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Transpiration and stomatal conductance as potential mechanisms to mitigate the heat load in Mexico City

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ABSTRACT

Transpiration rates and stomatal and canopy conductances were monitored in *Eucalyptus camaldulensis*, *Fraxinus uhdei*, *Liquidambar styraciflua* and *Ligustrum lucidum* in México City, to explore the potential of trees to reduce the urban heat load. The experiment was carried out over a 2-week period between 11 and 27 April 2013. Four trees of each species were used. Total conductance was obtained from daily measurements of transpiration and vapor pressure deficit between 22 and 27 April, and canopy conductance from stomatal conductance and leaf area index measurements. *L. styraciflua* registered the highest average (4.35 $L\,d^{-1}$) transpiration rate, whereas *F. uhdei* registered the minima (3.64 $L\,d^{-1}$). Averaged canopy conductance registered values between 40 $mm\,s^{-1}$ (*E. camaldulensis*) and 50 $mm\,s^{-1}$ (*L. lucidum*). These results show that transpiration was strongly dominated by vapor pressure deficit (VPD) and controlled by stomatal conductance. According to the envelope function model, stomata was more sensitive to VPD than irradiance or air temperature. Finally, the presented transpiration rates are capable to reduce up to 20% of net radiation in Mexico City. With these results, it is possible to build tree arrangements to dissipate the greatest possible amount of heat produced in the city.

1. Introduction

The urban heat island (UHI) is one of the most common forms of thermal pollution, since air temperature increases in urban area compared to surrounding rural, vegetated areas (e.g. Lee, 1991; Oke, 1995; Kuttler, 1998; Unger, 1999). Because the urban surface is impervious, evapotranspiration (latent heat flux) is reduced drastically and sensible heat flux increases UHI intensity. This contamination increases the human heat load, and people experience thermal discomfort (heat stress) which can affect human productivity mainly in the spring-summer period in temperate and subtropical regions. At present, air conditioning systems are used to mitigate this heat load, increasing energy consumption (mainly electricity). However, these air conditioner systems have a very low efficiency and “take” the heat from the inside and “put” it in the outside of the buildings, producing a probable feedback that could enhance UHI and therefore thermal pollution with a possible increase in energy consumption.

This urban heat island phenomenon is very noticeable in Mexico City (Jauregui, 1997). Average minimum temperature differences between the historical center and the rural area ($T_{U\text{-}R}$) can reach up to 6 °C (Jauregui and Luyando, 1998), and has remained relatively constant. However, to date UHI is also established during the daytime, with maximum temperature differences up to 10 °C ($T_{U\text{-}R}$) (Ballinas, 2011).

Mitigating UHI is important not only because increased urban temperatures differences can affect human health and productivity and increase energy consumption. The total sale of electricity in Mexico City in 1996 was 121.579 $GW\,h^{-1}$ of which 28.4 $GW\,h^{-1}$ (23.4%) was consumed by the domestic sector, 5.69 $GW\,h^{-1}$ was required to refresh the space inside buildings (air conditioning, evaporative cooling, fans) (Ramos, 1998), and 8.52 $GW\,h^{-1}$ in commercial buildings and services in the metropolitan area.

Nevertheless, with proper implementation of urban vegetation, it is possible to mitigate the UHI due to the cooling potential from shading and transpiration (Barradas, 1991, 2000; Susca et al., 2011).

Release of water vapor to the atmosphere by transpiring plants increases air humidity and decreases air temperature by converting sensible to latent heat. Typical rates of heat loss by evaporation in arid environments with good irrigation range from 24.5 to 29.5 $MJ\,m^{-2}\,d^{-1}$ whereas in humid temperate climates, rates range

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from <0.7 (winter) to 7.4 MJ m^{-2} d^{-1} (summer) (Jones, 1983). The volume of water vapor corresponding to these heat loss values ranges from 0.28 to 12 L m^{-2} d^{-1}.

However, in proposing the release of water vapor as a mechanism to mitigate the UHI, it is necessary to understand that water vapor exchange rate between the vegetated surface and the atmosphere is a key component of the energy exchange process at the air–land interface (Kumagai et al., 2004). Understanding how urban transpiration is affected by radiation and controlled by stomatal opening and closing is vital to selecting vegetation to mitigate the UHI. In particularly, microclimate and tree structural characteristics may affect tree conductance to water vapor that regulates transpiration

Conductance has two components, canopy conductances that depends on physiological behaviors, in series with aerodynamic conductance that defines coupling of stomata to the atmosphere (Herbst, 1995; Magnani et al., 1998). A decoupling coefficient represents the relative contribution of canopy and aerodynamic conductance in controlling rates of canopy transpiration (Jarvis and McNaughton, 1986). Meanwhile, canopy conductance strongly depends on variable stomatal responses to environment factors as vapor pressure deficit, air temperature (Schulze and Hall, 1981; Schulze, 1986; Maroco et al., 1997; Meinzer et al., 1997; Barradas et al., 2004) and irradiance (Pitman, 1996; Gao et al., 2002; Zweifel et al., 2009). All these factors are responsible for canopy transpiration as a whole (Jones, 1992), and their effects must be studied before establishing tree systems to mitigate UHI.

The objective of the work described here was to examine whole tree transpiration, and canopy conductance for four tree predominant urban tree species (*Fraxinus uhdei, Ligustrum lucidum*, *Eucaliptus camaldulensis* and *Liquidambar styraciflua*) in the urban environment in the dry season in Mexico City to examine the cooling potential of the UHI of each species.

2. Materials and methods

2.1. Study site

Measurements were made in Mexico City (19°19′N, 99°11′W, 2230 m asl). The mean annual rainfall (mean of 40 years) is 748 mm, and nearly 94% occurs during the rainy season (June–November). Winds are light and predominantly from the Northeast. Extreme temperatures occur in April (26 °C) and January (5.3 °C) (SARH, 1982), with a marked heat island effect in the urban areas (Jauregui, 1971), not only at night but also during daytime, with differences of up to 10 °C (T_{U-R}) compared to surrounding areas (Ballinas, 2011). Measurements were made in the dry season in the month of April, the warmest and one of the driest months of the year. During measurements, maximum average temperature was 28 °C and precipitation was registered only the last six days of March with 10.2 mm.

2.2. Plant material

Measurements were made on four individuals of four dominant species to Mexico City: *Fraxinus uhdei* (Wenz.) Lingelsh. (Oleaceae), *Ligustrum lucidum* W.T. Aiton (Oleaceae), *Eucaliptus camaldulensis* Dehnh. (Myrtaceae) and *Liquidambar styraciflua* L. (Hamamelidaceae). *F. uhdei* and *L. styraciflua* are deciduous trees and native to Mexico, whereas *L. lucidum* and *E. camaldulensis* are evergreen and introduced species. Trees were located in a suburban area in the south of the city in the National University campus around the football stadium. The trees were located along a street sidewalk forming a single row of planted trees completely surrounded (around a radius of 300 m) by paved areas of asphalt and cement, in an area with no buildings around, and a water collection area (bare soil) around the trunks of the trees of 0.25 m^2 (square of 0.5 m). Trees were planted intermixed in north-south rows spaced 6 m apart with no overlapping of their crowns and they were randomly selected. Tree species structural parameters are shown in Table 1. Urban vegetation in public areas is administered by the municipality.

Table 1
Leaf area indices (LAI, m^2 m^{-2}), diameter at breast height (DBH, cm), crown diameter (CD, m) and leaf size (LS, long (l, cm), wide (w, cm)) for the studied species. LAI was estimated with a canopy analyzer (LAI-2000, LI-COR Ltd., Lincoln, Nebraska, USA) (n = 4 for LAI) and (n = 40 for LS).

Species	LAI	DBH	H	CD	Leaf Size (l,w)
F. uhdei	4.5	21.0	15.0	11.0	8.02 (1.57), 3.50 (1.16)
L. lucidum	4.0	14.8	13.0	8.10	6.13 (1.14), 3.02 (0.86)
E. camaldulensis	4.1	15.1	14.0	7.2	11.63 (2.42), 3.15 (0.81)
L. styraciflua	4.5	26.5	14.0	14.5	6.25 (1.17), 5.95 (1.38)

2.3. Measurements

Transpiration was estimated from sap flow measurements made in the trunk using steady-state xylem water mass-flow metering systems similar to those described by Čermák et al. (1984) and Schulze et al. (1985) with one instrumental set per tree. Sap flow (F) was calculated from $F = (P_S - P_1)k/(C_W \Delta T)$, where Ps is input power to the heater, C_W is the heat capacity of water, k is the dimensionless relation of measured segment length to total tree circumference, ΔT is the temperature difference across the heater which is maintained constant and P_1 reflects heat loss due to conduction and convection which is determined during nights when sap flow is absent. During steady-state the applied power does not normally exceed 2 W (with a potential maximum of 20 W). During the measuring period, 5 electrodes per system of the size 60 × 15 × 1 mm were inserted up to 50 mm into the trunk while depth of insertion of thermocouples was 25 mm according to the measured sapwood depth (3–4.5 cm) obtained by taking samples with a Pressler drill. The measuring point was insulated with a polyurethane and aluminized mylar jacket from outside by protecting against weathering and to minimize external effects on ΔT. Water mass-flowmeters were connected to a data logger (21XL, Campbell Scientific, Logan, Utah, USA); voltage and gauge signals were scanned every 20 s and averages were logged every 30 min. Heat storage in the stem segment during each 30 min interval was estimated by measuring the changes in stem temperature during the first and the last minutes of each interval.

Stomatal conductance (g_S) was measured in the same individuals as used for sap flow measurements of each species on at least five total including sunlit and shaded expanded leaves per plant in the mid level of the tree, with a steady-state diffusion porometer (LI-1600, LI-COR, Lincoln, Nebraska, USA); air temperature (T_A), relative humidity (RH) and photosynthetically active radiation (PAR) were also measured with the mounted sensors in the porometer. Concomitantly, irradiance, air temperature and humidity, wind speed and direction were measured with a pyranometer (Eppley PSP, Campbell-Scientific, USA), a temperature-humidity probe (HMP35C, Campbell-Scientific, USA), and an anemometer and vane set (03001, RM Young, USA), respectively. Irradiance, wind sensors and temperature-humidity probe were installed 3 m above the highest tree canopy in a telescopic tube, that is to say these sensors were installed 18 m above the floor surface. The outputs from all sensors were connected to a data logger (21×, Campbell Scientific, USA) and scanned every 30 s and 30 min averages logged. Sensors above the canopy were calibrated before the study and cleaned every week during the study period. Measurements were made during 16 days in April in Mexico City from 07:00 to 20:00 LST,