BENEFITS OF WELL-WATERED TREES ON STREET MICROCLIMATE: WHAT IS THE INFLUENCE OF METEOROLOGICAL CONDITIONS?

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Abstract : The microclimate benefits of well-watered street trees were investigated in a reduced scale (1:5) North-South oriented canyon street over 120 summer days, comprising a wide range of meteorological conditions. Statistical analysis showed that the trees significantly decrease air temperature and heat stress under their crown at midday. Daily global radiation is the meteorological variable having the strongest influence on Mean Radiant Temperature and UTCI reduction by the trees. Finally, the level of thermal comfort improvement can be predicted from daily global radiation thanks to a simple empirical linear relationship derived from the present data.

Keywords: thermal comfort, canyon street, tree benefits, urban microclimate

Introduction

In a context of more frequent and intense heatwaves, cities are looking for adaptation strategies to reduce thermal stress during summer time. Urban trees, thanks to the combined effect of their shade and transpiration are promising solutions. Bowler et al. (2010) carried out a review on urban vegetation benefits, and found multiple evidence of air temperature reduction by trees during daytime, which amplitude depends on the surrounding urban environment, background climate, and trees characteristics (specie, planting density, leaf-area index...). Shashua and Hoffman (2000) investigated the reduction of air temperature provided by street trees at the beginning of the afternoon during a couple of summer days with low wind conditions in Tel-Aviv. An average reduction of 3K was found, which increased with partial shaded area and background air temperature. In Melbourne city, Coutts et al. (2016) showed that, the lower the sky view factor (thanks to the trees and buildings), the lower the thermal stress in the street during daytime. The trees were found to induce a maximum reduction of 7°C in Universal Thermal Climate Index (UTCI). Urban trees benefits, and especially transpiration, also depend on water availability, which is rarely reported and even less controlled in in-situ experiments. Reduced-scale experiments on model streets allow to standardize the urban configuration and its environment, but only few of them are vegetated to allow the study of tree benefits. For instance, in Mballo et al. (2021), a reduction of 8°C of UTCI by well-watered trees was evidenced during one individual sunny day in a 1:5 reduced-scale canyon street.

In the present contribution, we propose to analyze the microclimate benefits of well-watered urban trees with two summers of data acquisition in a reduced-scale canyon street in Angers, France. The variability of these benefits is assessed, and the influence of meteorological conditions on the climatic variables involved in human thermal comfort is investigated. Finally, the available information on tree leaf area index is also put in relation with the variation of UTCI reduction by the trees.

1. Material and Methods

1.1 Measurements

The microclimate data were acquired over two summers (2020 and 2021) in the canyon street facility of Institut Agro in Angers, France (47° 28′ 47′′ N, 0° 36′ 33′′ W). This facility consists in a 15.6 m long and 2 m wide canyon street, bordered by 2 m high buildings, resulting in an aspect ratio of 1 and a reduced scale of 1:5 (compared with a full-scale reference building height of 10 m). The street is North-South oriented, with white walls and asphalt on the ground. It is organized in three zones: a purely mineral area at the South of the street, and two treed areas, each comprising an alignment of 5 ornamental apple trees (*Malus Coccinella*® 'Courtarou'), in the center and North of the street. The soil was sealed and all trees were planted in individual containers and irrigated with drippers. The soil water availability was monitored with tensiometers and soil moisture sensors. The Northern row was always kept in well-watered conditions, while the center row was occasionally submitted to water-stress conditions during summer 2021. This study focuses on the well-watered zone.

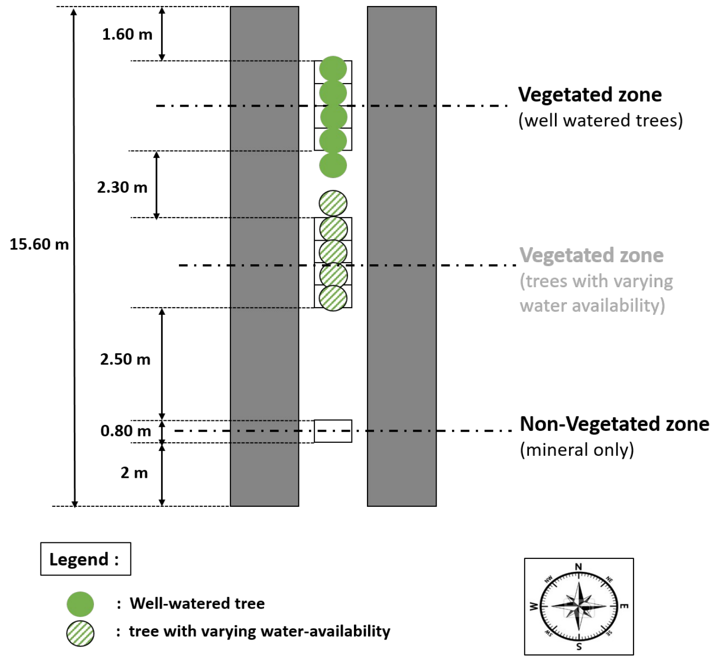

Figure 2: Top view of Institut Agro Canyon street, with the position of the different areas (treed or mineral)

Figure 1: Photography of the street and ornamental apple trees, taken from the south of the street on 2020-09-04

Once every summer, in July, the trees were trimmed at the height z=1.6 m and at a width of 1.2 m to contain their development within the street dimensions. The leaf area of the three central trees in each zone was measured just before and after these trimmings by an allometric procedure, as well as the dimensions of the crown bounding volume (approximated to a parallelepiped). The values measured before trimming were assumed to be valid over the whole preceding week, and those after trimming over the two following weeks (tree aerial development stopped over this period after trimming). This resulted in 4 sub-periods with distinct LAI values comprised within the range [2.5,3.3] on average for the Northern row of trees.

In each of these two zones (the well-watered treed and the mineral one), the air temperature (Ta), relative humidity (RH) and globe temperature were measured at 40 cm from the ground (corresponding to a full-scale height of 2 m, relevant for human height) using Vaisala HMP sensors (+/-0.2°C and +/- 2% for RH in [0%;90%]) and a Pt100 sensor (+/-0.15°C) in a 15 cm diameter copper black-painted sphere, respectively. The Mean radiant temperature (MRT) was derived from globe temperature using a correction for convective heat loss. The absolute humidity (AH) was derived from RH and Ta, using an analytical function for water vapor saturation pressure. In the street, the wind speed was measured in the mineral area only, with a CSAT3 3D sonic anemometer (+/-0.08 m/s) at z=40 cm, and a LCJ CV7 2D sonic anemometer (+/-0.13 m/s) at z=2m, assuming that the average wind speed at these two heights (being strictly below and above the tree crown) would not be much impacted by the trees. The UTCI thermal comfort index (Bröde et al., 2012) was then calculated in each zone from these variables.

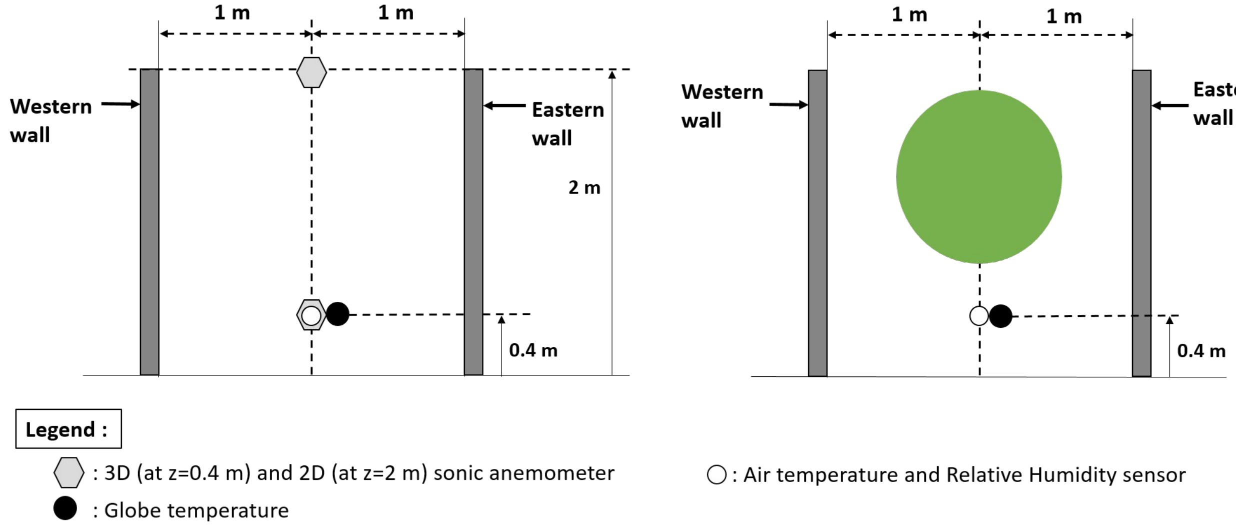

Figure 3: Sensor positions in the non-vegetated (left) and vegetated (right) zones of the street

The meteorological conditions on the experimental site were retrieved in two ways: at first, from the Meteo-France weather station of Beaucouzé located 400 m from the canyon street, and secondly in the immediate outer environment of the street from two meteorological masts, equipped with 2D sonic sensors at 2 m and 10 m from the ground and air temperature, humidity, and globe temperature sensors at 40cm, 1.5m and 2m from the ground. All sensors were scanned every 10 seconds by data-loggers, and average values were recorded every 10 minutes.

1.2 Methods

The final microclimate database finally consists in:

- 120 days of valid microclimate data, during summers 2020 and 2021.
- 39 days (among the 120 days cited hereinabove) with leaf surface information

The benefits of well-watered trees are analyzed by comparing the microclimate and thermal comfort in the vegetated and non-vegetated zones of the street under the tree crown at z=40cm (corresponding to human height at full scale), and also with the outer environment. After looking at mean daily evolution, a focus is realized on solar noon (between 11h and 13h UTC) when maximum benefits were observed. The role of background meteorological variables is then investigated using Principal Component Analysis (PCA).

2. Results

2.1. Mean daily evolution of Air temperature and UTCI

Overall the qualitative evolution of the average air temperature and UTCI shown in Figure 4 in the three modalities over the 120 days investigated is consistent with the findings of Mballo et al. (2021) conducted on a single sunny day, with differences in absolute values since all meteorological conditions are averaged here.

At night, the air temperature is higher in the street than in the outside environment, indicating an urban over-heating, especially in the non-vegetated zone. No effect of radiative trapping from the trees is visible. During daytime, the shadowing effect of the walls of our North-South oriented street is clearly visible in the morning and afternoon, with the UTCI being lower inside than outside the street. Around solar noon, the street does not benefit from the shadowing of the walls anymore, but the vegetated modality is shadowed by the tree crowns. The tree benefits are maximum at this period of the day, maintaining the street in the no-thermal stress zone, while moderate heat stress is experienced in both other modalities. This average evolution of street thermal stress is consistent with the findings of Coutts et al. (2016) over one summer month in Melbourne city.

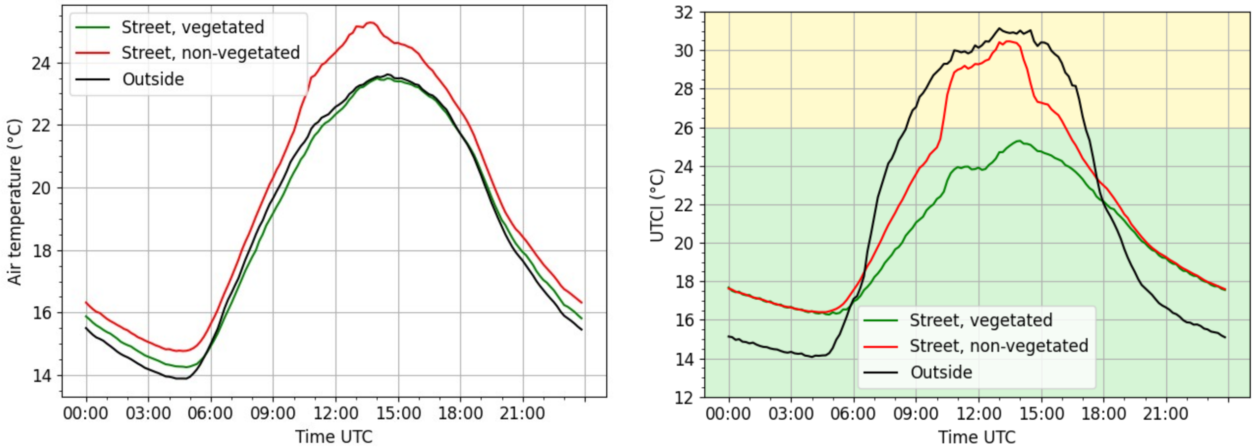

Figure 4: Mean daily evolution over 120 days of air temperature (left) and UTCI (right) in the vegetated and non-vegetated zones of the street at z=40cm, compared to outside of the street. Color bands on UTCI graph: green: no thermal stress (9-26 °C), yellow: moderate heat stress (26-32 °C).

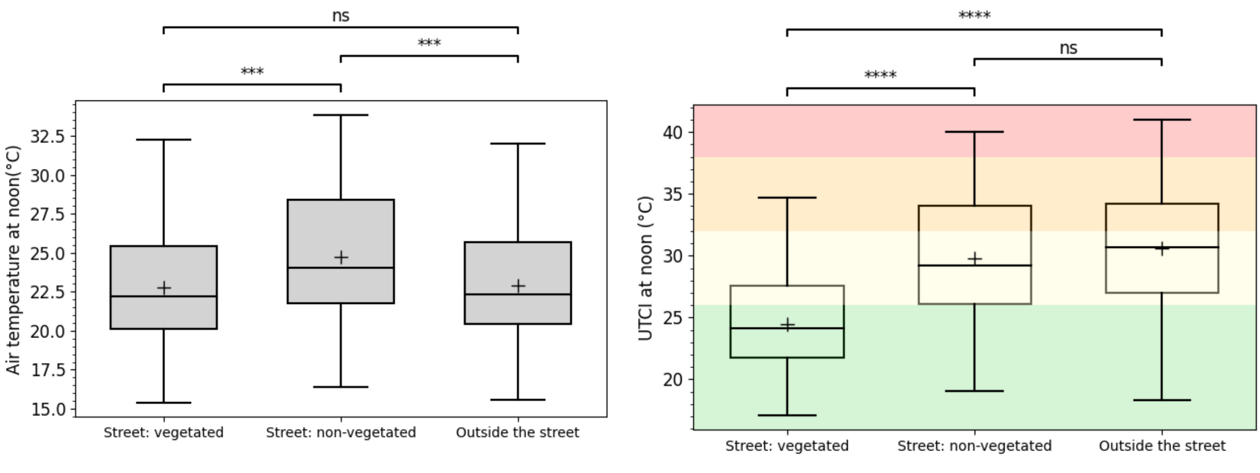

*Figure 5: box-plot of air temperature (left) and UTCI (right) in the vegetated and non-vegetated zones of the street, and outside the street between 11h and 13h UTC. Kruskal-Wallis test (N=120): ns: 0.05 < p ≤ 1.0; **: 1.0e-3 < p ≤ 1.0e-2 ; ***: 1.0e-4 < p ≤ 1.0e-3; ****: p ≤ 1.0e-4. Color bands on UTCI graph: green: no thermal stress (9 to 26 °C); yellow: moderate heat stress (26- 32 °C); orange: strong heat stress (32-38 °C); red: very strong heat stress (38-46°C)*

2.2. Analysis of air temperature and UTCI variability

As shown in figure 5, between 11h and 13h UTC (when maximum benefits were observed in section 2.1), the air temperature in the non-vegetated zone of the street ("NV") is significantly higher than in the outer environment ("Out") ($\Delta Ta_{NV\text{-}Out}$ ϵ [0.6;3.9], mean=1.8°C), but without significant difference on UTCI. The trees ("V") significantly decrease the air temperature compared to the non-vegetated zone ("NV") of the street

($\Delta Ta_{V\text{-}NV} \in [-3.6;-0.7]$, mean=-2°C) and improve thermal comfort ($\Delta UTCI_{V\text{-}NV} \in [-9.2;-1.3]$, mean= -5.3°C). The order of magnitude of the maximum benefits is consistent with the findings of Coutts et al. (2016) and Mballo et al. (2021). At solar noon, the vegetated zone is significantly more comfortable than both the non-vegetated zone and the outside environment, without a single day in 'very strong thermal stress' level (contrary to the two other zones). These findings confirm the strong benefit of urban trees on daytime microclimate, for a wide range of meteorological conditions.

2.2. Influence of meteorological conditions on trees' benefits

The influence of meteorological conditions on tree microclimate benefits at noon was investigated using a Principal Component Analysis (figure 6) on daily meteorological variables from Meteo-France weather station: global radiation ("GLO_mf"), mean wind speed ("FFM_mf"), mean air temperature ("TM_mf"), precipitations ("RR_mf"), and reference evapotranspiration ("ETPMON_mf"). The microclimate and UTCI differences between 11h and 13h UTC between the non-vegetated and vegetated zones at z=40cm are then used as illustrative variables (ΔUTCI, ΔTa, ΔAH, ΔMRT).

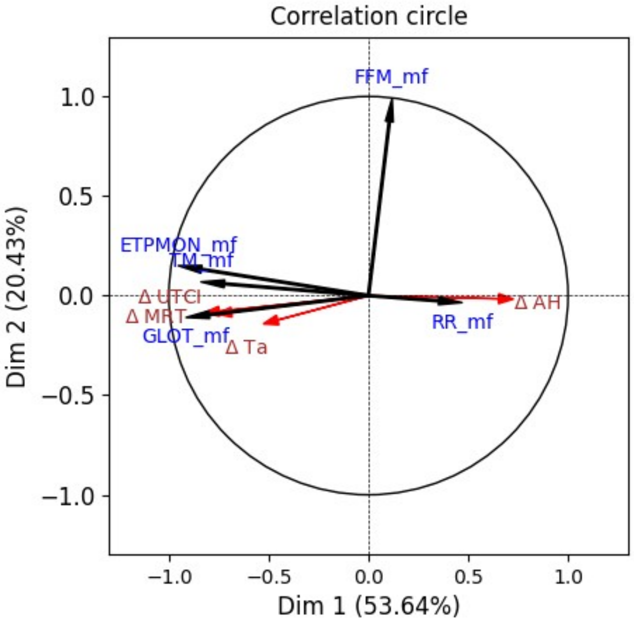

Figure 6: PCA analysis (N=120) of daily meteorological conditions (blue, explanatory variables) and microclimate difference between the non-vegetated and vegetated zones of the street (red, illustrative variables)

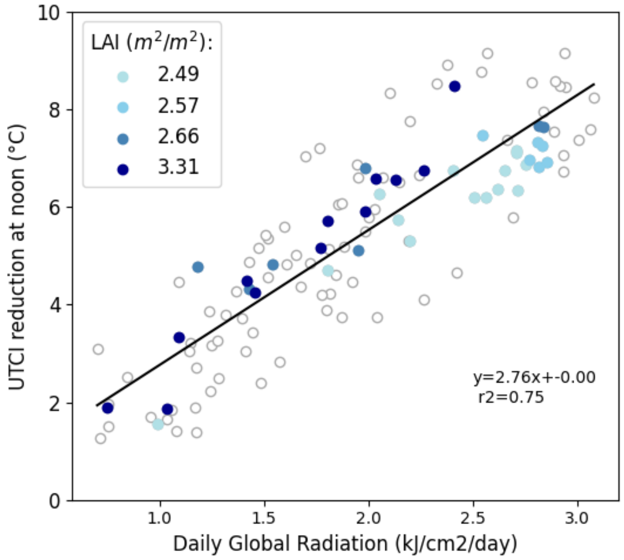

Figure 7: UTCI reduction from the trees as a function of daily global radiation (N=120) and Leaf Area Index (LAI) (N=39)

The first component (Dim 1) is linked to global radiation, and the second component (Dim 2) is linked to wind speed. The third component (not shown here) is linked to precipitations. MRT and UTCI differences created by the trees are strongly correlated with daily global radiation, and there is very little impact of wind speed. For MRT, it is logical as this variable represents radiative exchanges to the human body, and for UTCI, it can be explained by its strong dependence on MRT (Kantor and Unger, 2011). However, in our experimental setup, the UTCI in both mineral and vegetated zones of the street are calculated from the same 3D sonic anemometer, which surely tends to minimize the influence of this factor on UTCI difference. The absolute humidity difference (ΔAH) between the non-vegetated and vegetated zones of the street is negatively correlated with global radiation, due to the effect of tree transpiration. For air temperature difference (ΔTa), the correlation level in this plane is weak.

The UTCI reduction by the trees at solar noon is now analyzed as a function of daily global radiation (figure 7), since the two variables are strongly correlated. We find again the range of UTCI reduction at noon [1.3; 9.2] already mentioned in the previous section. A linear regression of the data shows it can be approximated by the relation: $\Delta UTCI_{NV-V}$=2.76 GLO + 0.0, with GLO the daily global radiation in KJ/cm^2/day, with R^2=0.75, and $p < 10^{-4}$. The 0 value of the intercept (which was not forced) indicates that the tree benefits become negligible in the absence of global radiation, as expected since shading and transpiration both require global radiation.

In an attempt to explain the remaining variability of UTCI, the LAI information was added on figure 7 on the 39 days when it was available. As it can be seen, a trend showing an increase of UTCI reduction with LAI is visible, but the range of LAI values is quite narrow. More frequent measurements of leaf surface areas over the whole growing period would be required to further investigate the influence of this variable.

Conclusion

Microclimate data acquired over two summers in a reduced-scale canyon street for a wide range of meteorological conditions showed that well-watered trees significantly improve human thermal comfort in the street at midday. The UTCI reduction is strongly correlated to global radiation, and the level of benefit at noon can be predicted from daily global radiation using a linear regression of the data. It can reach up to 9°C under sunny conditions. As a next step of this study, the impact of leaf area index will be further investigated, and the influence of water-restriction will be addressed.

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