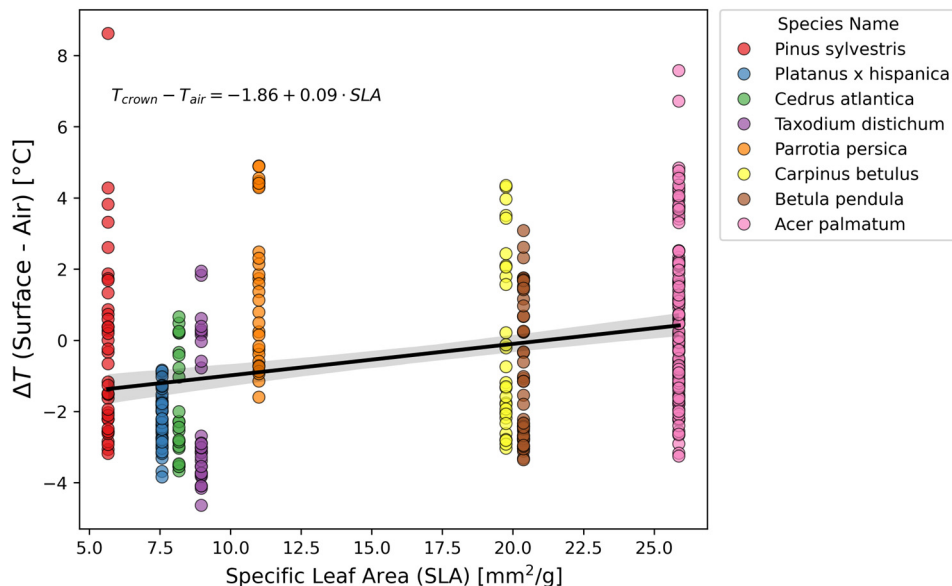


Fig. 5: Linear regression line showing relationship between raw SLA values and temperature differences for all dates for each tree (LME: $\beta = 0.09$, $p < 0.001$). Each point represents an independent tree measurement. Measurements were taken on 11 July and 18 August 2022, and 16 August 2023.

4 Discussion

The effects of climate change are increasingly being seen all over the world, leading urban planners and landscape architects to identify ways to reduce the effects on everyday life. This is especially the case in cities, where increased temperatures experienced as the urban heat island effect are causing problems including increased elderly deaths, uncomfortable temperatures, increased electricity use for cooling, etc. (FEIBEL et al. 2018, SMID et al. 2019, IUNG-MAN et al. 2023). While it is known that vegetation, especially tree cover with its shading and evaporative cooling effect helps reducing these overheating effects, little work has investigated how individual tree species can influence microclimate cooling.

This study used drone-collected thermal imagery to analyse surface temperatures of eight different tree species frequently used in landscape architecture, as well as different urban surfaces such as lawns and gravel paths to understand how they differed from air temperatures in summer in a managed park (ETM) in northeastern Switzerland. Significantly, we found two species whose tree-crown temperatures were consistently the warmest compared to ambient air temperature, and three species that were consistently the coolest compared to ambient air temperature. *Parrotia persica* and *Acer palmatum* consistently had warmer temperatures than air temperature, and warmer crown temperatures than the other species. Alternatively, the tree-crown temperature of *Platanus x hispanica* was found to be lower than the air temperature for all three dates. Two other trees, *Taxodium distichum* and *Cedrus atlantica*, consistently showed lower tree crown temperatures than the other trees in the study. As ex-

pected, we found shaded areas to be cooler than non-shaded grassy areas on sunny days, but also noted cooler tree-crown temperatures on the cloudy day. This study identified consistent differences in tree-crown surface temperature with air temperature across eight different tree species commonly used in landscape architecture projects in Switzerland across different summer weather conditions. This suggests that proper species choices for urban tree planting may help promote cooling.

The data was collected at three different points in time and represents three different weather conditions. We found that SLA and date, as well as interactions between SLA and date, significantly contributed to explaining variation in temperature difference. A higher SLA – hence thinner leaves, i.e. less biomass per leaf area – was significantly correlated with higher tree crown temperatures than air temperature. The thinner and less drought resistant leaves of tree species with a higher SLA might heat up faster and may have closed their stomata earlier during midday heat due to water stress than trees with leaves with a lower SLA. However, precise stomatal conductance measurements are needed to understand the functional mechanisms leading to differences in leaf surface temperatures associated with SLA. Our results are consistent with research observing that thicker leaves with higher water content and high stomatal conductance were more effective at cooling than thinner leaves (ARNOLD et al. 2025, ZHANG et al. 2025). These SLA results suggest that we can use knowledge of leaf morphology for green infrastructure design and help inform planners to consider different leaf morphologies with the goal of creating cooler microclimates. However, additional tree properties also play a role in the temperature differences suggesting that more research is needed to determine the effects of tree properties such as age, height, crown diameter, and trunk diameter at breast height as well as wood anatomy (e. g. ring-porous wood vs. coniferous wood with different tracheid diameters). Hence, more extensive studies can help city planners identify suitable tree species and combinations of tree species (e. g. a combination of fast-growing trees with thinner leaves with a high SLA and tree species investing in longer lasting leaves with a lower SLA) to optimise tree community cooling at different times of the day to reduce impacts of UHI, especially in climates where predicted temperature and rainfall changes could affect long-term survival of traditionally used species.

These inter-species differences in the tree-crown surface temperatures suggest that planting of some species could help reduce the temperature differences seen in urban heat islands more than others, and that future planners could concentrate on using some species over others to help promote localized cooling of microclimate in cities and settlements. Importantly, soil quality and surface covers also influence the urban microclimate. Our analyses showed that the mean shaded gravel temperature was only about 0.2°C cooler than air temperature across all three dates. However, trees planted in urban contexts are often surrounded by gravel, which helps reduce maintenance costs and may have some biodiversity effects for ruderal species. Our findings suggest that the overall effect of gravel shade on cooling is not much, as the shaded areas were almost the same temperature as the air. This does not take physiological equivalent temperature into account, and surely it is cooler in the shade than in the open sun on a hot day, but it is interesting to note that preferring gravel may not have overall cooling effects (especially in comparison with shaded lawns that were 2.7°C cooler than air temperature and 16.1°C cooler than gravel). These findings are consistent with previous research (ZITER et al. 2019) suggesting that removing sealed surfaces has the greatest effects on cooling in cities.

This project focused on observing the tree-crown temperature differences between species, while other studies have investigated the effects of morphological, and locational differences in tree cooling (RAHMAN et al. 2015, RAHMAN et al. 2019, HELLETSGRUBER et al. 2020). While tree-crown temperature readings based on thermal images are not directly comparable to air temperature readings around the tree, CHEUNG et al. (2021) found drone-based thermal images were highly and significantly correlated with below-canopy surface temperature and below-canopy air temperature. Similar to our study, HELLETSGRUBER et al. (2020) found *Platanus x hispanica* to have high cooling potential due to having the largest mean difference with reference wet bulb globe-temperature (-4.72 ± 0.40 °C), and air temperature at 1.1 m (-5.70 ± 1.03 °C) across multiple European cities. Our study suggests the drone-based tree-crown temperature method might be suitable for identifying which trees offer the most cooling in summer.

This study aimed to determine if drone-based thermal images could identify consistent species differences in tree-crown temperatures compared to ambient temperature on days with different weather conditions. An advantage of using a drone to record thermal images at arboreta such as the Enea Tree Museum is collecting many recordings all at once. While further studies need to be done to validate the correlation of drone thermal measures and human comfort, this method could lead to more efficient data collection over large areas in a relatively short amount of time, offering substantial benefits for spatial planners seeking to compare the cooling effects of different tree species planted under varying planting contexts (e. g., along roads, in parks, in residential areas) on the same day at similar times (BARTES-AGHI-KOC et al. 2021).

Data collection from drones can be relatively quick compared to collecting individual tree measures. Results from this study are similar to other, more detailed studies in terms of species temperature differences with air temperature, suggesting this method could be more efficient in terms of data collection. More studies in different locations and at different times of day will be needed to verify these findings, as well as to collect tree-based air temperature recordings and investigate other impacts on cooling including leaf area index and diameter at breast height. This may be difficult in practice due to management and environmental differences in trees planted in different locations. The ETM provided a controlled environment with the same environmental and management conditions for all trees, thus reducing the number of outside variables that could potentially lead to differences seen between study locations. Future longer-term research will revolve around monitoring year-round air temperature and humidity below the tree crown to determine if the temperature differences between species hold true. Future drone flights using thermal imagery can also help determine the correlation between tree crown temperature and below tree crown air temperatures. Additionally, flying the drone at different times of the day will increase understanding of how tree crown temperatures change through the day. It will also be important to see how air temperature and tree crown temperature are correlated in the evenings to help understand how tree crowns retain heat.

The information gained from this, and future studies can be incorporated into tree selection tools for cities and settlements in similar climate regimes as Rapperswil-Jona. Tools like Citree (<https://citree.de>, VOGT et al. 2017) can incorporate thermal information to help planners consider cooling when choosing which trees to plant. Incorporating thermal information into emerging planning schemes like the “sponge city” we can further improve the way cities aim to tackle UHI effects, drought, flooding and other impacts of climate change. It will be

important to choose the right tree species and combination of tree species for each climate and location (MORAKINYO et al. 2020). It is also important to consider biodiversity and water use, as these factors can support landscape architects in planning for increasingly variable climate conditions and in preparing for a range of future scenarios. This is particularly relevant in regions where more frequent droughts may limit water availability, even for tree species that provide strong cooling effects.

References

- ARMSON, D., RAHMAN, M. A. & ENNOS, A. R. (2013), A Comparison of the Shading Effectiveness of Five Different Street Tree Species in Manchester, UK. *Arboriculture & Urban Forestry*, 39 (4), 157-164.
- ARNOLD, P. A., WHITE, M. J., COOK, A. M., LEIGH, A., BRICEÑO, V. F. & NICOTRA, A. B. (2025), Plants originating from more extreme biomes have improved leaf thermoregulation. *Annals of botany*, 136 (1), 199-213.
- BARTESAGHI-KOC, C., HADDAD, S., PIGNATTA, G., PAOLINI, R., PRASAD, D. & SANTAMOURIS, M. (2021), Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. *Solar Energy*, 216, 564-588.
- CHEUNG, P. K., JIM, C. Y. & HUNG, P. L. (2021), Preliminary study on the temperature relationship at remotely-sensed tree canopy and below-canopy air and ground surface. *Building and Environment*, 204, 108169.
- CHI, D., MANOLI, G., LIN, B., AERTS, R., YANG, J., HAHS, A., RICHARDS, D., MEILI, N., ZHU, Y., QIU, Y. et al. (2025), Residential tree canopy configuration and mortality in 6 million Swiss adults: a longitudinal study. *The Lancet Planetary Health*, 9 (3), e186-e195.
- ETTINGER, A. K., BRATMAN, G. N., CAREY, M., HEBERT, R., HILL, O., KETT, H., LEVIN, P., MURPHY-WILLIAMS, M. & WYSE, L. (2024), Street trees provide an opportunity to mitigate urban heat and reduce risk of high heat exposure. *Scientific Reports*, 14 (1), 3266.
- FEIBEL, A., SWART, E. & MARCH, S. (2018), The Impact of Work Ability on Work Motivation and Health: A Longitudinal Study Based on Older Employees. *Journal of Occupational and Environmental Medicine*, 60 (5), e238-e244.
- GEORGI, J. N. & DIMITRIOU, D. (2010), The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece. *Building and Environment*, 45 (6), 1401-1414.
- GRIMM, N. B., FAETH, S. H., GOLUBIEWSKI, N. E., REDMAN, C. L., WU, J., BAI, X. & BRIGGS, J. M. (2008), Global change and the ecology of cities. *Science (New York, N.Y.)*, 319 (5864), 756-760.
- HAMBUCKERS, A., TROLLIET, F., DURY, M., HENROT, A.-J., PORTEMAN, K., EL HASNAOUI, Y., VAN DEN BULCKE, J., MIL, T. DE, REMY, C. C., CHEDDADI, R. & FRANÇOIS, L. (2022), Towards a More Realistic Simulation of Plant Species with a Dynamic Vegetation Model Using Field-Measured Traits: The Atlas Cedar, a Case Study. *Forests*, 13 (3), 446.
- HELLETSGRUBER, C., GILLNER, S., GULYÁS, Á., JUNKER, R. R., TANÁCS, E. & HOF, A. (2020), Identifying Tree Traits for Cooling Urban Heat Islands. A Cross-City Empirical Analysis. *Forests*, 11 (10), 1064.

- IPCC (2023), Summary for Policymakers. In: Lee, H. & Romero, J. (Eds.), Climate Change 2023. Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 34 pp.
- IUNGMAN, T., CIRACH, M., MARANDO, F., BARBOZA, E. P., KHOMENKO, S., MASSELOT, P., QUIJAL-ZAMORANO, M., MUELLER, N., GASPARRINI, A., URQUIZA, J., HERIS, M., THONDOO, M. & NIEUWENHUIJSEN, M. (2023), Cooling cities through urban green infrastructure: a health impact assessment of European cities. *The Lancet*, 401 (10376), 577-589.
- JOHNSON, D. P. & WILSON, J. S. (2009), The socio-spatial dynamics of extreme urban heat events: The case of heat-related deaths in Philadelphia. *Applied Geography*, 29 (3), 419-434.
- JOSHI, J., BRÄNNHAGE, J., ISMAIL, S., KRIEGER, M., KRIEGER, S. & KÜFFER, C. (2024), Habitate und Pflanzenarten für das Siedlungsgebiet: Eine Orientierungshilfe zur Förderung der Biodiversität und Landschaftsqualität. Nr. 26, Zenodo.
- KATABUCHI, M. (2015), LeafArea: An R Package for Rapid Digital Image Analysis of Leaf Area. *Ecological Research*, 30 (6), 1073-1077.
- KATTGE, J., BÖNISCH, G., DÍAZ, S., LAVOREL, S., PRENTICE, I. C., LEADLEY, P., TAUTENHAHN, S., DA WERNER, G., AAKALA, T., ABEDI, M. & OTHERS (2020), TRY plant trait database-enhanced coverage and open access. *Global change biology*, 26 (1), 119-188.
- KLEEREKOPER, L., VAN ESCH, M. & SALCEDO, T. B. (2012), How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*, 64, 30-38.
- LARA-ROMERO, C., RUIZ-BENITO, P. & CASTRO-DÍEZ, P. (2022), Functional traits and propagule pressure explain changes in the distribution and demography of non-native trees in Spain. – *Journal of Vegetation Science*, 33 (3), e13131.
- MORAKINYO, T. E., OUYANG, W., LAU, K. K.-L., REN, C. & NG, E. (2020), Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation, development and evaluation. *The Science of the total environment*, 719, 137461.
- OKE, T. (1982), The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108 (455), 1-24.
- R CORE TEAM (2025), R: A language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing.
- RAHMAN, M. A., ARMSON, D. & ENNOS, A. R. (2015), A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. *Urban Ecosystems*, 18 (2), 371-389.
- RAHMAN, M. A., MOSER, A., RÖTZER, T. & PAULEIT, S. (2019), Comparing the transpirational and shading effects of two contrasting urban tree species. *Urban Ecosystems*, 22 (4), 683-697.
- ROLOFF, A. & BÄRTELS, A. (2018), Flora der Gehölze. Bestimmung-Eigenschaften-Verwendung. Fünfte, aktualisierte Auflage. Eugen Ulmer, Stuttgart (Hohenheim).
- SAKSCHESKI, B., BLOH, W. V., BOIT, A., POORTER, L., PEÑA-CLAROS, M., HEINKE, J., JOSHI, J. & THONICKE, K. (2016), Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, 6 (11), 1032-1036.
- SCHMUTZ, M. (2024), Klimaanalyse Rapperswil-Jona: Beiblatt zum Bericht «Klimaanalyse Kanton St. Gallen - Klimaszenarien» mit gemeindespezifischen Klimadiagrammen, Meteotest AG.

- SCHWAAB, J., MEIER, R., MUSSETTI, G., SENEVIRATNE, S., BÜRGI, C. & DAVIN, E. L. (2021), The role of urban trees in reducing land surface temperatures in European cities. *Nature communications*, 12 (1), 6763.
- SHAHIDAN, M. F. (2015), Potential of Individual and Cluster Tree Cooling Effect Performances Through Tree Canopy Density Model Evaluation in Improving Urban Microclimate. *Current World Environment*, 10 (2).
- SHARMIN, M., TJOELKER, M. G., PFAUTSCH, S., ESPERON-RODRIGUEZ, M., RYMER, P. D. & POWER, S. A. (2023), Tree crown traits and planting context contribute to reducing urban heat. *Urban Forestry & Urban Greening*, 83, 127913.
- SMID, M., RUSSO, S., COSTA, A., GRANELL, C. & PEBESMA, E. (2019), Ranking European capitals by exposure to heat waves and cold waves. *Urban Climate*, 27, 388-402.
- VOGT, J., GILLNER, S., HOFMANN, M., THARANG, A., DETTMANN, S., GERSTENBERG, T., SCHMIDT, C., GEBAUER, H., VAN DE RIET, K., BERGER, U. & ROLOFF, A. (2017), Citree: A database supporting tree selection for urban areas in temperate climate. *Landscape and Urban Planning*, 157, 14-25.
- ZHANG, J., KAISER, E., ZHANG, H., MARCELIS, L. F. M. & VIALET-CHABRAND, S. (2025), A simple new method to determine leaf specific heat capacity. *Plant methods*, 21 (1), 6.
- ZITER, C. D., PEDERSEN, E. J., KUCHARIK, C. J. & TURNER, M. G. (2019), Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the United States of America*, 116 (15), 7575-7580.
- ZÖLCH, T., MADERSPACHER, J., WAMSLER, C. & PAULEIT, S. (2016), Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, 20, 305-316.

Appendix

Table A1: Meteorological mean values and flight information for the three drone flight dates. Meteorological data from the Eastern Switzerland University of Applied Sciences' Institute of Solar Technology at Rapperswil, approximately 3.6 km from the study site.

Date	Mean flight time of day	Flight height (m)	Mosaic pixel resolution (m)	Mean air temperature (°C)	Mean relative humidity (%)	Mean wind speed (m/s)	Mean intensity of solar radiation (W/m ²)
11 July 2022	12:45	61	0.03	25.2	31.0	1.9	942.0
18 August 2022	11:24	71	0.05	22.9	55.0	1.6	545.1
16 August 2023	11:14	61	0.03	28.0	41.6	1.7	797.0

Table A2: Properties of trees analysed. Data on Specific leaf area (SLA) were collected to analyse their correlation with the temperature differences between tree-crown temperature and air temperature. (n) values shown for the different species analysed.

Species (n)	Origin	Taxonomic classification	Life-form	Specific leaf area [mm ² /mg]	Wood anatomy	Winter Hardiness Zone	Habitat
<i>Acer palmatum</i> Thunb. (41)	Japan, Taiwan, China	Angiosperms, Sapindaceae	deciduous	25.87 ¹	Diffuse porous	6b	Cool and moist mountain forests, sun tolerating
<i>Betula pendula</i> Roth (17)	Europe, North Africa, Caucasus, Middle East, Western Siberia	Angiosperms, Betulaceae	deciduous	20.38 ¹	Diffuse porous	2	Pioneer species on nutrient poor, dry or wet soils
<i>Carpinus betulus</i> L. (10)	Europe, Caucasus, Middle East	Angiosperms, Betulaceae	deciduous	19.75 ¹	Diffuse porous	5b	Mixed deciduous forests on moderately dry to fresh soils
<i>Cedrus atlantica</i> (Endl.) Manetti ex. Carrière (8)	Algeria, Morocco	Gymnosperms, Pinaceae	evergreen	8.17 ^{1,2}	Coniferous wood, small tracheids	7a	Forests in the Atlas mountains, mesic soils with short droughts

Table A2 (continued)

Species (n)	Origin	Taxonomic classification	Life-form	Specific leaf area [mm ² /mg]	Wood anatomy	Winter Hardness Zone	Habitat
<i>Parrotia persica</i> C. A. Mey. Persian Iron-wood (10)	Northern Iran	Angiosperms, Hamamelidaceae	deciduous	11.0 ¹	Diffuse porous	6a	Hyrcanian forests. Alluvial mesic forests with periodic flooding and coastal plains of the Caspian Sea, thermophilic, sun loving, fire resistant
<i>Pinus sylvestris</i> L. (13)	Europe, Central Asia, Caucasus, Middle East	Gymnosperms, Pinaceae	ever-green	5.66 ¹	Coniferous wood	1	Pioneer species on nutrient poor, dry to wet soils, thermophilic
<i>Platanus x hispanica</i> Münchh. (15)	–	Angiosperms, Platanaceae	deciduous	7.57 ³	Diffuse to semi-ring porous	6b	Alluvial forests, well drained, consistently moist soils, thermophilic
<i>Taxodium distichum</i> (L.) Rich. (10)	North-Eastern USA to Central America	Gymnosperms, Cupressaceae	ever-green	8.96 ¹	Coniferous wood, large tracheids	6b	Coastal Plains on saturated and seasonally inundated soils, alluvial forests, thermophilic

Nomenclature follows WFO (2025): World Flora Online; www.worldfloraonline.org (accessed on: 23 Jul 2025). Life form and Habitat according to ROLOFF & BÄRTELS 2018, JOSHI et al. 2024, FloraVeg.EU – Database of European Vegetation, Habitats and Flora. www.floraveg.eu.

SLA values were mainly obtained from published values listed in the TRY database (KATTGE et al. 2020¹), as well as data from LARA-ROMERO et al. 2022² and HAMBUECKERS et al. 2022³. Data on wood anatomy were obtained from www.wood-database.com/wood-filter/ (accessed on: 23 Jul 2025) and SCHOCH et al. 2004 www.woodanatomy.ch (accessed on: 23 Jul 2025).

Table A3: Results of mixed-effect model examining different effects on temperature differences between crown temperature and air temperature

Predictor	Coefficient (β)	Std. Error	z-value	p-value	95% CI
Fixed Effects					
Intercept	-1.071	0.14	-7.63	< 0.001	[-1.35, -0.80]
Date (Aug 16, 2023)	2.889	0.131	22.05	< 0.001	[2.63, 3.15]
Date (Aug 18, 2022)	-0.875	0.131	-6.68	< 0.001	[-1.13, -0.62]
SLA (centered)	0.094	0.017	5.44	< 0.001	[0.06, 0.13]
Date (Aug 16, 2023):SLA	0.034	0.016	2.09	0.036	[0.00, 0.07]
Date (Aug 18, 2022):SLA	-0.052	0.016	-3.21	0.001	[-0.08, -0.02]
Random Effects					
Tree ID (Variance)	1.377	0.263	—	—	—

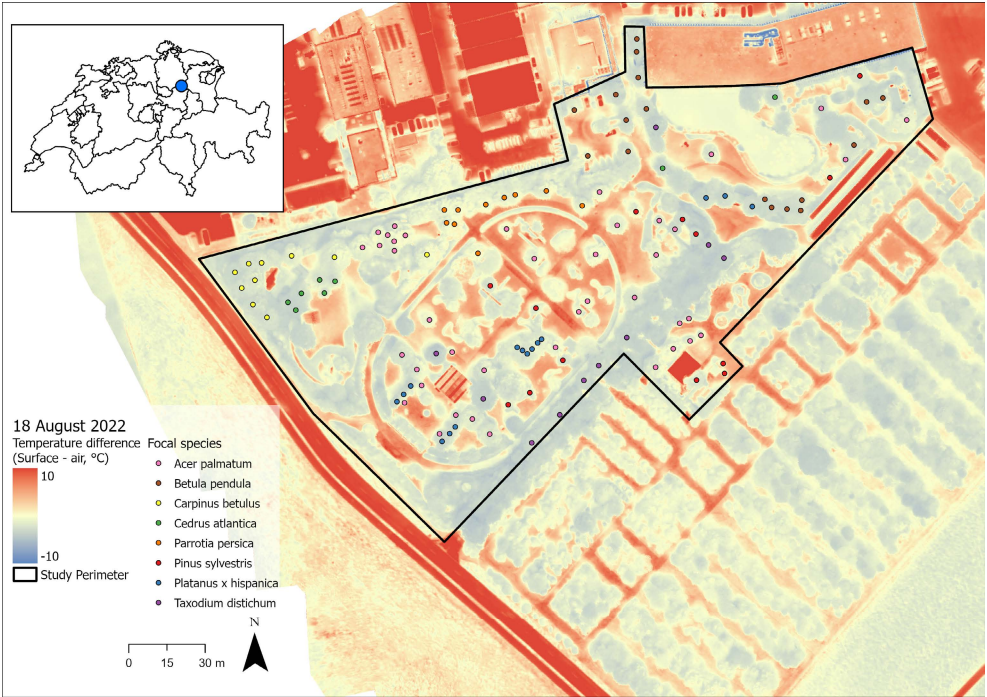


Fig. A1: Surface temperature differences with ambient air temperature on 18 August 2022, which was the cloudiest and coolest day of the study. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.

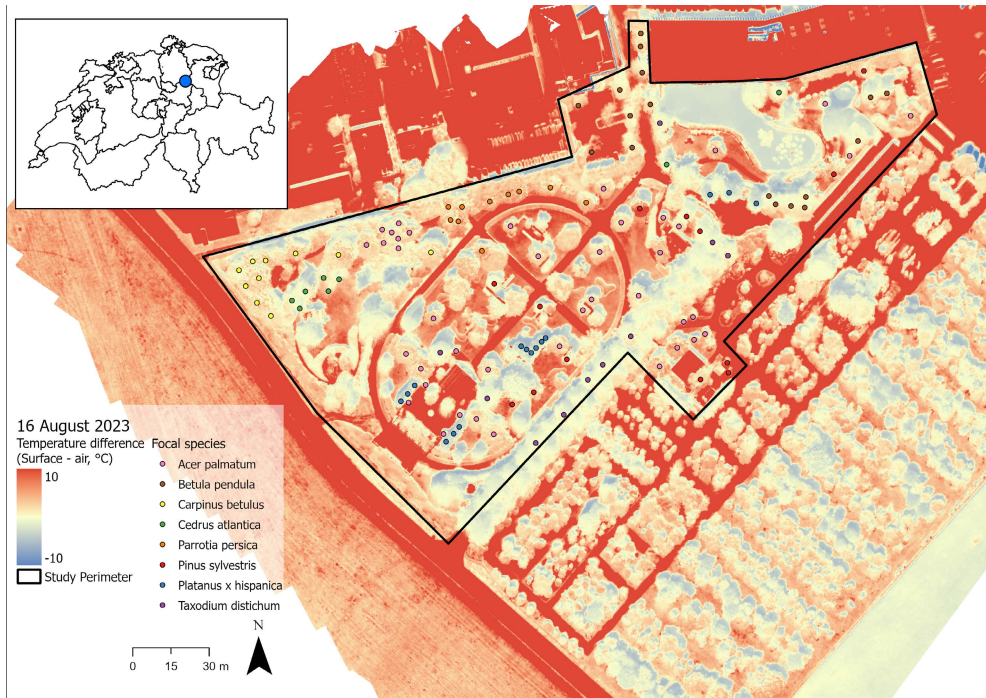


Fig. A2: Surface temperature differences with ambient air temperature on 16 August 2023, which was the sunniest and warmest day of the study. Values above zero (towards red) indicate warmer surface temperatures than air temperature, while values below zero (towards blue) indicate cooler surface temperatures than air temperature.