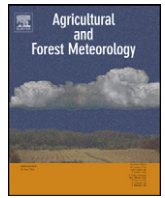




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Tree surface temperature in an urban environment

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ABSTRACT

Trees are essential in a dense urban environment not only because of their aesthetic value, but also for their cooling effect during hot periods, which impacts directly on the local microclimate. However, certain trees cope better with high urban temperatures than others. Here, we report tree crown temperatures of 10 common tree species frequently planted in Central European cities (in part, supplemented with stomatal conductance data, g_s). Parts of the city of Basel, Switzerland (7°41'E/47°34'N) were scanned from a helicopter using a high-resolution thermal camera. A histogram of the composite image shows peaks at 18 °C (water), 26 °C (vegetation), 37 °C (streets) and a less obvious one at 45 °C (roofs). At an ambient temperature of c. 25 °C, tree crown temperatures ranged from c. 24 °C (*Aesculus hippocastanum* trees located in a park) to 29 °C in *Acer platanoides* trees, located in a street. Trees in parks were significantly cooler (c. 26 °C) than trees surrounded by sealed ground (c. 27 °C). The only coniferous species, *Pinus sylvestris* did not vary in temperature with location (park or street) and exhibited foliage temperature close to air temperature. Generally, small-leaved trees remained cooler than large-leaved trees. Stomatal conductance data collected during similar weather conditions suggest that there was no bias in crown temperatures due to locally different water supply between trees. Although the highest leaf temperatures of individuals of *A. platanoides* reached over 5 K leaf-to-air temperature difference (ΔT_{L-A}), we do not expect temperature stress to occur in these conditions. In order to estimate possible effects of future temperature extremes on ΔT_{L-A} , we evaluated the leaf energy balance for a range of stomatal responses and air temperatures, using leaf size, wind speed and the measured species-specific leaf boundary layer resistance. At an ambient temperature of 40 °C, ΔT_{L-A} ranged from 2 to 5 K when g_s was assumed to drop linearly to 50% of its maximum value. When g_s was compromised further (20% of species-specific maxima), the difference in ΔT_{L-A} between species became larger with rising ambient temperature (range 4–10 K). Those species with the lowest leaf temperatures at 25 °C were not necessarily coolest at 40 °C. Species-specific differences in ΔT_{L-A} under extreme temperatures as shown here may be useful for urban tree planning in order to optimise management cost and human comfort.

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1. Introduction

Leaf temperature is the outcome of the energy balance at leaf level, which depends on a series of anatomical (leaf mass, size, shape, angle, reflectance properties, etc.), physical (incoming radiative energy, air temperature, wind) and biological (transpiration, controlled by stomatal conductance) phenomena (Monteith and Unsworth, 1990). All of these change at various temporal scales ranging from seconds to weeks. The resulting leaf temperature, or, integrated over a plant canopy, foliage tempera-

ture has important consequences for the plant itself, but also for the environment surrounding the plant. Due to their strong atmospheric coupling, foliage temperature of trees is particularly important for the local to global climate. Surveying vegetation cover with infrared cameras is possible from satellites (Soer, 1980), but does not provide high-resolution data to infer differences between species. In an earlier study however, we have shown that differences in foliage temperature between species can be substantial in a mixed deciduous forest (Leuzinger and Körner, 2007). From a human perspective, foliage temperature of urban trees are of particular interest due to their cooling effect on urban climate (Pauleit, 2003). However, very little data exists on urban tree temperatures despite its current and potential economic value in both aesthetical and microclimatic terms. For example, the additional energy cost associated with the urban overheating of Los Angeles compared to surrounding land is estimated at \$100

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million per year (Akbari et al., 2001). Not only costs for air conditioning increase, there are also health implications and human discomfort (Harlan et al., 2006). Jenerette et al. (2007) were able to show a positive correlation between the wealth of a neighbourhood and the amount of cooling from trees, emphasising the socio-economic role of urban vegetation. However, not all tree species have the same cooling effect, and heat tolerance of urban tree plantings may become a limiting factor for tree survival in such high Bowen ratio environments, particularly in a warming climate. Therefore, urban tree plantations need to be planned thoroughly since unsuitable species selection inevitably involves high costs.

The immediate coupling of leaf temperature with its latent heat loss (Jones and Leinonen, 2003) calls for a description of plant water status, particularly when water supply is highly variable. Temperate forests showed little sensitivity towards the prolonged 2003 summer drought and heat wave over Europe in terms of canopy temperature and NDVI (Zaitchik et al., 2006). This is in line with water relations data from a mixed deciduous forest during the 2003 summer drought, showing that it takes over 3 weeks of continuous drought to significantly reduce daily sap flow peaks in some, though not all species (Leuzinger et al., 2005). Oak, for instance, was not affected over more than 2 months of drought. We expect that leaf temperature characteristics of urban trees are relatively robust and less dependent on short-term variation in soil moisture than other types of vegetation such as grassland and crops. The reason for this may be that ground sealing removes competition for soil moisture. Also, during prolonged rainless periods, urban trees are often irrigated.

The aim of this study is to provide a basic data set on species-specific tree crown temperatures of urban trees. Additionally, some surface temperatures of non-plant surfaces are shown. We compare tree crown temperatures from trees growing in parks and those of trees surrounded by sealed ground. Practical advantages of such a multispecies survey of tree crown temperatures in a city like Basel are that species occur in many, similarly sized replicates, each individual is unconstrained by other crowns (well spaced) and all tree locations are georeferenced. We substantiate our discussion by accounting for leaf diffusive conductance in order to check for systematic differences in water supply. Based on this, we apply an energy balance approach, discussing differences in foliage temperature between species in a warming climate.

2. Materials and methods

The study was conducted in the city of Basel, Switzerland. While there are approximately 200 different tree species and subspecies planted in the city of Basel, we selected those that could be adequately replicated (subspecies were pooled and treated as one species): *Acer platanoides* Globosum, *Acer platanoides* Reitenbachii, *Acer saccharinum*, *Tilia cordata*, *Tilia x euchlora* (pooled with *Tilia cordata*), *Tilia platyphyllos*, *Tilia tomentosa*, *Tilia tomentosa* Brabant, *Robinia pseudoacacia*, *Aesculus hippocastanum*, *Gleditsia triacanthos*, *Pinus sylvestris* and *Platanus acerifolia*. Only trees with dense crowns that could be clearly delimited against their surroundings were used. The centre of the tree crowns was selected, comprising both north and south exposed patches, but allowing for a wide enough margin in order to ensure no temperature readings of adjacent objects were included. The bias from sunlit/shaded crown patches and areas close to the edge was therefore constant across all measurements. The city has a data base with all tree individuals recorded (position, species, planting date, etc.). This data base was used for identification of taxa in IR images and ground data collection. Tree height varied between 10 and 25 m at an average of 17 m.

We used a state-of-the-art thermal camera (VarioCam, Infratec, Dresden, Germany) sensitive in the spectral range of 7.5–14 μm and

with a resolution of 240×320 pixels, providing 76,800 temperature readings with a 0.1 K resolution. The northwestern part of the city covering a number of parks was systematically overflown in a helicopter with the thermal camera pointing directly downwards. Brightness temperature was calculated by inverting Planck's law using a constant emissivity, which is a reasonable approximation (Norman and Becker, 1995). As we did not apply neither an atmospheric correction nor a correction for the reflected sky irradiance we did not derive thermodynamic surface temperatures. For the range of emissivities of vegetation, however, the relative effect of the correction is small and can be neglected. For temperatures calculated as mentioned, we use the term 'surface temperature'. The thermal images were sampled at 2 Hz and later georeferenced and stitched to a composite, which was used for the extraction of tree crown temperatures. The helicopter flight took place on 16 July 2004 from 11:44 to 12:10 CET to minimise tree crown shading. The height of the flight legs was close to 400 m which resulted in a pixel resolution of 0.7 m. Emissivity of leaves among different species only varies within a narrow bandwidth of c. 0.94 and 0.99 (Idso et al., 1969), but in accordance with Spronken-Smith and Oke (1998), we assumed an emissivity of 1 since no data for the investigated species were available. The weather was cloudfree. Air temperature was measured in 10-min intervals at two built-up sites at 38 and 40 m above street level (approx. 1.8 times above mean building height) and at an open park site at 2 m above ground. The reference air temperature was calculated as the mean of the average temperature readings at each of the three sites (average range within site 0.4 K, average range between sites 0.9 K). The water vapour pressure deficit (vpd) during the flight time was around 1.5 kPa and net radiation around 661 W m^{-2} . Light winds were blowing at a constant rate of 2 m s^{-1} from NE. Precipitation during the three preceding months was slightly less than average but during the 10 days before the flight it rained 34 mm, so soil water availability was likely not limiting. Therefore, the leaf temperatures of the studied trees can be expected to reflect conditions of unrestricted access to soil moisture and hence, we expect little stomatal downregulation and close to maximum evaporative cooling.

In order to identify potential systematic site differences, stomatal conductance measurements (SC-1, Decagon Devices, Pullman, USA) were taken on a subsample of the population of trees used for thermography between noon and 15 h on 24 and 27 August 2007. Fully sunlit leaves were selected from the central top crown at a height of 10–25 m in order to be comparable to the field of view of the thermal camera. Not all species were covered for reasons of limited accessibility due to street traffic. Depending on the accessibility of the trees and logistic restraints, 6–19 trees were sampled per species, and 2–5 sunlit leaves from different areas of the top of the tree crowns were averaged per tree in order to minimise the spatial variation. Further, depending on within-species variation, 20–50 leaves per species were harvested to determine typical surface area per leaf or leaflet. Due to logistic reasons and in order to complete all measurements in a small time-window, the order of the measured trees was not completely random because closely located trees had to be sampled together. Literature data were used for those trees for which measurements could not be performed. Peak temperatures during the 2 days on which porometry measurements were conducted were slightly higher than during the flight and ranged between 25 and 28 °C. Maxima of water (vapour pressure deficit) vpd varied accordingly between 1.7 and 2.4 kPa. Although precipitation was 50% above average during the 3 months before the porometry measurements, the 2 weeks immediately before were characterized by rather dry weather (20 mm of rain). Therefore, the soil water status during porometry measurements was similar to the one during the helicopter survey.

Thermal images were analysed using the software provided with the camera (Irbis professional, Infratec, Dresden, Germany).



Fig. 1. False-colour thermal image taken on 16 July 2004, c. 12:00 CET. The image shows an intersection in the city of Basel at an air temperature of c. 25 °C. Temperatures range from around 22 °C (shaded tree crowns) to c. 40 °C (asphalted streets) and up to 50 °C (roofs).

Thermal images were stitched and analysed using ENVI 4.4 and IDL 6.4 (ITT Visual Information Solution). The free software package 'R', version 2.1.6 (R Development Core Team, 2007) was used for all other data processing and statistical analyses.

3. Results

Fig. 1 shows an example of a single thermal image from a suburban area. The composite image, which is put together from 131 single scenes, is displayed as a false-colour thermal image in **Fig. 2**. The area covered by all pixels is roughly 4.8 km². The 'Rhine knee' is visible in the centre of the picture (the area where the river Rhine turns from east–west to south–north).

3.1. Tree temperatures

Mean air temperature during the flight was 25.1 °C across all three measurement sites. The mean temperature at the park site (at 2 m above ground) was slightly higher than at the two built-up

sites (25.9 °C vs. 24.5 °C). Tree canopy temperatures ranged from 1 K below (*Aesculus hippocastanum* trees in a park) to 4 K above mean air temperature (*Acer platanoides* trees in streets, **Fig. 3**). The standard deviation within the tree crowns was typically in the range of 0.8–1.3 K and similar to the intertree variation. Fifteen individuals of *Acer platanoides* showed crown temperatures >5 K above air temperature. Across all 475 surveyed trees, park trees were c. 1 K colder (on average 26.1 ± 0.18 s.e. °C, $n = 148$) than street trees (27.2 ± 0.13 s.e. °C, $n = 348$, Student's t -test $p < 0.001$). In five out of ten species, concurrent canopy temperatures of trees in parks were cooler than those of trees located in streets (Student's t -test results indicated in **Fig. 3**). The only coniferous species, *Pinus sylvestris*, showed only a small temperature range c. 1 K above ambient air temperature and there was no difference between trees in parks and trees in streets in this species. Among the broad-leaved deciduous taxa, *Tilia* sp. (lime) were the only species that showed no significant difference between park and street locations or even higher leaf temperatures in parks compared to streets. The estimated mean leaf areas for each species are indicated in **Fig. 3**. Larger leaves generally showed higher leaf temperatures.

The water status of plants is intimately coupled with their foliage temperature. To ascertain that trees that showed high canopy temperatures were not generally short of water (e.g. because of a disease), we measured stomatal conductance on a subsample of trees per species. There was no trend for lower mean stomatal conductance in trees with higher canopy temperature in none of the investigated species. There was no difference in stomatal conductance between park and street trees either. On the other hand, there were marked differences between species: midday stomatal conductance ranged from 125 to 150 mmol m⁻² s⁻¹ for all species except *Tilia tomentosa*, *Tilia cordata* and *Platanus acerifolia*, which showed values of around 200 mmol m⁻² s⁻¹ (**Fig. 3**), which is in line with an average maximum value for temperate deciduous forest trees of 190 mmol m⁻² s⁻¹ indicated by Körner (1994).

3.2. Concurrent temperatures of non-plant surfaces

With surface temperatures around 18 °C the river Rhine marks the lower boundary of the temperature spectrum. In the eastern part, the German railway station 'Badischer Bahnhof' can be discerned showing the highest average temperatures of up to 60 °C

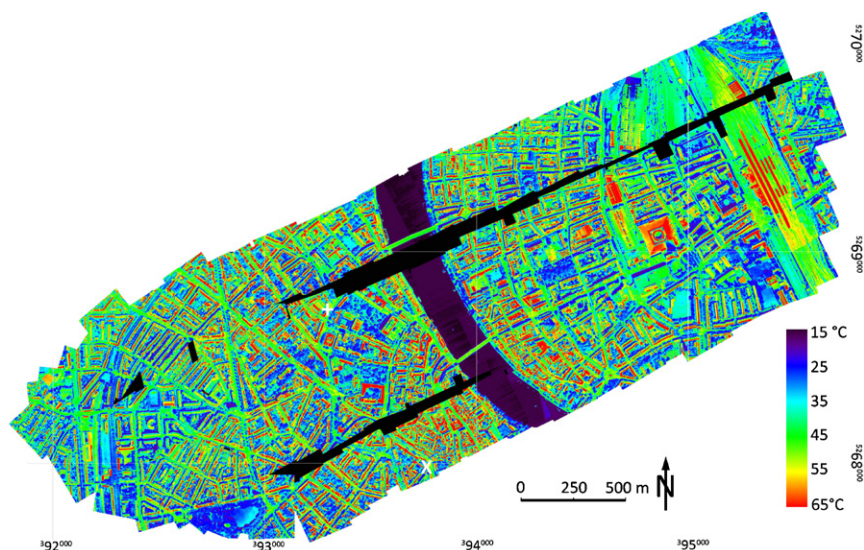


Fig. 2. Complete assembled picture with false colours (legend showing corresponding temperatures on the right). Some areas (black) were not covered due to helicopter movement. Ground surface temperature monitoring sites are shown with white crosses, the measurement site for the park temperature lies outside the scanned area.

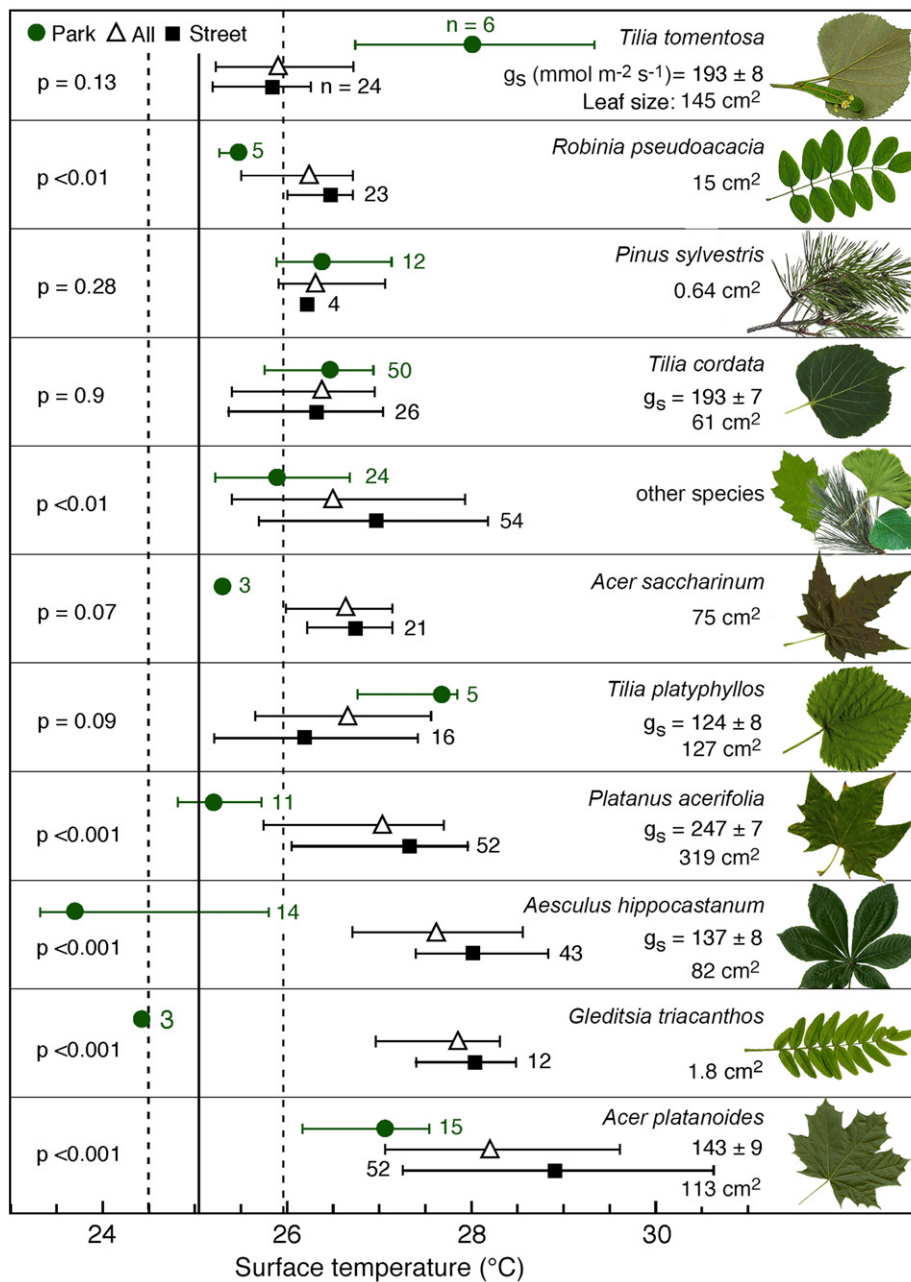


Fig. 3. Median of surface temperatures of tree crowns ± 1 quartile of 10 different tree species in the city of Basel on 16 July 2004 around noon CET, sorted by increasing leaf temperature. Range of temperatures in the urban canopy layer are indicated. Mean air temperature indicated by the solid line (25.1 °C, minimum 24.5 °C, maximum 25.9 °C). Replication of park and street trees are displayed for tree species class. Total tree number is 475. Where n is less than 5 then the average value is plotted. p-Values refer to t-tests of street vs. park tree temperatures. Leaf size: estimate of typical area per leaf or leaflet, stomatal conductance g_s in $\text{mmol m}^{-2} \text{s}^{-1}$.

(Fig. 2). The square buildings of the exhibition centre (Messe Basel) west of the train station show similarly high values. The old centre of Basel (situated to the left and right of the southern bridge) shows higher temperatures than the remaining part of the city. Dark blue colours typically represent tree crowns and light blue grassy patches. Green (c. 37 °C) is typical for streets and paved areas and yellow and red for roofs. The latter class is relatively wide-spread depending on roof material and orientation of the roof and ranges from c. 35 °C to 60 °C. Fig. 4 gives a statistical summary of the thermal image for the various surface categories. Here, 'park' marks the average tree temperatures of the 'Schützenmatt Park' which is located in the southwestern part of the composite image. Apart from the river Rhine, shadows of trees and houses are the only surfaces cooler than that park area. The bend in the histogram around 32 °C separates the relatively narrowly distributed

temperatures of green surfaces (c. 26 °C) from the wide-spread values of other urban fabric (c. 37 °C), with roofs hottest (c. 45 °C).

4. Discussion

The resolution of the presented urban surface temperature data for the first time allows to determine mean canopy temperatures of individual trees belonging to different species. The average tree foliage temperature measured here (c. 27 °C) at c. 25 °C air temperature, range 24.1–26.0 °C, measuring height 2–40 m) seems low and suggests ample water supply at the time of the thermal scanning (Ansari and Loomis, 1959). Based on this and our stomatal conductance measurements, which did not depend on tree foliage temperature within species, we assume that the trees that were scanned with the thermal camera were generally healthy

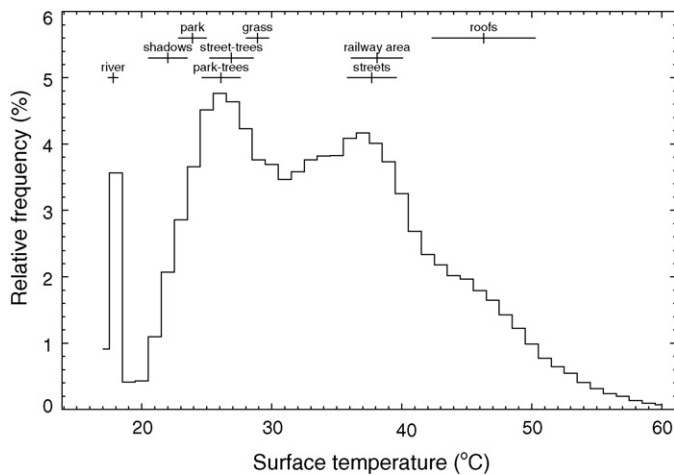


Fig. 4. Frequency distribution (1 K bins) of pixel values of the composite image. The average of all pixels is 33.6 °C. Indicated are also typical surface types with the corresponding average \pm one standard deviation.

and transpiring at unrestricted rates. The leaf-to-air temperature difference (ΔT_{L-A}) is strongly influenced by wind (Grace, 1977), which was relatively low and constant during our measurements (c. 2 m s⁻¹). Therefore, this factor had a small and constant cooling effect on leaf temperatures and the differences observed in ΔT_{L-A} can be attributed to other factors such as leaf size (see the evaluation of the leaf energy balance below).

4.1. Differences between park and street trees

Across all species, we found significantly lower tree crown temperatures in park trees compared to street trees. The effect was most apparent in trees within larger parks (*Aesculus hippocastanum*). Based on our stomatal conductance measurements, we assume that the latent heat loss in both park and street trees was similar. With the assumption of the other components of the energy balance (see below) remaining constant while foliage temperature was c. 1 K cooler in park trees, we argue that the incoming energy flux may have been larger for street trees because of higher radiation load of the surrounding fabric, both in the short- and longwave range. This is consistent with studies that have shown that the thermal discomfort in cities is rather due to higher radiation than to higher air temperature (Emmanuel, 2005). Nevertheless, our study shows that the cooling effect of urban trees is species-specific. Trees with lower foliage temperature will cool their immediate environment more than warmer trees.

4.2. Present and future leaf-to-air temperature differences

As expected and previously shown for forest trees (Leuzinger and Körner, 2007), trees with larger leaves (e.g. *Acer platanoides*, *Aesculus hippocastanum*, *Platanus acerifolia*) tended to have higher crown temperatures, while trees with smaller leaves (e.g. *Robinia pseudoacacia*, *Pinus sylvestris*) generally showed lower crown temperatures. The large-leaved *Tilia tomentosa* did not follow this trend, possibly because of its comparatively high mean stomatal conductance. Similarly, *Gleditsia triacanthos* showed high canopy temperatures despite small leaves. *Tilia platyphyllos* did not exhibit high crown temperatures as found in an earlier study, where tree crowns of the same species within a forest stand were on average 5 K above air temperature during similar microclimatic conditions (Leuzinger and Körner, 2007). A reason for this may have been the varieties and crossbreds used for this study, which feature completely different canopy architectures (e.g. open vs. closed).

Other factors differing between wild trees and cultivated forms which may be equally important (leaf shape, -angle, -surface, and canopy properties such as height, density, branching habit and roughness, Grace, 1977; Jones, 1992).

In order to discuss possible effects of high air temperatures on the leaf-to-air temperature difference ΔT_{L-A} in the future, we solved the leaf energy balance for the leaf boundary layer resistance to water vapour r_{aW} (Leuzinger and Körner, 2007; Jones, 1992):

$$r_{aW} = \frac{\rho_a c_p r_{aH} (\delta e + \Delta T_{L-AS})}{\gamma (r_{aH} Q_n - \Delta T_{L-A} \rho_a c_p)} - r_{IW} \quad (1)$$

with air density, ρ_a (1.175 kg m⁻³), specific heat capacity of dry air, c_p (1012 J kg⁻¹ K⁻¹), the psychrometer constant, γ (66.5 Pa K⁻¹), the net radiation, Q_n (661 W m⁻²), the slope s (temperature dependent, Pa K⁻¹) of the linearised relationship between the leaf-to-air temperature difference and the vapour pressure deficit of the air, δe (1.5 kPa). The leaf resistance to water vapour, r_{IW} (s m⁻¹) is the inverse of stomatal conductance as indicated for the measured species in Fig. 3. For the remaining species, we used $g_{s,max}$ values from the literature (*Robinia pseudoacacia* 140 mmol m⁻² s⁻¹, Gao et al., 2005; *Pinus sylvestris*, 120 mmol m⁻² s⁻¹, Willert et al., 1995; *Acer saccharinum* 150 mmol m⁻² s⁻¹, Yang et al., 1998). The mean maximum stomatal conductance for temperate deciduous forest trees was assumed for *Gleditsia triacanthos* (190 mmol m⁻² s⁻¹, Körner, 1994) because no literature data were available. The leaf boundary layer resistance to heat, r_{aH} was calculated according to Monteith and Unsworth (1990) and Jones (1992): $r_{aH} = k(u/d)^{-0.5}$ with u the wind speed (constant at 2 m s⁻¹), k a constant most realistically set to 0.1 s^{0.5} m⁻¹, and d the typical leaf width in m (square root of leaf surface areas indicated in Fig. 3). Based on the species-specific r_{aW} values calculated using Eq. (1), we thus evaluated the leaf energy balance

$$\Delta T_{L-A} = \frac{r_{aH} (r_{aW} + r_{IW}) \gamma Q_n}{\rho_a c_p (\gamma (r_{aW} + r_{IW}) + s r_{aH})} - \frac{r_{aH} \delta e}{\gamma (r_{aW} + r_{IW}) + s r_{aH}} \quad (2)$$

for a temperature range relevant for the study site in the upcoming decades (OcCC, 2008). According to Schär et al. (2004), summer heat waves with peak temperatures close to 40 °C could become common for the studied area until 2050. Since our estimates of stomatal conductance are based on trees with ample water supply, we assumed a linear decrease to 50 and 20% of maximum g_s values as temperature increases (corresponding to panel A and B of Fig. 5). All other parameters were held constant. Surprisingly, the species with the largest leaves, *Platanus acerifolia*, showed the smallest increase in ΔT_{L-A} as temperature rises, but the effect is diminished at stronger stomatal downregulation (Fig. 5). On the other hand, the two species with the smallest leaves (*Gleditsia triacanthos* and *Pinus sylvestris*) remained relatively constant even at higher stomatal downregulation in hot conditions according to our analysis (Fig. 5B). The other species warm exponentially under conditions of strong stomatal downregulation. *Acer platanoides*, the species with the highest leaf temperature during our survey, may warm to almost 10 K above air temperature at 40 °C. The subform ‘Globosum’ of this species creates very dense, perfectly round crowns, preventing air circulation between leaves, which may cause such high canopy temperatures. *Tilia platyphyllos* showed the highest ΔT_{L-A} in both scenarios of stomatal downregulation at high ambient temperatures. This species also showed highest ΔT_{L-A} in a natural mixed deciduous forest (Leuzinger and Körner, 2007). Given our assumptions, we predict a range of ΔT_{L-A} of c. 2–5 K for the tested species at an ambient temperature of 40 °C and a linear decrease of g_s of 50% and a 4–10 K increase at more drastic stomatal downregulation to 20% of the species-specific maxima. Wind speed was held constant at 2 m s⁻¹, higher wind speeds

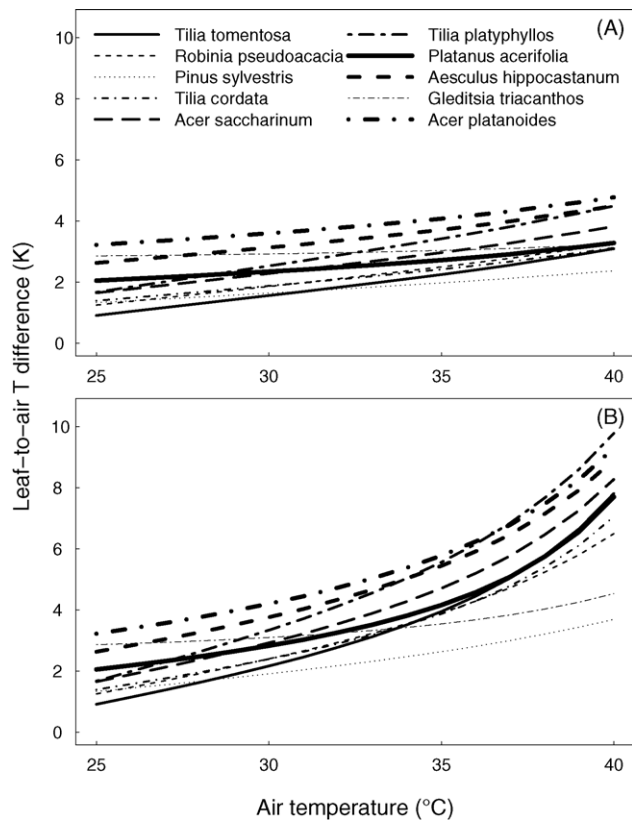


Fig. 5. Evaluation of the leaf energy balance using the species-specific leaf boundary layer resistance to water vapour r_{aW} calculated based on maximum leaf conductances $g_{s,max}$ indicated in Fig. 3 and from measured leaf temperatures; (A) assuming a linear decrease of g_s to 50% of $g_{s,max}$ and (B) assuming a linear decrease of g_s to 20% of $g_{s,max}$ as air temperature rises from 25 to 40 °C. The line widths are proportional to the leaf size.

would thus reduce absolute ΔT_{L-A} , but not the relative differences between species. Fig. 5B shows that species-specific differences in ΔT_{L-A} become important at air temperatures greater than 35 °C. While photosynthesis is clearly inhibited at leaf temperatures >40°, heat damage to proteins is not likely to occur until ΔT_{L-A} reaches >50 °C. Our analysis shows that small-leaved trees will have an advantage in terms of leaf-to-air temperature difference only at very high ambient temperature (>35 °C) and severe stomatal downregulation. Such a situation may arise when urban trees are not irrigated during prolonged heat spells.

4.3. Concurrent temperatures of non-plant surfaces

Our study further allows to discern other surface fabrics and may be useful for surface cover analysis, particularly to distinguish between sealed or built-up areas and evapotranspiring surfaces (Gill et al., 2008). The histogram of the composite image (Fig. 4) shows three main peaks and therefore permits a straightforward categorisation of water surfaces, green surfaces and streets. Our study, as opposed to a wide body of literature using thermal imagery with much lower resolution (e.g. Nichol and Wong, 2005), can be used for high-resolution surface cover analysis, at least for the rough categories water, green surfaces, streets and roofs.

5. Conclusion

We conclude that urban tree temperatures are species-specific and depend on the location of the tree, its leaf size, stomatal conductance and other traits such as canopy architecture. Based on our evaluation of the leaf energy balance under extreme

temperatures, we estimate that at air temperatures of 40 °C, maximum leaf temperatures of certain species (*Tilia platyphyllos*) rise exponentially and reach up to 10 K above ambient temperature, provided there is no irrigation. Those species coolest at an ambient temperature of 25 °C are not necessarily coolest at extreme temperatures. Small-leaved species remain relatively cooler at high ambient temperature. *Gleditsia triacanthos* seems to be able to maintain relatively constant foliage temperature, even at extreme temperatures and strong stomatal downregulation. This species may therefore be particularly suitable for locations where high air temperatures are expected to occur frequently in the future.

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