The role of urban vegetation in temperature and heat island effects in Querétaro city, Mexico

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RESUMEN

La alteración de las condiciones climáticas y el efecto de isla urbana de calor (EIC) son resultado del incremento de la población y de sus actividades en las zonas urbanas. En ciudades medianas como Querétaro es importante determinar la magnitud del EIC y promover la planeación del crecimiento urbano. Conservar y aumentar las áreas con vegetación es una buena opción para mitigar el EIC. En este estudio se analizaron la intensidad del EIC y el efecto de la cobertura vegetal sobre la regularización de la temperatura del aire. Se definieron cuatro zonas climáticas locales para el estudio, tres urbanas y una rural. En cada zona se ubicó una parcela de medición en la cual se consideraron dos niveles de cobertura vegetal en función del índice de área foliar: bajo y alto (0.5 y 2.0, respectivamente). La temperatura del aire se midió con recolectores de datos a intervalos de 30 min entre junio de 2012 y mayo de 2013. También se analizaron datos climáticos de seis estaciones meteorológicas. La temperatura media diaria aumentó a razón de 0.75 ºC por década ($r^2 = 0.38$, P < 0.0001); este aumento se relacionó con la dinámica poblacional ($r^2 = 0.52$, P < 0.0001). Los patrones estacionales de temperatura se describieron como temporada fría de julio a marzo y temporada cálida de abril a junio para la temperatura máxima, y temporada fría de noviembre a marzo y temporada cálida de abril a octubre para la temperatura mínima. La diferencia entre las temporadas cálida y fría fue del orden de 5 ºC (P < 0.0001). No se identificaron diferencias en la temperatura mínima en función de los niveles de cobertura de la vegetación. Sin embargo, la humedad relativa fue mayor en el nivel alto de la cobertura vegetal. La relación entre la intensidad del EIC y la fracción de superficie impermeable fue inversamente proporcional. La intensidad del EIC fue similar para la temporada cálida y fría y varió de 0.1 a 5 ºC. La vegetación con mayor cobertura presentó menor temperatura a las 17:00 horas y mayor de las 9:00 a las 10:00 horas durante la temporada cálida. Al aumentar 50% la cobertura vegetal en la zona urbana se lograría reducir la intensidad del EIC en 2.05 ºC. En conclusión, una mayor cobertura de la vegetación mejora las condiciones ambientales en términos de humedad relativa y regularización de los extremos de temperatura durante la temporada cálida.

ABSTRACT

Alteration of climatic conditions and the urban heat island effect (UHI) are consequences of increased human population and activities in urban zones. Determining the magnitude of the UHI is important to improve urban planning in medium-size cities like Querétaro. Increase and conservation of vegetated areas is a mitigation option for UHI. Here we characterized both the UHI and the role of vegetation cover over temperature regularization in urban zones. Four local climatic zones were defined: three urban and one rural, each with two plots with low and high canopy cover defined by their average leaf area index (0.5 and 2.0, respectively). Air temperature and relative humidity were measured with data loggers at a 30 min time step from June 2012 to May 2013. Climatic data from six weather stations was also analyzed. Daily mean temperature increased at a rate of 0.75 ºC per decade ($r^2 = 0.38$, P < 0.0001), and this was related to population dynamics ($r^2 = 0.52$, P < 0.0001). Patterns of air temperature defined a cold and a warm season: July to March and April to June for maximum temperature, and November to March and April to October for minimum temperature. The difference between cold and warm seasons was 5 ºC (P < 0.0001). The minimum temperature was similar

between canopy cover levels. However, relative humidity was higher in high canopy cover plots. The relationship between UHI and the pervious surface fraction of the city was inversely proportional. The UHI ranged from 0.1 to 5 ºC and this magnitude was similar between the warm and cold seasons. Vegetation with high canopy cover had lower temperature at 17:00 LT and higher at 9:00 to 10:00 LT during the warm season. Increasing the urban zone canopy cover by 50% would reduce the UHI by 2.05 ºC. In conclusion, vegetation with higher canopy cover improved environmental conditions in terms of relative humidity and regularization of extreme temperatures during the warm season.

Keywords: Climate change, urban heat island effect, urban planning, Querétaro, vegetation.

1. Introduction

According to the population report of the United Nations (2014), 54% of human population lives in urban areas and it is increasing at a rate of 1.8% per year. By year 2050 rural population would decrease to one third of its present size. Urban concentration of human population causes deep modifications in the city and its surrounding landscapes, affecting environmental and climatic conditions (Yu and Hien, 2006; Um *et al.*, 2007). The effect and dynamics of the urban heat island (UHI) are well-known and deeply studied climatic processes (García-Cueto *et al*., 2007; Doick and Hutchings, 2013). The UHI effect is described as the difference in environmental temperature between the urban area and its rural periphery (Oke, 1973; Stewart, 2011; Li *et al.*, 2013). The variation of air temperature associated with the UHI intensity depends on factors such as infrastructure and building design and density, among many others (García-Cueto *et al.*, 2009; Li *et al.*, 2013). Compared to the countryside, the low albedo and high heat absorption of city surfaces (Doick and Hutchings, 2013), coupled with the generation of greenhouse gases (GHG) and dust from industrial processes and anthropogenic activities (Wilby, 2003; Hunt *et al.*, 2007), contributes to the increase in air temperature, and modifies surface wind flow and air quality (Blake *et al.*, 2011; Doick and Hutchings, 2013).

The increase of vegetation areas is a main option explored to mitigate UHI (Anyanwu and Kanu, 2006; Li *et al.,* 2013). Urban vegetation regulates climate mainly by shading (Emmanuel, 2005), CO_2 sequestration (Lin e*t al.,* 2011) and evapotranspiration (Yu and Hien, 2006). The mitigation potential of urban vegetation needs additional research because native vegetation and climate are strongly related, and this types of plants should be preferred as a robust mitigation option; nevertheless, exotic trees are common in the urban context.

In this paper, we analyzed the UHI for Querétaro City, Mexico. This study is an effort of the Programa Estatal de Acción ante el Cambio Climático-Querétaro (State of Querétaro Action Program Addressing Climate Change, PEACC-Q) (Suzán-Azpiri *et al.*, 2014). The aims of this study were to evaluate (1) the role of vegetation in urban temperature regularization, and (2) the role of vegetation cover in the adaptation to UHI effects.

2. Methodology

2.1 Study area

The study area is the city of Querétaro (Fig. 1), located in the southwestern portion of the State of Querétaro, Mexico (20º 35' 34.8'' N, 100º 23' 31.6'' W). It covers an area of 759.9 km^2 with a population of 626 495 (INEGI, 2010). Its predominant climate is semiarid with summer rains, annual precipitation average of 549 mm and annual average temperature of 18 ºC. The landscape comprises plains and small hills (Baltazar *et al.*, 2004).
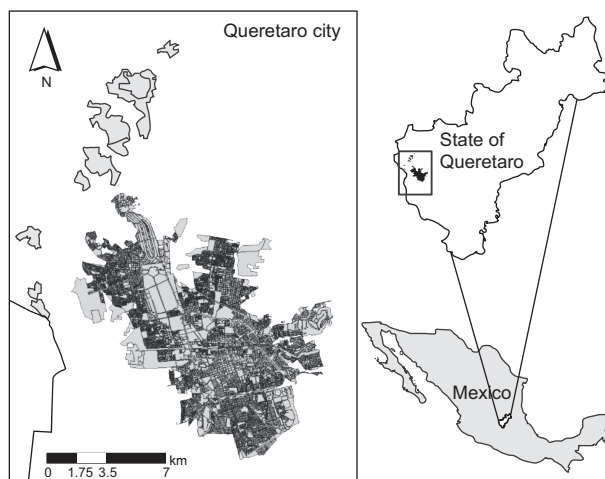

Fig. 1. Geographic location of the study area (Querétaro City).

The city of Querétaro can be classified as polycentric, with main urban cores associated to industrial and commercial areas (Álvarez de la Torre, 2010). The historic downtown is mainly composed of baroque buildings less than six stories tall. Almost 90% of the streets in the center of the city and its surroundings are paved with cobblestone, and the rest have asphalt surfaces. Industrial plots are allotted within industrial parks located to the north, east and southwest of the city; they are main land use changes that contribute to urban growth (Icazuriaga and Osorio, 2007). Concrete and steel buildings, as well as asphalt roads, are representative of these areas. Finally, 70% of the households are less than three stories single-family buildings; the rest are multi-family complexes and two level houses of social interest located on the periphery. Concrete, metal, bricks, tiles and polystyrene are the main construction materials on households. The streets are mainly asphalt roads and in some cases they are covered with cobblestone (Aragón and López, 2013).

Using Landsat 8 imagery (Sensor OLI_TIRS_L1T, December 5, 2013, USGS Global Visualization Viewer) we created a supervised classification of the city using ENVI 5 (ITT Visual Information Solutions). Approximately 65% is constructed; 37% is paved; 28% is covered by vegetation or bare soil; and less than 1% is occupied by water (dams and artificial reservoirs).

2.2 Study zones
To avoid the arbitrary designation of urban and rural zones (Stewart, 2007), we used the climate-based classification system developed by Stewart and Oke (2012). This system describes the local physical conditions around the measuring field sites, classifying them into local climate zones (LCZs). Four circular zones with a 500 m radius (78.5 ha) (WMO, 2008) were selected randomly within the range of 1 to 99% vegetation cover. We used satellite imagery to estimate the mean height of trees and buildings, the building surface fraction, and the impervious and pervious fractions (Table I). The rest of the values were taken from literature (Oke, 2006; Stewart and Oke, 2012). The four zones were classified accordingly as scattered trees (LCZ B), open low-rise (LCZ 6), compact low-rise (LCZ 3), and compact mid-rise (LCZ 2).

2.3 Local climate zones
2.3.1 LCZ B (scattered trees)
Described as lightly dense vegetation comprised by shrubs, cacti (*Opuntia* sp. and *Myrtillocactus geometrizans*), tropical dry forests (TDF) and reforestation patches (i.e. *Jacaranda mimosifolia, Eucalyptus globulus*). It constitutes one of the best-preserved climate zones in the municipality of Querétaro (Baltazar *et al.*, 2004), and is located in the southern periphery of the city (Fig. 2).

2.3.2 LCZ 6 (open low-rise)
It is composed of one to three stories small buildings of diverse construction materials (concrete, stones, bricks, tiles and metal). Fifty percent of the surface is covered with scattered shrubs and TDF. It has medium traffic flow, and residential (row housing

Table I. Parameters of geometric and surface cover properties for the LCZs of Querétaro City, according to the Stewart and Oke (2012) classification.

Properties	LCZ B	LCZ 6	LCZ 3	LCZ 2
Sky view factor (Ψ_{sky})	0.5-0.8	0.6-0.9	0.2-0.6	0.3-0.6
Aspect ratio (H/W)	0.25-0.75	0.3-0.75	0.75-1.5	0.75-2
Mean height of trees/buildings (z_H) (m)	2	13	9	< 20
Terrain roughness class	5	5	6	6
Building surface fraction (λ_b) (%)	0.11	30.14	58.03	64.39
Impervious surface fraction (λ_i) (%)	0.14	27.46	26.95	34.28
Pervious surface fraction (λ_v)(%)	99.75	42.40	15.02	1.33
Surface admittance (μ) (J m^{-2} s$^{-\frac{1}{2}}$ K^{-1})	1000-1800	1200-1800	1200-1800	1500-2200
Surface albedo (α) (%)	0.15-0.25	0.12-0.25	0.10-0.20	0.10-0.20
Anthropogenic heat flux (Q_F) (W m^{-2})	0	< 25	< 75	< 75

LCZ B: scattered trees; LCZ 6: open low-rise; LCZ 3: compact low-rise; LCZ 2: compact mid-rise.
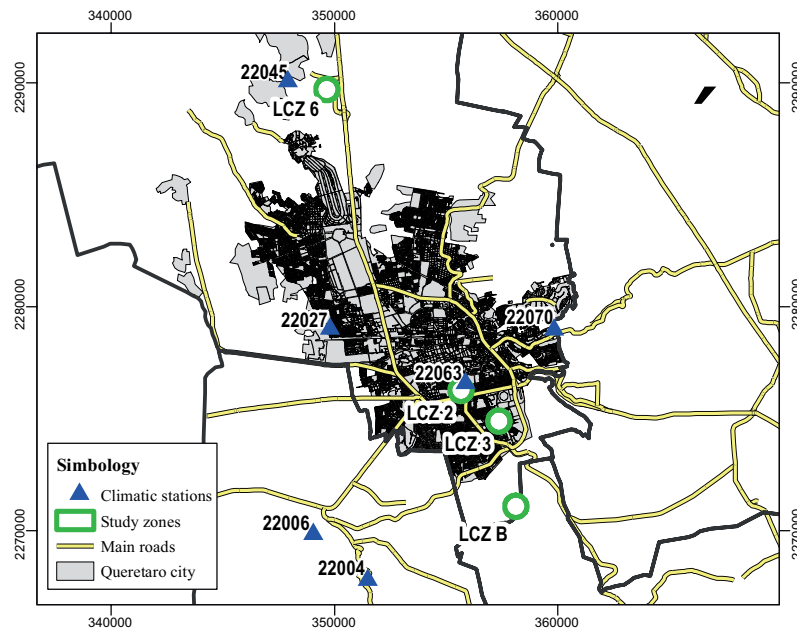
Fig. 2. Location of the four delimited local climate zones (LCZ B, LCZ 2, LCZ 3, LCZ 6) and situation of the climatic stations of the Sistema Meteorológico Nacional (National Meteorological System, SMN) (CNA-SMN, 2014) within the city of Querétaro.

and apartments) and commercial use (small shopping centers). These suburbs are located on the northern periphery of the city.

2.3.3 LCZ 3 (compact low-rise)
A dense mix of low-rise buildings with less than three stories and diverse construction materials (concrete, stone, tiles and bricks). Pavement and cobblestone cover most of the streets with a few scattered trees. It is located within the city core (medium density) and has residential use (single unit households).

2.3.4 LCZ 2 (compact mid-rise)
Dense mix of mid-rise buildings lower than nine stories of diverse construction materials (concrete, stone, tiles, bricks and metal). Most of the streets are covered with pavement and cobblestone, with a few scattered trees (*Eucalyptus* sp., *Ficus* sp. and *Jacaranda* sp.). It is adjacent to the city center and has residential use (scattered single unit households).

2.4 Sampling
In each LCZ we established random sampling points according to two different vegetation cover categories: high (+C) and low (–C) (Table II).

The characterization of each category was determined by the leaf area index (LAI), one-sided green leaf area per unit ground surface (m²/m²). The LAI was measured using a LAI-2000 Plant Canopy Analyzer (Li-Cor Inc., USA) which evaluates the transmission of light through the canopy in terms of gap fraction. For each LAI data, the average of three measurements under the canopy (separated by one meter each in a north-south direction), and one measurement above the canopy were obtained (Guevara *et al.,* 2012). For each sampling point ($n = 12$), air temperature and relative humidity were measured with a climatic data logger EL-USB-2 (Hobo Pro v.2, LASCAR, USA). The data loggers were programmed to record every 30 min from June 1, 2012 to May 31, 2013.

2.5 Temperature corrections
Heating and cooling of air is considered to be an adiabatic process responding to the variation in gas pressures (Lutgens and Tarbuck, 2012). In this context, air temperature is directly affected by altitude, and we standardized altitude and pressure by an adjustment with a Poisson function (Eq. 1). The resulting value, known as potential temperature (θ), is defined

Table II. Leaf area index (LAI), geographic coordinates and altitude values of the sampling points in each local climate zone (LCZ).

LCZ	Land cover category*	LAI	Latitude (dd)	Longitude (dd)	Altitude (masl)
LCZ B	+C	2.055	20.530611	−100.361917	2334
LCZ B	+C	2.11	20.536028	−100.3605	2204
LCZ B	−C	0.54	20.535528	−100.360722	2208
LCZ B	−C	0.375	20.531306	−100.360806	2319
LCZ 6	+C	2.52	20.699139	−100.444111	1908
LCZ 6	+C	2.31	20.702056	−100.443611	1932
LCZ 6	−C	0.635	20.70075	−100.443639	1920
LCZ 6	−C	0.285	20.701306	−100.442556	1921
LCZ 3	+C	1.175	20.567639	−100.368361	1883
LCZ 3	−C	0.755	20.567611	−100.368389	1883
LCZ 2	+C	0.295	20.579944	−100.384806	1829
LCZ 2	−C	0.255	20.579917	−100.384806	1829

* High (+C) and low (−C). dd: decimal degrees; masl: meters above sea level.

as "the temperature that a parcel of air would have if it were expanded or compressed adiabatically from its existing pressure and temperature to a standard pressure" (Wallace and Hobbs, 2006; Mohanakumar, 2008). Mathematically, it is expressed as:

$$\theta = T \left(\frac{p_0}{p} \right)^{R/c_p} \tag{1}$$

where θ = potential temperature, T = original temperature, p_0 = standard pressure of 1000 hPa, p = original pressure, R = universal gas constant (287 J K^{-1} kg^{-1}); and c_p = specific heat constant (1004 J K^{-1} kg^{-1}).

To calculate the pressure corresponding to temperature data we used the hypsometric or barometric equation (Eq. 2), which relates pressure and temperature at a certain atmospheric altitude (Adamson, 2012):

$$p_h = p_0 \, e^{(-mgh/RT)} \tag{2}$$

where: p_h = pressure at h height, p_0 = pressure at ground level (1013.25 hPa), M = the mass or a mole of particles of air (0.029 kg mol^{-1}), g = gravitational acceleration (9.8 m s^{-2}), h = height in meters, R = universal gas constant (8.314472 J K^{-1} mol^{-1}), and T = average temperature at height (ºK).

2.6 The role of vegetation in urban temperature dynamics
In a global scale, a rise in minimum temperature has a greater impact on average daily temperature than

maximum temperature (IPCC, 1997). Therefore, the effects of climate change are mainly detected in minimum daily temperatures (IPCC, 2007). In order to prove this hypothesis within the city of Querétaro we analyzed daily average minimum temperatures (T_{min}, ºC) and maximum temperatures (T_{max}, ºC) between 1982 and 2011 from six climate stations (Table III). Data were obtained from the databases of the SMN (CNA-SMN, 2014). In the case of Querétaro, all stations were previously verified with the RClimDex software (Zhang and Yang, 2004), developed within the PEACC project (Suzán-Azpiri *et al.,* 2014). Moreover, the databases of the six stations were filtered to ensure temporal homogeneity throughout the 30 years. Additionally, we analyzed the relationship between variations in T_{min} and T_{max} as a function of population size, according to the demographic censuses conducted between 1990 and

Table III. Geographic coordinates and altitude values for the seven climate stations of the SMN (CNA-SMN, 2014).

Code	Name	Latitude (dd)	Longitude (dd)	Altitude (masl)
22004	El Batán	−100.424	20.504	1886
22006	El Pueblito	−100.448	20.522	1830
22027	Carrillo	−100.441	20.604	1802
22045	Juriquilla	−100.459	20.704	1877
22063	Querétaro	−100.383	20.583	1827
22070	Plantel 7	−100.344	20.606	1857

SMN: National Meteorological System.

2010 (INEGI, 1990, 2010). Finally, we studied the oscillation in a monthly scale to identify extreme periods in both T_{min} and $T_{max.}$

In order to evaluate the role of vegetation cover in urban temperature dynamics, we evaluated the changes in T_{min} and average relative humidity (RH, %) in function of the different LCZs, canopy cover status (+C and –C) and pervious surface fraction (PSF, %) –defined as the percentage of vegetated surface–, between June 1, 2012 and May 31, 2013.

2.7 Vegetation cover and effect of the UHI

According to Stewart and Oke (2012), the UHI is represented as a function of the intensity difference (ΔT) between LCZs temperatures according to the degree of urbanization. Mathematically it is defined as:

$$UHI = \Delta T_{LCZ \, x-y} \, (^\circ C) \tag{3}$$

where *UHI* is the intensity of the urban heat island effect, ΔT is the temperature difference between LCZs, *LCZx* is the zone with more urban components (Table I), and *LCZy* is the zone with less number of urban components (Table I).

In this study, we quantified the differences between average minimum temperatures (ΔT_{min}, ºC) between the four described climate zones in six possible arrangements: LCZ_{2-3}, LCZ_{2-6}, LCZ_{2-B}, LCZ_{3-6}, LCZ_{3-B} and LCZ_{6-B}. The role of vegetation in UHI dynamics was evaluated through the fluctuation in ΔT_{min} for the LCZ_{x-y} arrangements according to the cover status (+C y –C), and seasonality (cold and warm seasons). Additionally, a daily profile of UHI (24 h) changes was studied.

2.8 Statistical analysis

A linear regression (LR) analysis was applied to evaluate the annual increase in daily average minimum and maximum temperatures from six meteorological stations, with the function:

$$Y = \beta_1 + \beta_0 X \tag{4}$$

where *Y* is the dependent variable (T_{min} and T_{max}), β_1 is the intercept, β_0 is the slope, and *X* is the independent variable (year).

In order to estimate T_{min} and RH_{ave} differences among the LCZs zones, according to the status of vegetation cover (+C and –C), a full factorial analysis was performed with the model:

$$Y_{ijk} = m + M_i + L_j + S_k + M*L_{ij} + M*S_{ik} + L*S_{jk} + M*L*S_{ijk} + e_{ijk} \tag{5}$$

where μ is the general average value, M_i is the monthly effect, L_j is the zone, S_k is the effect for the *k*-th status of vegetation, $M*L_{ij}$ is the interaction month-zone, $M*S_{ik}$ is the interaction month-status, $S*L_{kj}$ is the interaction status-zone, $M*L*S_{ijk}$ is the interaction month-zone-status, and e_{ijk} is the random error.

A simple linear regression analysis was applied to explore the relation between the T_{min} and the pervious surface fraction (PSF, %) (Table I) of the four LCZs with the function:

$$Y = \beta_1 + \beta_0 X \tag{6}$$

where *Y* is the dependent variable (T_{min}), β_1 is the intercept, β_0 is the slope, and *X* is the independent variable (PSF).

The monthly changes in the UHI associated to the status of the cover (+C and –C) in each LCZ_{x-y}, were analyzed with the model:

$$Y_{ijk} = m + M_i + C_j + S_k + M*C_{ij} + M*S_{ik} + C*S_{jk} + M*C*S_{ijk} + e_{ijk} \tag{7}$$

where μ is the average value, M_i is the effect for the *i*-th month, C_j is the effect for the *j*-th LCZ_{x-y}, S_k is the effect for the *k*-th status of vegetation, $M*C_{ij}$ is the interaction month-LCZ_{x-y}, $M*S_{ik}$ is the interaction month-status, $S*L_{kj}$ is the interaction status-zone, $M*L*S_{ijk}$ is the interaction month-zone-status, and e_{ijk} is the random error.

Linear regression analysis was applied to explore the relation between the UHI and the difference between the pervious surface fraction (ΔPSF, %) in the six arrangements LCZ_{x-y}, with the function:

$$Y = \beta_1 + \beta_0 X \tag{8}$$

where *Y* is the dependent variable (ΔT_{min}), β_1 is the intercept, β_0 is the slope, and *X* is the independent variable (ΔPSF).

The hourly behavior of the UHI at high and low temperature phases between the LCZ_{x-y}, was evaluated with the model:

$$Y_{ij} = m + E_i + H_j + E*H_{ij} + e_{ij} \qquad (9)$$

where μ is the general average, F_i is the effect of the de i-th fase, C_j is the effect for the j-th LCZ$_{x\text{-}y}$, H_k is the effect of the j-th hour, $F*C_{ij}$ is the interaction phase LCZ$_{x\text{-}y}$, $F*H_{ik}$ is the interaction phase-hour, $C*H_{jk}$ is the interaction LCZ$_{x\text{-}y}$-hour, $F*C*H_{ijk}$ is the interaction phase-LCZ$_{x\text{-}y}$-hour, and e_{ijk} is the random error.

3. Results and discussion
3.1 Historic and annual temperature oscillation
The temperature comparison for the period 1982-2011 from six climate stations within the city of Querétaro showed significant differences between the daily T_{max} (P < 0.0001, F = 49.99, 29, 929) and T_{min} (P < 0.0001, F = 122.53, 29, 900) among the 30 years. The LR exhibited a low significant linear trend for the increase in annual T_{max} (P < 0.0001, r^2 = 0.07) (Fig. 3a). In contrast, T_{min} had a more significant trend (P < 0.0001, r^2 = 0.38) of 0.751 ºC per decade (Fig. 3c). This differential trend agreed with the global pattern, where minimum daily temperatures increase faster than maximums. However, the rate was higher than

the global decadal range (0.254 to 0.273 ºC) between 1979 and 2012 (IPCC, 2013).

This increase was higher than in other Mexican cities, where values of 0.57 ºC for large metropolis (bigger than one million inhabitants) and 0.37 ºC for medium size cities (smaller than one million) are found (Jáuregui, 2005). Particularly the city of Querétaro, with less than one million inhabitants, has experienced a high rate of urban growth (Icazuriaga and Osorio, 2007) of about 33% between 1990 and 2010 (INEGI, 1990, 2010). This growth was significantly correlated with the daily annual average T_{min} increase (r^2 = 0.52, P < 0.0001) (Fig. 3d), but not with the T_{max} (r^2 = 0.0018, P < 0.0001) (Fig. 3b). Therefore, factors related to the urbanization process like the increase in building surface fraction and impervious surface fraction, the change in surface albedo and the rise of anthropogenic heat flux, could explain the T_{min} increase.

In a monthly scale we detected significant differences in T_{max} (P < 0.0001, F = 115.27, 11, 348) (Fig. 4a) and in T_{min} (P < 0.0001, F = 180.69, 11, 348) (Fig. 4b). During the cold season for T_{max} (defined as July to March) the mean and standard deviation were
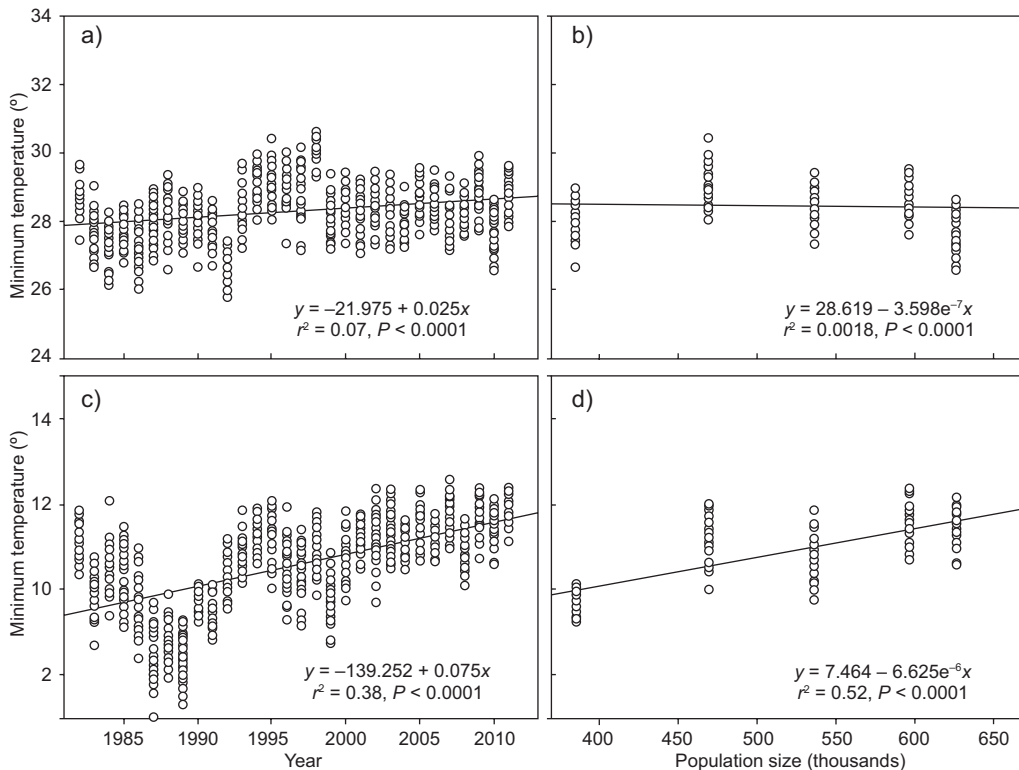

Fig. 3. Scatterplots and linear regressions between daily average temperature on time (a and c) and Querétaro city population size (b and d), from six climate stations of the SMA (CNA-SMN, 2014).
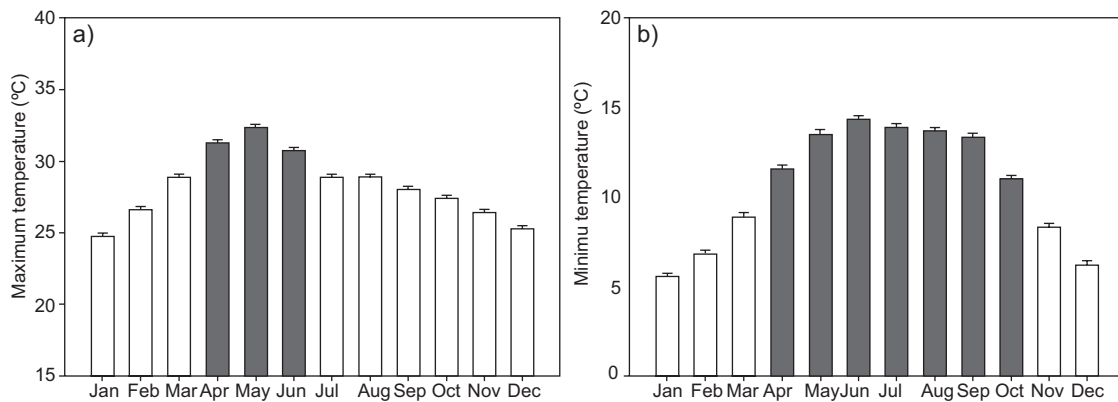
Fig. 4. Monthly average for maximum temperature (T_{max}) and minimum temperature (T_{min}) between 1982 and 2011 for six climate stations of the SMA (CNA-SMN, 2014). Black bars (warm season) are significantly different from white bars (cold season). Line bars are the standard errors of the mean.

27.24 ± 1.58 ºC, while these values during the warm season for T_{max} (April to June) were 31.45 ± 0.85 ºC (Fig. 4). In contrast, the cold season for T_{min} (November to March) had a mean and standard deviation of 7.51 ± 1.40 ºC, while these values during the warm season (April to October) for the same variable were 13.13 ± 1.43 ºC. Both trends in temperature agree with the pattern detected for a larger region in Mexico (Morillón *et al.*, 2002).

3.2 The role of vegetation in urban temperature
For the studied period, average T_{min} was 13 ºC with a maximum of 14.89 ºC and a minimum of 10.79 ºC. Significant differences between the studied zones were detected (P < 0.0001, F = 85.42, 3, 87). These differences oscillated from 1.6 ºC between LCZ 3 and LCZ 6, to 4 ºC between LCZ 2 and LCZ B. In agreement with Alexander and Mills (2014), the areas with more urban elements such as high anthropogenic heat flux percentages, impervious surface and building surface fraction, had temperatures over the mean (LCZ 2 and LCZ 3), while the less urbanized areas had temperatures below the mean (LCZ 6 and LCZ B). Among the annual seasons, a 5 ºC difference between cold and warm seasons was detected (P < 0.0001, F = 602.93, 1, 87). These results agree with the findings reported by Romero-Dávila *et al.* (2011) for the city of Toluca, Mexico.

No significant differences were found between –C and +C for T_{min} (P = 0.80, F = 0.06, 1, 87) (Fig. 5). However, Yu and Hien (2006) proved that foliar density (LAI) within a green area has an effect on air temperature; particularly in urban gardens, high

values in the LAI (> 7) were associated with lower temperatures. Therefore, we deduced that the difference between +C and –C for each climate zone was insufficient to detect an effect on T_{min}.

Relative humidity was different between LCZ 2 and LCZ B (P = 0.0074, F = 4.25, 3, 89), but it was not related to seasonality (Fig. 6). The lower RH in LCZ 2 results from fast evaporation as a consequence of high surface temperature and high runoff rates through water-drainages (Um *et al.*, 2007). In contrast, the high canopy cover for LCZ B maintained high humidity values resulting from lower mixing ratios for evapotranspiration, possibly due to lower wind speeds. Liu *et al.* (2009) found a similar result.
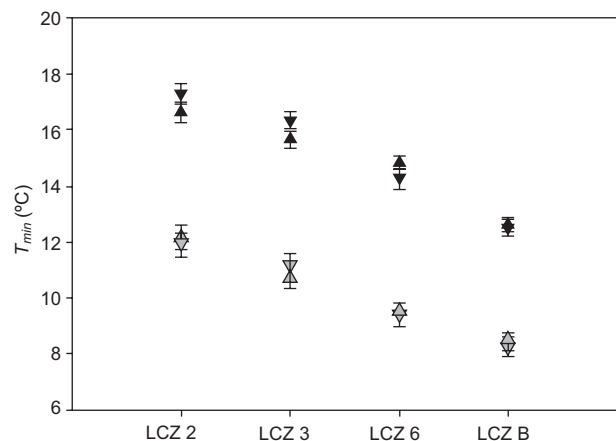

Fig. 5. Average of minimum temperature (T_{min}) for the local climate zones (LCZ) according to low (–C) and high (+C) canopy cover categories during the cold and warm season described in Fig. 4. Cold: ▼ –C, ▲ +C. Warm: ▼ –C, ▲ +C. Line bars are the standard errors of the mean.
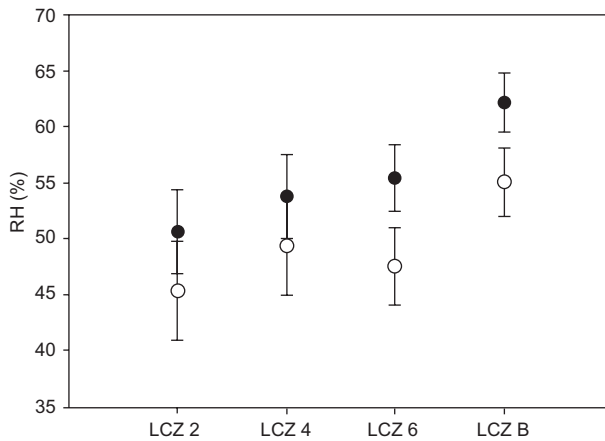
Fig. 6. Average of relative humidity (RH) for local climate zones (LCZ) during the cold (○) and warm (●) seasons as described in Fig. 4. Line bars are the standard errors of the mean.

The relationship between PSF and T_{min} was significant for the cold and warm seasons ($r^2 = 0.72$, $P < 0.0001$). According to the equation's model of linear regression (Fig. 7a and 7b), a 50% increase in PSF produced a decrease of approximately 1.75 and 2.18 ℃ in T_{min} for both seasons. Yan *et al.* (2014) demonstrated a similar relationship between canopy cover and temperature in urban parks; an increase of 50% in vegetation cover produced a decrease of 0.6 ℃ in air temperature, reinforcing the idea that canopy cover is a regulator of environmental temperature (Yu and Hien, 2006; Li *et al.*, 2013).

According to Wilby (2003) and Lin *et al.* (2011), through evapotranspiration vegetation acts as an evaporative cooling system, creating an albedo 15% higher than urban surface due to smaller heat absorption and higher reflected radiation (Doick and Hutchings, 2013). Also, the shade effect decreases incident radiation and the micro greenhouse effect within buildings (Emmanuel, 2005; Anyanwu and Kanu, 2006), which promotes energy savings by decreasing the demand in cooling systems; it also reduces health risks by decreasing atmospheric pollutants while increasing CO_2 sequestration (Lin *et al.*, 2011).

3.3 Effect of the urban heat island (UHI)

Significant temperature differences were found between LCZ_{2-B} and LCZ_{3-6} ($P < 0.0001$, F = 155.88, 5, 120; Tukey-Kramer $\alpha = 0.05$, Q = 2.89), with a 4.94 ℃ maximum intensity and a 0.48 ℃ minimum intensity (Fig. 8). Alexander and Mills (2014) found similar results between LCZ_{2-D} (4.8 ℃). During the warm season an UHI of 2.64 ℃ in average, with a 5 ℃ maximum and a 0.82 ℃ minimum, was detected. In the cold season, UHI values had a 2.46 ℃ average, ranging from a 4.88 ℃ maximum to a 0.14 ℃ minimum. These values agreed with the maximum UHI reported for the city of Mexicali, Mexico; 5.4 ℃ during the summer (García-Cueto *et al.,* 2007) and 4.5 ℃ during winter (García-Cueto *et al.,* 2009); and also for Toluca, Mexico with values of 5 ℃ for winter and summer (Romero-Dávila *et al.*, 2011). There was no effect of the canopy cover (–C and +C) over UHI intensities (P = 0.2073, F = 1.60, 1, 120).

The relationship between the UHI and the difference in canopy cover (ΔPSF) in the LCZ_{x-y} was
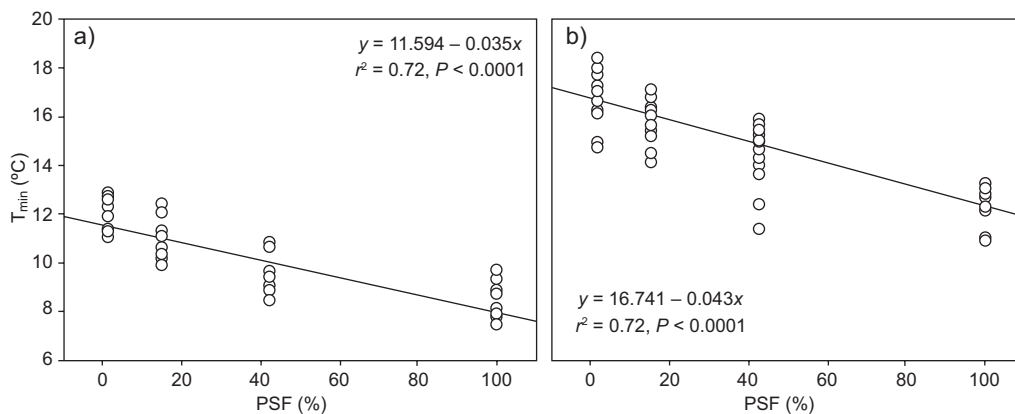

Fig. 7. Relationship between monthly average minimum temperature (T_{min}) and pervious surface fraction (PSF) of the four local climate zones during (a) cold and (b) warm seasons, as described in Fig. 4.
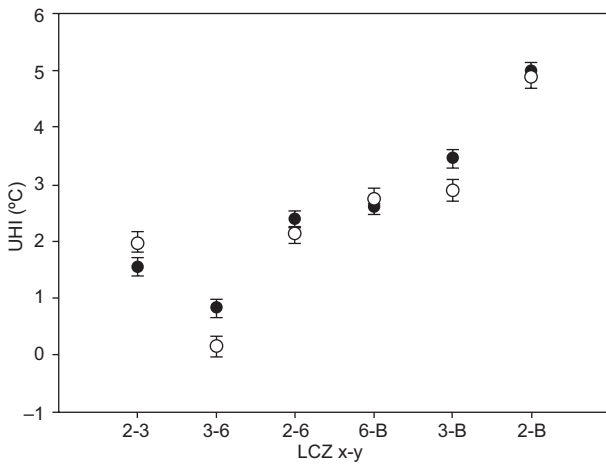
Fig. 8. Urban heat island (UHI) intensity of monthly average minimum temperature (ΔT_{min}) between local climate zones (LCZs), during cold (○) and warm (●) seasons as described in Fig. 4, where *x* and *y* represent more and less urbanized zones, respectively. Line bars are the standard errors of the mean.

significant according to the proposed seasons ($r^2 = 0.67$, P < 0.0001). For the cold season (Fig. 9a) 57% of the UHI values were explained by ΔPSF ($r^2 = 0.58$, P < 0.0001), while during the warm season (Fig. 9b) the explained variance was about 73% ($r^2 = 0.74$, P < 0.0001). According to the linear regression model, a difference of 50% in ΔPSF between more and less urbanized zones (LCZ_{x-y}), will produce a difference of 1.9 and 2.05 ºC in the UHI for the cold and warm season, respectively. Steeneveld *et al.* (2011) found a similar relationship for a green cover increase of 50% which resulted in an average decrease of 2.9 ºC in air

temperature. The close relationship between increase in seasonal UHI and the ΔPSF within each LCZ also was in agreement with the work of Shahmohamadi *et al.* (2010) which reported a smaller UHI, but similar values in canopy cover as the present study.

According to Stewart (2011), hourly observations are recommended for detection of the daily maximum and minimum UHI. When we examined the variability of the UHI on hourly intervals (Fig. 10) we found no interaction between the season effect (Fig. 10a) (P = 0.58, F = 0.30, 1, 235) and the canopy cover (Fig. 10b) (P = 0.47, F = 0.50, 1, 235). However, significant differences through the hours were detected (P < 0.0001, F = 5.05, 23, 235). The UHI was slightly more intense during warm nights and days according to Jáuregui (1997) and Romero-Dávila *et al.* (2011), who state that during the summer (warm) more and less urbanized zones receive high amounts of radiation, although they have different albedos. Therefore, differences among T_{min} were not considerable. Nevertheless, during the night the response to the slow rate of heat dissipation was significant in more urbanized areas (Shahmohamadi *et al.*, 2010).

A pattern in UHI variation was detected independently of the season and status of the canopy cover. During the first hours of the day (0:00 to 11:00 LT) the intensity remains between 2 and 3 ºC. A substantial increase reaching a maximum of 5 ºC between 15:00 and 16:00 LT is achieved later. Between 17:00-19:00 LT the UHI diminishes and remains between 2-3 ºC (Fig. 10) throughout the night. Two minor intensity peaks were detected associated with the sunrise and sunset, and the differential
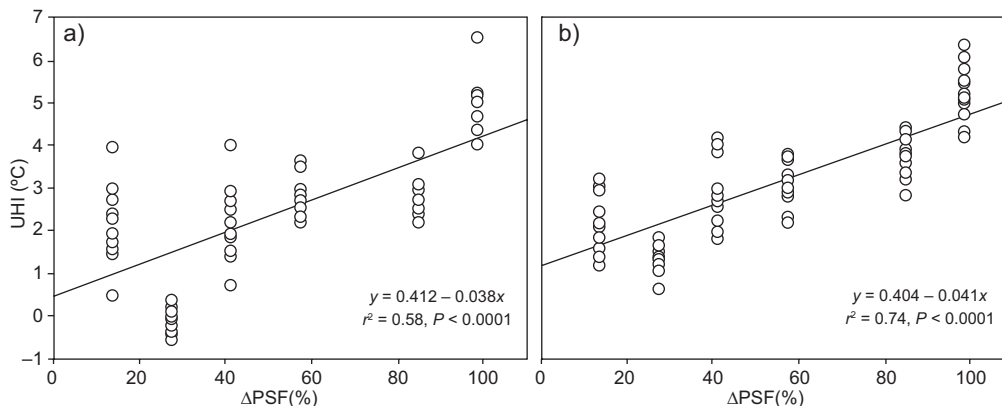

Fig. 9. Relationship between urban heat island (UHI) intensity and difference in the pervious surface fraction (ΔPSF) during the (a) cold and (b) warm seasons described in Fig. 4.
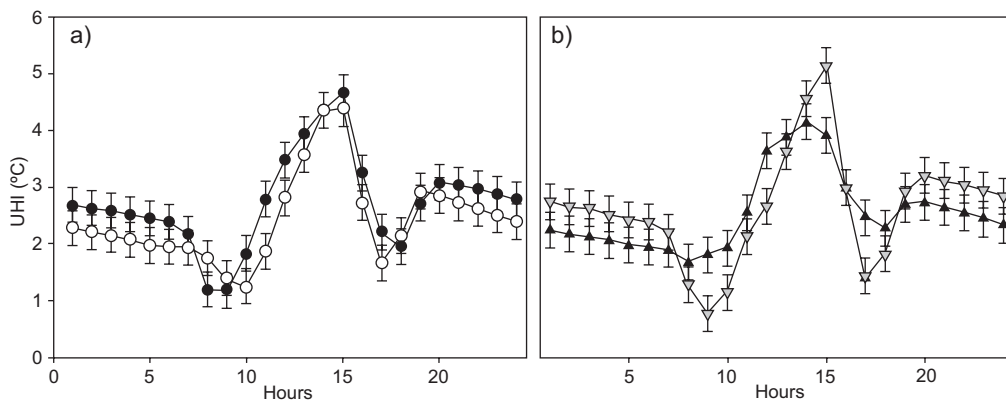
Fig. 10. Time hourly series for (a) urban heat island (UHI) intensity of monthly average minimum temperature (ΔT_{min}) throughout a day, during the cold (○) and warm (●) seasons described in Fig. 4, and (b) low (▽ –C) and high (▲ +C) cover categories. Line bars are the standard errors of the mean.

between more and less urbanized zones was minimal (Landsberg, 1981). Maximum UHI peaks were observed through the afternoon during the hours of highest solar radiation. This energy is absorbed and stored by the most urbanized surfaces, whereas less urbanized zones with greater percentages of permeable surfaces (including vegetation) reflected more radiation and therefore maintained smaller superficial temperatures (Emmanuel, 2005; Blake *et al.,* 2011).

3.4 General considerations
The vegetation cover examined in the present work had a seasonal effect on air temperature and reduced the UHI intensity, although LAI peaks were relatively low (2.05 to 2.52), and vegetation types and their phenological activity were reduced because many species are deciduous during the cold season, and also as a result of the predominant summer rainfall distribution. In other studies a decrease in the UHI effect is reported, but the LAI is typically higher due to the temperate nature of vegetation and higher and more uniform rainfall regimes (Potchter *et al.*, 2006; Leuzinger *et al.*, 2010). Although the watering costs may reduce the environmental benefits of urban vegetation (Doick and Hutchings, 2013), here we have shown that vegetation types adapted to low rainfall are useful for reducing climate change effects. The cooling effect of urban vegetation, with likely higher water availability, was similar in magnitude to that of native species present in suburban areas and located at hill slopes. A further work should examine the

performance of native species under water-restricted regimes within the urban context.

The increase of green areas within the cities is an efficient strategy to buffer environmental temperatures (Anyanwu and Kanu, 2006; Yu and Hien, 2006; Li *et al.*, 2013). However, there are some drawbacks that should be considered when including trees in the urban landscape, such as litter production, infrastructure damage by roots, and emission of harmful volatile compounds (Anyanwu and Kanu, 2006; DEFRA, 2007; Doick and Hutchings, 2013). Therefore, careful selection of tree species and thorough planning are advised.

Urban parks are conspicuous and urban expansion is fast in Querétaro; therefore, a planned integration of adequate green areas is urgent. When increasing green land areas, sizeable areas should be considered because their thermal influence depends on size (Jáuregui, 1990; Ca *et al*., 1998; Yan *et al*., 2014). Even though the studied urban sites are small patches or household gardens, they still have an ameliorating effect. Besides the planning of big urban parks, empty lots could be reclaimed, which is important because some residential developments still have over 25% of unconstructed area after decades of being inaugurated.

4. Conclusions
Within the city of Querétaro, minimum daily temperature increased at a rate of 0.751 ºC per decade during the period 1982-2011, while population increased 33% during the last two decades.

More urbanized zones, higher temperature and a decreasing temperature gradient were associated to increasing vegetation cover. The effect of local climate zones could be associated to factors such as construction materials, infrastructure, extension of the impermeable surfaces, percentage of construction and fraction of permeable surface (vegetal cover and naked ground). Particularly, we demonstrated the importance of green areas, since a 50% increase in the permeable surface diminished T_{min} by 1.76 ºC during the cold season and 2.18 ºC during the warm season.

The UHI effect was similar regardless of the season (cold or warm), oscillating between 0.14 and 5 ºC. The UHI had a daily maximum of 4.2 ºC between 13:00-16:00 LT, while a daily minima of the order of 1.5 ºC was nearly coincident with sunrise and sunset hours.

According to the relation showed by canopy cover and UHI intensity, a 50% increase in vegetation cover in urbanized zones could mitigate the UHI intensity up to 2.05 ºC during the warmest period.

Finally, it is important to emphasize that including green areas in urban planning is utterly important, since they have a potential for temperature mitigation. However, the design, extent and species composition of the canopy should take into account the existing urban climate and the species adaptation to climate variability.

Acknowledgments

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