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Impacts of the urban environment on well-watered tree architectural development and tree climate services

S. Demotes-Mainard[1], S. Herpin[2], A. Boukouya[1], S. Mballo[2], B. Dubuc[1], L. Ledroit[1], C. Le Lebras[1], D. Lemesle[2], P.E. Bournet[2]

[1]Univ Angers, Institut Agro, INRAE, IRHS, SFR QUASAV, F-49000 Angers, France ; [2]Institut Agro, EPHOR, 49000 Angers, France

Abstract
Trees in cities can help improve thermal comfort by shading and transpiration, two processes intrinsically linked with tree architecture and ecophysiology. Urban trees experience particular microclimatic conditions, including sudden and extreme changes in radiation and high temperatures. Yet, most of the knowledge on tree functioning was acquired in forests or orchards. To better assess the level of climate services that can be expected, it is thus important to understand how the urban environment affects tree development and ecophysiology. Our objective was to study how the built environment of a canyon street impacts the architectural development of trees, and to quantify climate services provided by these trees. The study was carried out in Angers, France, using an original outdoor facility with alignments of ornamental apple trees: a group of trees grew inside a 1/5th scale canyon street, and the other group (same age and variety) benefited from a rural-like atmospheric environment outside the street. All trees were well-watered and grown inside individual pits. Street trees were more vigorous than those outside street: their axes were longer with more leaves and larger leaf size and they developed a 55% higher leaf area in July, which resulted in higher light interception. In the street the trees were able to improve by up to 7.3°C the thermal comfort index score at midday, lowering the heat stress category from high to moderate. The proportion of the benefits due to shading and transpiration were analyzed. Results evidence the need to consider the effects of the urban microclimate on tree architecture to assess their potential services. In the next stage, the effects of water shortage, frequent in cities, and the interaction with the genotype will be studied, to help stakeholders choose the most suitable species.

Keywords: leaf area, architecture, light interception, transpiration, microclimate, temperature, canyon street

INTRODUCTION

The rise in temperature due to climate change, especially the increase in intensity and frequency of heat waves, is a major concern for public health (IPCC, 2021). In cities high temperatures are intensified due to heat accumulation in impervious materials, radiative trapping, city morphology and human activities, yet there is a body of evidence that vegetation, and especially trees, can reduce excessive heat and improve human thermal comfort in cities (Bowler et al., 2010; Jamei et al., 2016). Trees mitigate urban heat through transpiration, that reduces air temperature, and through shading, that decreases the energy reaching the ground and buildings (Rahman et al., 2020). In their review Jamei et al. (2016) report 1.5-5.6°C cooler air temperature under tree canopies compared to surrounding areas and large effects of trees on different variables measuring human thermal comfort. The magnitude of climate services depends on the surrounding environment (parks, squares, streets and their characteristics), the climatic conditions, tree implantation (position relative to the buildings and pavements, planting density), tree water status and tree characteristics. Indeed, tree climate services are dependent on all tree traits that determine shading (i.e. light interception) and transpiration, which are under control of the genotype and the environment. Leaf area index (LAI) and leaf area density (LAD) appear to be major determinants of shade effect (Gillner et al., 2015; Rahman et al., 2020). Transpiration depends on local environmental factors (irradiance, air humidity, temperature and atmospheric CO2 concentration, soil water availability) through complex regulation mechanisms (Damour et al., 2010) and in continental climate, urban tree transpiration tends to increase with tree leaf area (Rahman et al., 2020).

Altogether these results point out the major role of tree structure in both shading and transpiration cooling services. Tree structure itself depends on tree architectural development, that relies on processes as branching that determines the number and position of axes, organogenetic activity of meristems that determines leaf number, internode elongation, leaf expansion and organ orientation. In an urban environment the levels of environmental factors and their combination is different from rural environments (higher temperature and CO_2, highly variable radiation, drought, pollutants, reduced rooting volume and modified soil properties) as well as tree management practices (pruning) and can affect tree growth and architectural development. Several studies reported negative effects of urban environment on tree growth, notably due to poor rooting conditions and reduced water availability, but often the overall effect of urban environments stimulates tree growth as observed through changes in tree diameter or above ground biomass (Gregg et al. 2003; Searle et al., 2012; Pretzsch et al., 2017; Yu et al., 2018). Yet, little is known on how the urban environment affects tree architecture and the consequences on light interception, which is determinant for climate services. In this regard, our objective was first to study how the mineral environment of a canyon street impacts the architectural development and light interception of well-watered trees and then to quantify the tree cooling services in this environment.

MATERIAL AND METHODS

Experimental facility and plant material

The experiment was conducted in Angers, France (47° 28' N, 0° 33' E), in an experimental facility consisting in a reduced scale 1/5 canyon street oriented north-south with an aspect ratio of 1 and a grassy area outside the street. The street was 2m wide covered with asphalt and bordered by 2 m high white painted buildings, representing 10 m high buildings at full scale (Fig. 1). The north and central zones of the street (zones A and B) were occupied by a central alignment of five trees, and the south zone (C) was purely mineral. Another alignment of five trees oriented north-south was positioned in the grassy area south-west from the street (zone D), and 2 masts equipped with sensors were installed over the grass zone without trees nearby (zone E), one 6.25 m north of the street, and the other 8m west. All trees were 3-year-old ornamental apple trees *Malus coccinella* 'Courtarou'® transplanted in the facility in winter 2018-2019. The trees had been pruned the previous winters to obtain branched tree crowns at desirable height relatively to the size of the street, and flowers were removed to prevent light interception by fruits. All trees were grown in containers, the ground over the containers was sealed with the same material in all zones, the trees were drip-irrigated and maintained in water comfort, based on tensiometers readings.

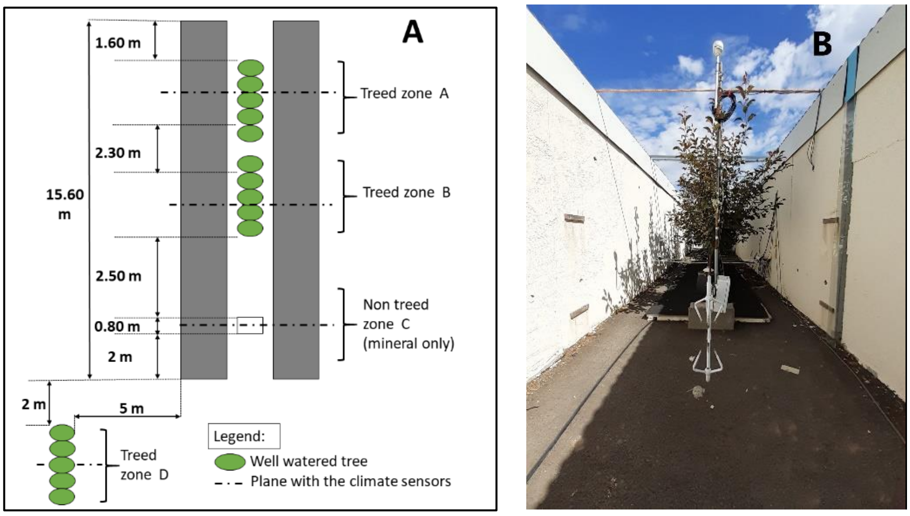

Figure 1. Top view (A) and photography (B) of the canyon street. Photography is taken from the south C mineral zone.

Tree characterization

In mid-July, the tree architecture was measured on the 3 central trees of each alignment (6 trees in the street and 3 trees outside). The trunk diameter was measured 60 cm above the ground of the street and the diameter of all axes inserting on the trunk was measured at their base with a caliper. Apple trees have “short” axes with few leaves and internodes that do not or little elongate, and “long” axes, with more leaves and elongating internodes. All current year axes were counted according to their type, the length of all long axes was measured with a ruler. On a sample of 4 long and 4 short axes per tree, the leaf length and width were measured and individual leaf area was calculated by allometry, and the average internode length of long axes was measured. The tree leaf area was then deduced with an allometric method from the combination of the previous measurements. The dimensions of the crown enclosing volume approximated to a parallelepiped was measured based on branch positions and used to calculate leaf area index (LAI) and leaf area density (LAD).

Microclimate measurements

Under each alignment of street trees (zones A-B), in the mineral zone of the street (zone C) and on the 2 masts located over grass in a no-treed area (zone E) air temperature, relative humidity 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 and a Pt100 sensor in a 15 cm diameter copper black-painted sphere, respectively. The mean radiant temperature was derived from the globe temperature using a correction for convective heat loss. In the street, the wind speed was measured in the mineral zone only, with a CSAT3 3D sonic anemometer at z=40 cm, and a LCJ CV7 2D sonic anemometer 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 radiant temperature and UTCI thermal comfort index (Bröde et al., 2012) were then calculated in each zone from these variables. To calculate the reduction of the energy flux density due to trees and buildings the incoming global radiation was measured at 2 m high by 3 net radiometers sensors used as a common reference for all zones and at 0.4 m under the trees of zones A, B, D, and in the street mineral zone C by pyranometers. To estimate photosynthetically active radiation (PAR) interception by the trees at midday, PAR was measured by 30 cm long sensors (SOLEMs PAR/LE). Two were positioned above the street at 2 m and served as a common reference of incident PAR for all zones and one PAR sensor was positioned at 0.65 cm in zones A, B and D, just under tree crown. Microclimatic data of the two treed street zones (A and B) were averaged as the trees were in similar conditions. Four street trees containers were each equipped of 2 capacitive ECH2O sensors that enabled to calculate transpiration with a water balance method. Climatic and transpiration data are presented for 12/07/2020 sunny day.

RESULTS AND DISCUSSION

Tree architectural development

In mid-July 2020, trees growing in the street had on average a 55 % higher leaf area than trees growing outside street in open area nearby (Fig. 2A). LAI of street trees was significantly higher than that of outside trees and their LAD was also higher, although the difference was only significant at $P<0.1$. The LAI and LAD of street trees were within the range of urban trees measured in full-scale studies (Rahman et al., 2020).

Long axes contributed to over 80% of the leaf area. Only the axes formed during the current year develop leaves in deciduous woody plants, and although trees in the street developed more short and long axes in 2020, the difference was not significant (Tab. 1). The higher leaf area of street trees was linked to street trees having formed during the current year larger leaves and longer "long" axes. As internode length was not different between the two environments, it implies that more internodes, and thus more leaves, were formed on long axes of street trees. Further research is needed to investigate whether this is due to a higher rate of leaf emission, possibly linked with changes in temperature, or to a delayed stop of leaf emission. Street trees also presented higher secondary growth, as they had larger diameter of both the trunk and the branches inserted directly on the trunk than the trees growing outside the street, this difference resulted from a cumulated effect over the two years of growth within the street. As there was no anthropic heat release in the street and as both groups of trees were grown with identical rooting and water conditions, the observed differences in tree architecture between street and outside trees are attributable to differences in microclimate induced by the presence of urban constructions (buildings and asphalt street ground). A range of microclimatic factors changed between the street and outside (Mballo et al., 2021), the combination of them appears to have favored in well-watered conditions tree architectural development in the street. Unlike in the study of Kjelgren et al. (1992) in a 50-100 m deep canyon street, our results do not suggest a typical shading response of street trees, since the higher secondary growth demonstrated a good vigor. This is probably due to a better access of trees to light in our canyon. Our results are in agreement with the increase of aerial biomass and leaf area in urban compared to rural area for seedlings of red oak (Searle et al., 2012) and cottonwood (Gregg et al., 2003), that were attributed to higher temperature and lower ozone concentration, respectively. Their results also point out the interaction of the urban conditions with the genotype as, unlike read oak, cottonwood was insensitive to temperature change.

Table 1. Architectural characteristics of trees growing in the street and outside street

Growth location	No. of long axes formed in 2020 /tree	No. of short axes formed in 2020 /tree	Individual leaf area (cm^2/leaf)	2020 long axis length (cm)	2020 long axis internode length (cm)	Trunk diameter (mm)	Diameter of all axes inserted on the trunk (mm)
Street	63.2 ± 8.3	76.8 ± 11.0	18.5 ± 0.5	39.8 ± 1.4	2.1 ± 0.1	26.56 ± 1.57	8.43 ± 0.33
Outside	56.3 ± 9.7	57.0 ± 4.2	16.0 ± 0.5	33.5 ± 2.0	2.1 ± 0.1	21.01 ± 0.85	7.02 ± 0.42
	ns	ns	*	*	ns	*	*

Mean values ± se. Symbols bellow each column indicate the results of Mann-Withney test (ns: not significant; * $P<0.05$)

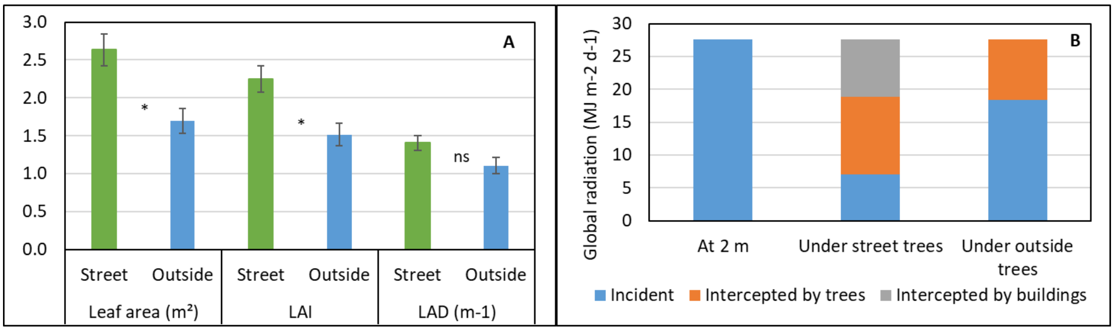

Figure 2. Leaf area and global radiation interception by trees. (A) Leaf area, LAI and LAD of street trees and outside trees; (B) daily integral of incident global radiation a sunny day at 2 m (above trees), under street trees and outside trees, and contribution of the building and trees to the radiation attenuation. Mean values ± se. Symbols between bars in (A) indicate the results of Mann-Withney test (ns: not significant; * $P<0.05$)

Radiation interception and transpiration

To assess the consequences of the changes in LAI on radiation interception by the trees, PAR interception was calculated over the two hours around solar noon a sunny day, to minimize the effects of the surroundings (buildings for street trees vs rural-like environment) on PAR interception. The trees in the street intercepted 94.0% of PAR vs 86.8% for outside trees, showing that the street environment, by enhancing the tree development and increasing the LAI, improved light interception. This increase most probably retroactively increased tree photosynthesis and thus tree growth, therefore enhancing the shade cast by the trees.

Tree shading contribution to the reduction of the energy flux density at human height (0.4 m, corresponding to 2 m height full scale) was estimated by comparing daily integral incoming global radiation above the street on the one hand to that measured at 0.4 m, either in the mineral street zone and under street trees, or under outside trees, on the other hand. On a 12/7/2020 sunny day only 25% (7.0 MJ m^{-2} d^{-1}) of the integral of incident radiation (27.6 MJ m^{-2} d^{-1}) reaches human height under the trees in the street, since 31% (8.6 MJ m^{-2} d^{-1}) was intercepted by buildings and 43% (11.9 MJ m^{-2} d^{-1}) by street trees. Under trees growing outside street, the integral of incident radiation reaching human height was higher (18.4 MJ m^{-2} d^{-1}), as no buildings shaded the area, and tree interception was only 33% (9.1 MJ m^{-2} d^{-1}) of incident global radiation (Fig. 2B). Altogether, these results show that the effects of the mineral built environment of the canyon street on tree architectural development increased tree shading and reduced incident short wavelength energy at human height.

Average transpiration measured on 4 street trees on the same sunny day was 1.84 ± 0.39 L d^{-1}. Divided by the projected enclosing crown area, it corresponds to 3.87 MJ m^{-2} d^{-1} on an energetic point of view. In total, street trees thus reduced the incoming energy flux density (27.6 MJ m^{-2} d^{-1}) by 57.3% (15.8 MJ m^{-2} d^{-1}), with 75% being due to shading (11.9 MJ m^{-2} d^{-1}) and 25% (3.9 MJ m^{-2} d^{-1}) to transpiration. These proportions are in agreement with the literature in full scale studies (Shashua-Bar and Hoffman., 2000) and for two other days in the same experimental facility (Mballo et al., 2021), indicating the relevance of the reduced scale approach to study the tree climate services.

Tree climate services

1. Air temperature reduction.

During the day the trees limited temperature rise in the street as shown by the lower temperature under street trees than in the non-vegetated part of the street, the largest difference being between 11:20 and 13:00 UTC with an average difference of 2.1°C over this period (Fig. 3A). During the hottest part of the day, the trees completely compensated the temperature elevation induced by the street environment (difference between temperature outside without trees and inside the non-vegetated zone of the street). At night, air temperature was higher in the mineral street zone than outside, with an average of 1.6°C, but trees had no effect on this night overheating. Canopy cover above temperature sensors was 66%, which is the range in which canopy cover provides an efficient reduction of day air temperature, but which should be combined with reduced impervious street cover to reduce night temperature (Ziter et al 2019).

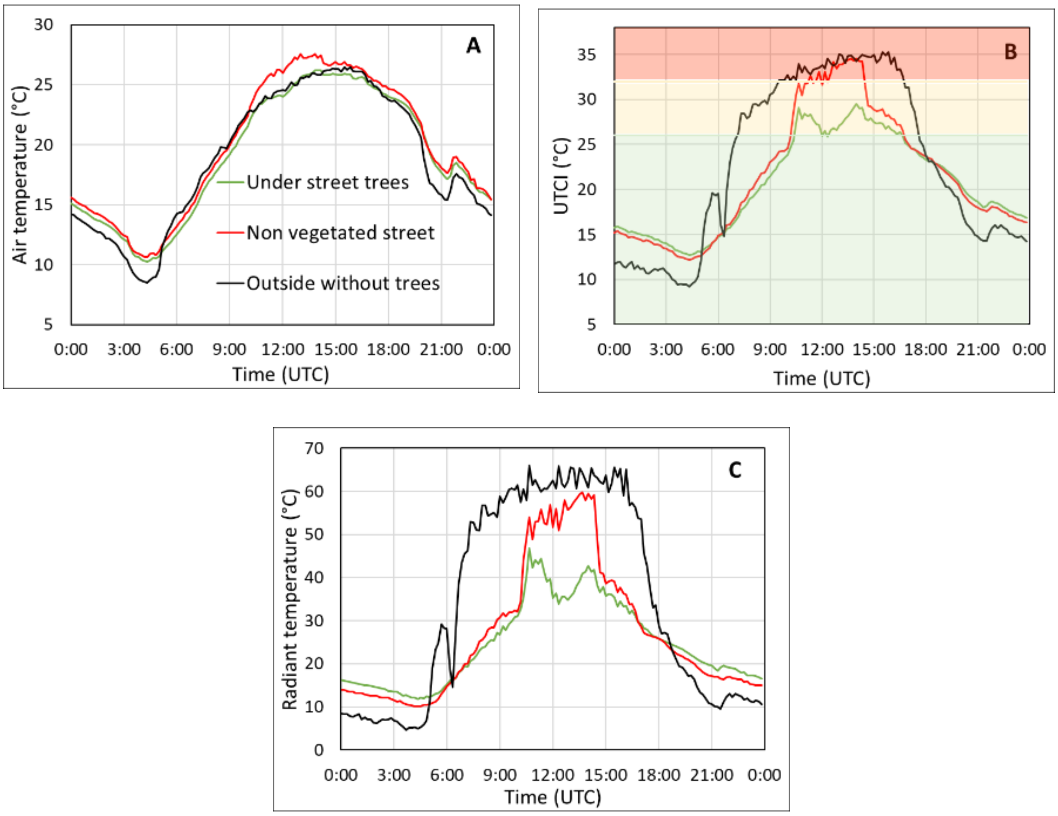

Figure 3. Evolution of air temperature (A), UTCI (B) and radiant temperature (C) at 40 cm from the ground under the street trees, in the non-vegetated part of the street, outside the street without trees. In (B) the green band corresponds to the thermal no stress domain (9≤UTCI<26°C), the yellow band to moderate stress (26≤UTCI<32°C) and the red band to strong stress (32≤UTCI<38°C).

2. Thermal comfort improvement.

Human thermal comfort was assessed at human height by UTCI (Fig. 3B), an index relying on thermal balance of the human body and an advanced human physiological model. UTCI was the highest between 1:10 and 16:50 but street trees maintained UTCI in the moderate heat stress zone (26≤UTCI<32°C) whereas UTCI was within the strong heat stress zone (32≤UTCI<38°C) both in the non-vegetated part of the street and outside without trees. The trees reduced UTCI by 7.3°C maximum, showing a great effect on thermal comfort despite a moderate effect on air temperature, in agreement with the results of Coutts et al (2016) and Mballo et al. (2021). UTCI is known to be much influenced by radiant temperature. The evolution of radiant temperature (Fig. 3C) was indeed very similar to that of UTCI.

Radiation interception by the buildings bordering the street, which represents 31% of integral of incident global radiation (Fig. 2), explains the large reduction of UTCI and radiant temperature before 10:00 and after 14:00 UTC in the non-vegetated part of the street compared to outside the street without trees. Between 10:00 and 14:00 street trees shaded the street, with a maximum effect at solar noon on both radiant temperature and UTCI, the latter almost reaching the no-stress zone at this time. Thus, our results show that although not frequent, an alignment tree implantation in the center of a canyon street oriented north-south with an aspect ratio of 1 and a canopy cover of 66% allows that the interception of radiation by the trees takes over from that of the buildings, ensuring a satisfactory level of human comfort throughout a sunny day. The effects of street orientation and tree position on wind circulation and resulting human comfort is less predictable than that of sun path (Jamei et al., 2016), nonetheless similar trends for UTCI were observed on an average of 120 days with winds with different directions and intensities (Herpin et al., 2022), indicating the preponderant role of radiative aspects in our environment.

Conclusion

The mineral built environment of the canyon street increased ornamental apple tree leaf area, LAI and LAD compared to identical trees growing outside the street. These changes resulted from architectural modifications: longer shoots, linked with higher internode number, and higher leaf size. As a consequence, radiation interception by street trees was higher than by the trees growing outside the street. Shading is the most prominent mechanism in reducing the energy flux density at human height in the street (75% for shading *vs* 25% for transpiration on the studied sunny day). It is thus important to take account of tree architectural plasticity in response to the urban environment to correctly estimate the climate services trees can provide, for instance, for modeling studies or greening planning purposes. In this study, the trees maintained the UTCI in the street in the moderate stress zone by reducing it up to 7.3°C on the basis of data acquired during a sunny summer day, their effect being greatest at the time when the temperature was highest. These results were obtained with well-watered trees, but water deficits are frequent in cities and can affect in the short-term transpiration and in the middle term shading and transpiration through changes in tree architecture. This work will be continued by studying how water deficits, frequent in cities, modify the climate services of trees according to the species, investigating the relationships between architectural development, water status and climate services.

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