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Suitable configurations for forested urban canyons to mitigate the UHI in the city of Mendoza, Argentina

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ABSTRACT

Urban heat island is a phenomenon that affects residential energy consumption, air quality and outdoor comfort, among others. This work focuses on the semi-arid city of Mendoza, Argentina defined by its wide and tree-lined streets. Our research aims to define and quantify which urban variables—urban forest, morphological, material and microclimatic—determine day and nighttime air temperatures and to identify the best urban configuration. For this purpose, we took measurements and a field survey during the summer in 19 representative urban canyons. The obtained data were processed by Principal Component Analysis and Multiple Linear Regressions. Two models (RMSE of 2.51% and 0.93%) and eight morphological expressions were obtained. The results show that daytime air temperature is more sensitive to the changes of urban variables than nighttime: 6.8 and 3.5 °C, respectively. For newer urban developments, low density configurations have the coolest performance in both periods. But, in high building densities, there is no single configuration that offers the best thermal performance for both periods. In addition, we conclude that the proper selection of materials is a good strategy. These results are useful for urban planners in order to allow them to design and renovate the city concerning thermal behavior.

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1. Introduction

Urban development should consider environmental and morphological variables when planning projects for public spaces. This has an impact on the socio-economic and functional aspects of the city (Da Cunha, 2005), and takes into account the sustainability and livability as a guiding principle for planning and policy (Ruth and Franklin, 2014).

The impact of the human activities, the existing infrastructures and the resources used define the quality of the city (Santamouris, 2002). Thus, according to Middel et al. (2014) sustainable urban development does not only entail smart growth, but also smart design.

In addition, cities can alter to a greater or lesser extent, all the parameters of their local climates. The combination of the increase in energy consumption and the difference in radiative balance makes cities hotter than rural areas. This gives rise to the phenomenon called urban heat island (UHI) which materializes in the higher temperatures of the urban center when compared to the surrounding rural spaces (Oke, 1982; Arnfield, 1982).

The urban heat island affects residential energy consumption, air quality and the use of the outdoor spaces, among others (Stathopoulou et al., 2008; Pantavou et al., 2011). High urban temperatures increase electricity consumption especially for air conditioning in the summer (Kolokotroni et al., 2012; Akbari et al., 1992). For example, in the countries that compose the Organization for Economic Cooperation and Development, electrical demand has increased 13% for air conditioning in residential areas for the summers between the 1990 and 2000 (IEA, 2005).

The thermal behavior of cities is largely a by-product of urban morphology or, more specifically, the composition and three-dimensional structure of materials that constitute the urban frame (McPherson, 1994). Urban greening is the most widely applied strategy to mitigate this phenomenon which can achieve huge temperature reductions (Solecki et al., 2005; Rizwan et al., 2008).

This work focuses on the Mendoza Metropolitan Area (MMA) which is located in central western Argentina (32°53′S, 68°51′W, 750 m asl), in a semi-arid continental climate with low percentages of relative atmospheric humidity and high heliophany. The MMA has been an oasis city since its origin. The urban frame is defined by wide streets and buildings composing square blocks which are lined with rows of trees. This forest frame creates shading and these "green tunnels" form an authentic forest within the city. However, this model has deteriorated since the 20th century due to population increase and lack of planning. Therefore, it is important to deeply investigate the consequences of planning decisions implemented on this urban climate.

Since 2003, the Laboratorio de Ambiente Humano y Vivienda from INCIHUSA-CONICET has been studying the urban climate of MMA. This research has been conducted in different stages. The first stage (2003–2008) assessed the spatial and temporal distribution of urban heat island and its behavior in different urban settings along the main directions of development of the city and in different weather conditions. The records of the continuous monitoring of the air temperature in the city reveal the existence of a heat island within the metropolitan area that reaches a maximum of 10.6 °C (Correa et al., 2008). This highlights the need to assess the relationship between morphological, climatic and urban forest characteristics of the MMA.

From these results, the second stage (2009–2012) focused on finding which urban forest combinations offer the best response to the thermal behavior and comfort for 19 typical urban canyons (UC). The selected case studies are 16, 20 and 30 m wide, and are inserted in high and low building densities and have different species of trees. This study pointed out that in MMA a generalized thermal discomfort exists during the daytime, with individuals stating uncomfort 46–62% of the time due to the heat in outdoor spaces. In addition, a contrast between the urban configuration that offers the best degree of comfort and the one that has best energy performance was observed (Correa et al., 2012).

In this framework, the current research proposes to analyze the interactions between different morphological and urban forest configurations. This allows us to detect the designs which best improve the thermal comfort of space and reduce urban heat island.

In urban canyons, the daytime thermal behavior determines the degree of comfort for spaces and the energy consumption in buildings. On the other hand, the nighttime thermal behavior demonstrates the cooling possibilities of the city and affects energy consumption.

Therefore, the aim of this research is to define and quantify which variables—morphological, urban forest and material—determine air temperature during the day and at night in order to identify the best urban configurations for summer.

Finally, the results will be useful for policy makers of urbanized and urbanizing areas in order to deal with the changing urban climates (Golden, 2004).

2. Methodology

2.1. Selection and morphological characterization of urban canyons

As stated above, the urban canyons of the MMA have three different widths: the narrowest streets are up to 16 m (25% of the area studied), the intermediary ones are from 17 to 25 m (representing 70% of the area studied), and avenues higher than 26 m (5% of the area studied).

In terms of building density, the city has the highest densities in the central area, which decreases progressively toward the periphery, where lower densities are found in residential areas. Low density configurations are the most prevalent for areas already developed and for new housing (Mesa and Giusso, 2014).

Regarding urban forest configurations, 79% of the existing trees in MMA correspond to three different species of first and second magnitude.[1] Into this group, "London plane" (*Platanus* × *hispanica*) is a first magnitude tree, and it accounts for 22% of this vegetation. The "white mulberry" (*Morus alba*) and "European ash" (*Fraxinus excelsior*), are second magnitude species and represent 38% and 19% of Mendocinean trees, respectively (Cantón et al., 2003). Pictures of the three "green tunneled streets" of Mendoza are shown in Fig. 1.

Based on these characteristics, 19 typical cases of the city were selected according to three axes: urban canyon width, building density and the existence of trees and its species. All selected urban canyons are oriented East–West to show the greatest difference in temperatures in the summer. One of the urban canyons has no trees. Table 1 lists the 19 cases and their Local Climate Zone (LCZ) according to Stewart and Oke (2012).

2.2. Determination of urban variables

Taking into account the features of the city, we decided to explore morphological, urban forest and materiality.

The following parameters were collected because they may be incorporated into building codes and used by developers and urban planners. The variables selected by category are as follows:

- *Morphological structure:* building volume (BV), compactness (*C*), urban canyon length (UCL), urban canyon width (UCW), mean building height (MBH), volume/length (BV/L), volume/width (BV/W) and height/width ratio (*H*/*W*). The explanation of each variable is shown in Fig. 2.
- *Urban forest structure:* solar radiation permeability of the tree species (SP), amount of trees (NT), trees per linear meter ratio (T/m) and mean tree height (MTH). The explanation of each variable is shown in Fig. 3. Solar radiation permeability of tree-species is defined as a characteristic of the tree canopy, which transmits the incoming global radiation. It is a value between 0 and 1.
- *Optical properties of materials:* horizontal surface albedo (HA) and vertical surface albedo (VA). The explanation of each variable is shown in Fig. 4.

2.3. Determination of microclimatic variables

Data from microclimatic variables were obtained through a 39-day measuring campaign from December 17, 2009 to January 25, 2010. A fixed sensor type H08-003-02 (HOBO®; Onset; Cape Cod,

[1] Forest magnitude refers to the final height of mature trees according to their genetic characteristics, which corresponds approximately to 20 years of age. The category *first magnitude* responds to the species whose final height exceeds 15 m and the *second magnitude* to trees of 10–15 m (Carrieri, 2004).

Fig. 1. Forested urban canyons of the MMA. (a) *Platanus × hispanica*, (b) *Morus alba* and (c) *Fraxinus excelsior*. Adapted from: Correa et al. (2010).

Table 1
Case studies and their Local Climate Zone (LCZ).

LCZ		Cases – Urban Canyons (UC)
2	Compact midrise	19
2_A	Compact midrise with dense trees	1 – 3 – 5 – 10
3_A	Compact low-rise with dense trees	4
3_B	Compact low-rise with scattered trees	12
6_A	Open low-rise with dense trees	9 – 13
6_B	Open low-rise with scattered trees	2 – 6 – 7 – 8 – 11 – 14 – 15 – 16 – 17 – 18

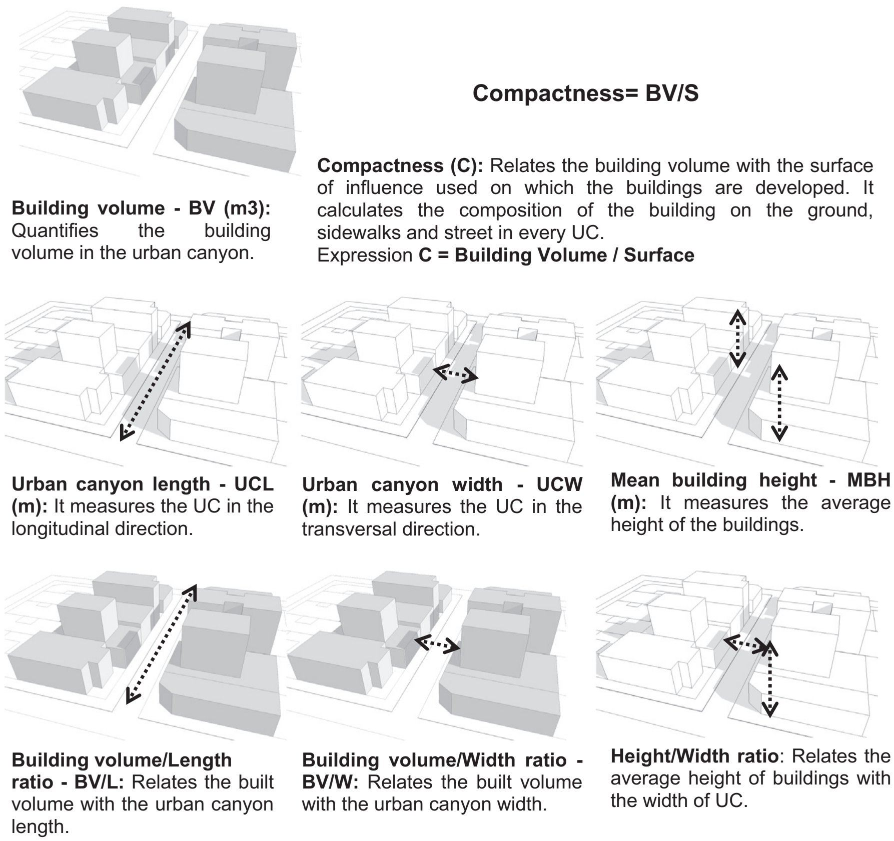


Fig. 2. Morphological structure variables.

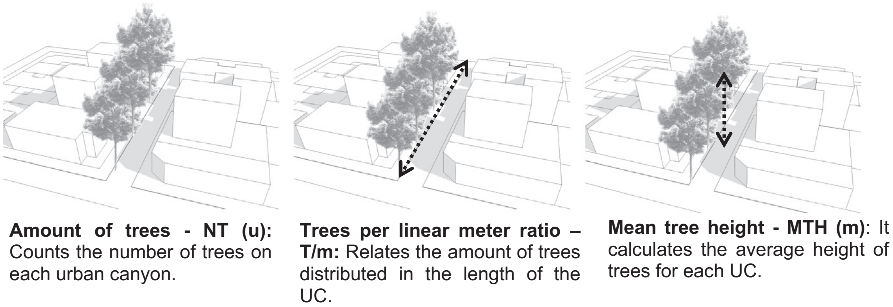


Fig. 3. Urban forest structure variables.

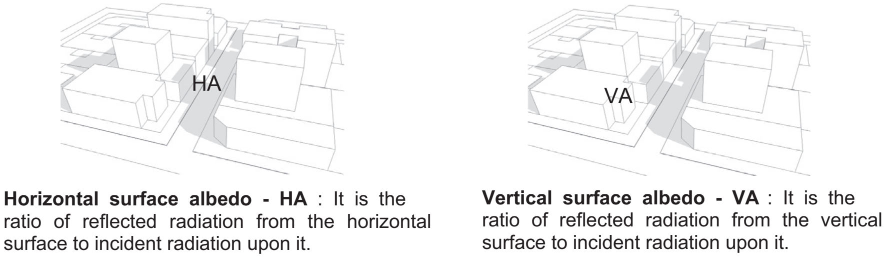


Fig. 4. Optical properties of materials variables.

MA) was installed in each urban canyon, at 2 m high from the ground, in a perforated PVC white box in order to prevent irradiation and ensure adequate air circulation (Oke, 2004). Measurements of temperature, relative humidity and absolute humidity were programmed every 15 min.

In addition, urban canyons were monitored from 8 am to 8 pm between January 8 and January 26, 2010 with a mobile weather station (H21-001; HOBO®; Cape Cod, MA). The data assessment was made for January 11, 2010 because it was a typical day for the city studied. It was a day without clouds, moderate wind and low relative humidity. The meteorological background condition during this day was characteristic and representative of the measurement period. Air temperature and relative humidity (S-THB-M002; HOBO®; Cape Cod, MA), wind speed (S-WSA-M003; HOBO®; Cape Cod, MA), wind direction (S-WDA-M003; HOBO®; Cape Cod, MA), and solar radiation (S-LIB-M003; HOBO®; Cape Cod, MA) were recorded every 15 min. Vertical and horizontal surface temperatures were measured with an infrared thermometer (Fluke 66; Fluke MEA; Dubai, United Arab Emirates). The specifications of measurement devices are described in Table 2.

Table 2
Specifications of measurement devices.

Device	Variable	Measure range	Accuracy	Resolution
H08-003-02	Air temperature	−20 °C to +70 °C	±0.7 °C at +21 °C	0.4 °C at +21 °C
	Relative humidity	25–95%, at 26 °C	±5%	0.1% HR, at 25 °C
S-THB-M002	Air temperature	−40 °C to 75 °C	0.2 °C, at 0–50 °C	0.02 °C, at 25 °C
	Relative humidity	0–100%	±2.5%, from 10% to 90% HR	0.1%HR, at 25 °C
S-WSA-M003	Wind speed	0–45 m/s	±1.1 m/s or 4%, whichever is higher	0.38 m/s
S-WDA-M003	Wind direction	0–355 grades	±5 grades	1.4 grades
S-LIB-M003	Solar radiation	0–1280 W/m^2	±10.0 W/m^2 or ±5%, whichever is higher	1.25 W/m^2
Fluke 66	Surface temperature	−32 to 600 °C	±1 °C or ±1%, whichever is higher	0.1 °C

A daytime period is considered from 8 am to 8 pm and nighttime from 8 pm to 8 am. The values of each variable have been averaged for each period. Thus, the variables are:

- *Microclimatic variables:* daytime air temperature (DTair), nighttime air temperature (NTair), daytime pavement surface temperature (DTpav), daytime sidewalk surface temperature (DTsw) and daytime wall surface temperature (DTwall).

Previous studies in the MMA (Alchapar et al., 2014) show that the values of albedo of the commonly used materials vary widely between 0.42 and 0.91. Instead emissivity values only vary between 0.80 and 0.98. Although the albedo is not involved in the night radiative balance, since the emissivity does not offer many possibilities for variation, it has privileged the daytime surface temperature measurements. In future studies the measurement period of this variable will be expanded.

2.4. Multivariate analysis

According to the data set and the goal of the investigation, it was decided to conduct Principal Component Analyzes (PCA) and then, Multiple Linear Regressions (MLR).

The PCA belongs to a group of multivariate statistical techniques eminently descriptive. Thus, it is used in this study as exploratory analysis. In this regard, the PCA allows us to discover interrelations among the data; and according to the results, propose the most appropriate statistical analysis. Principal component analysis obtains an optimized, low-dimensional representation of coordinated variable response along mutually orthogonal ordination axes in Euclidean space (Kenkel, 2006). In this case, the number of descriptive variables is lower than the number of case studies and it is used the correlation matrices because the variables are in different units. The PCAs were carried out using the Infostat software (Di Rienzo et al., 2011).

Based on the results of the PCAs, it is selected the MLR methodology as it is a quantitative technique and the dependent variables show a normal distribution and homogeneity of variance. Multiple Linear Regressions allow us to establish the relationship that occurs between a dependent variable Y and a set of independent variables. The MLRs were developed in R software (R Development Core Team, 2011).

The resulting principal components have not achieved a tangible meaning. Therefore they were not used in the MLR because they would not be appropriate to include them in the urban codes as the aim of the study proposes. In conclusion the original variables defined in the preceding sections were used as independent variables.

Finally, a synthesis of the results from both models was carried out. The urban canyon configurations that generate the best and the worst thermal behavior in both periods are presented.

3. Results

The results are presented in two sections: thermal behavior analysis and the best and the worst morphological expressions resulting from the findings.

3.1. Thermal behavior analysis

An examination of air temperature was performed from two principal component analyses. From the total of 18 variables, 6 variables involved in each PCA according to Pearson coefficients were selected. Table 3 shows the values of the Pearson coefficients with each dependent variable.

Fig. 5a shows a biplot with the results of the principal component analysis for diurnal time. Six variables were selected: number of trees (NT), trees per meter (T/m), mean building height (MBH), urban canyon width (UCW), horizontal surface albedo (HA) and daytime surface wall temperature (DTwall). The total variance of the 6 variables is repartitioned along orthogonal ordination axes. The first and the second components accumulate 70% of the total variance. According to Pearson

Table 3
Pearson correlation coefficients.

Variables	With DTaire	With NTair
Building volume (BV)	−0.22	0.63*
Urban canyon area (UCA)	−0.26	−0.18
Compactness (*C*)	−0.11	0.75*
Urban canyon length (UCL)	−0.33	0.00
Building volume/Width (BV/W)	0.05	0.59*
Urban canyon width (UCW)	−0.73*	0.03
Building volume/Length (BV/L)	−0.33	0.66*
Mean building height (MBH)	−0.49*	0.62*
Height/width (*H*/*W*)	0.15	0.78*
Solar permeability (SP)	0.28	0.38
Number of trees (NT)	−0.50*	−0.40
Trees per meter (T/m)	−0.54*	−0.40
Mean tree height (MTH)	−0.30	−0.15
Vertical surface albedo (VA)	−0.24	0.71*
Horizontal surface albedo (HA)	−0.72*	−0.13
Daytime pavement surface temperature (DTpav)	0.29	−0.05
Daytime sidewalk surface temperature (DTsw)	0.41	−0.17
Daytime wall surface temperature (DTwall)	0.51*	−0.04

* Significant values ($\alpha = 0.05$).

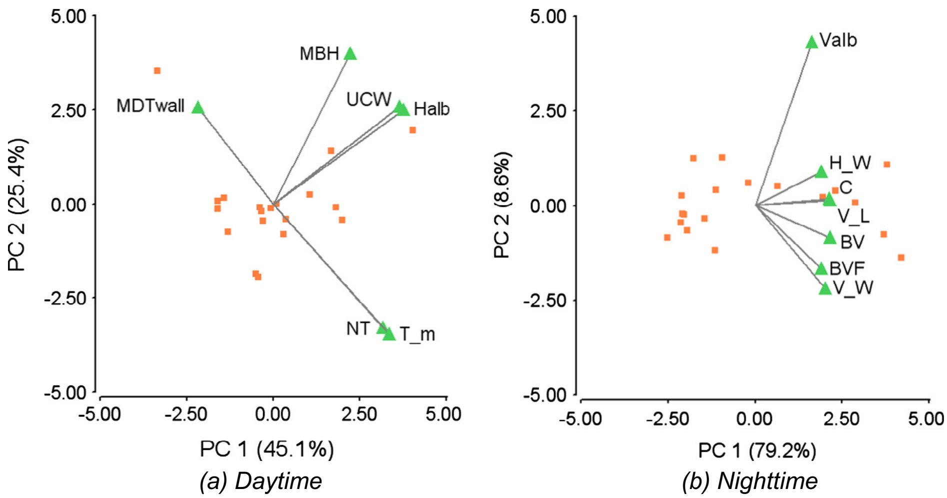


Fig. 5. Biplots of observations (green triangles) and variables (orange squares). (a) Daytime and (b) nighttime. PC: Principal component. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

coefficient, three groups of variables correlate with daytime air temperature: morphological, optical and urban forest.

This PCA reveals that NT and T/m are inversely proportional to the daytime surface temperature of the wall which concurs with the results from Berry et al. (2013). Tree canopies absorb and reflect large proportions of both solar and terrestrial radiation, which in summer can reduce the difference between internal and external building temperatures (Laband and Sophocleus, 2009). Otherwise, UCW, HA, and MBH are related in a positive linear sense (to a lesser degree).

For the nighttime period, eight variables were selected for the principal component analysis: building volume (BV), compactness (*C*), volume per width (*V*/*W*), volume per length (*V*/*L*), mean building height (MBH), height–width ratio (H/W), building view factor (BVF), and vertical surface albedo (VA). The first and the second components explain 87% of the total variance (Fig. 5b). Note that at night, in contrast to day, from the data obtained, only morphological and optical categories correlate with air temperature.

The first component is the most important and it comprises the totality of the variables in a positive sense. MBH, VA, and H/W are positive making up the second component; but BV, BVF, and V/W are negative.

In order to detect and weight the variables which influence on the day and nighttime thermal behavior, a set of multiple linear regressions were performed. As a result, two statistical models were obtained. The independent variables were selected for MLR as functional for the investigation and for the results of the PCA.

For the two models, the goodness of fit and the testing for assumptions are shown in Table 4.

The goodness of fit is reflected in the adjusted coefficient of determination R^2 which expresses the proportion of explained variability through the model. A value close to 1 is desirable. Otherwise, the root-mean-square error (RMSE) represents the sample standard deviation of the differences between predicted values and observed values. The lower the RMSE values, the better.

As for the testing for assumptions, the Shapiro–Wilk test is used to contrast the normality of a data set. It is considered one of the most powerful tests for a normality contrast, especially in small samples ($n < 30$). The null hypothesis is presented as a sample $x_1, \ldots, x_n$ and comes from a normally distributed population. The null hypothesis is rejected if W is too small. If the p-value is greater than alpha (not significant), the hypothesis is not rejected and it is concluded that the data follow a normal distribution. The Breusch–Pagan test is used to detect homoscedasticity in a linear regression model. If the test confirms that the independent variables are significant, then we can reject the null hypothesis of homoscedasticity.

3.1.1. Daytime temperature

For the regression model of daytime air temperature, the following variables were selected: trees per meter (urban forest variable) urban canyon width and mean building height (morphological variables), horizontal surface albedo (optical variable), and daytime surface temperature of walls (microclimatic variable).

The daytime model is showed in Eq. (1). All types of variables are part of this model so that daytime air temperature is related to the morphology, the optical properties of the materials, afforestation and microclimate. We can see that the most important variables are T/m and HA. This last variable has little range of variability (between 0 and 1), unlike MBH or UCW, which vary in the order of meters.

$$\mathrm{DTair} = 29.18 - 6.20 * \mathrm{T/m} - 0.05 * \mathrm{MBH} - 0.13 * \mathrm{UCW} - 6.97 * \mathrm{HA} + 0.28 * \mathrm{DTwall} \qquad (1)$$

From the multivariate regression model, four nomograms have been developed. A nomogram consists of a set of n scales, one for each variable in an equation. Knowing the values of $n - 1$ variables, the value of the unknown variable can be found, or by fixing the values of some variables, the relationship between the unfixed ones can be studied.

In Table 5 the values used for the daytime nomograms of the possible urban configurations are shown. The values of the morphological variables (BV, MBH and UCW) were selected as representative in the 19 urban canyons. The UC without forestation includes the trees per meter variable. For the

Table 4
Goodness of fit and testing for assumptions for each developed model. Note that the two models meet the assumptions.

Model	Goodness of fit		Normality	Homoscedasticity
	Adjusted R^2	RMSE	Shapiro–Wilks test	Studentized Breusch–Pagan test
	–	%	–	–
DTair	0.7227*	2.51	0.9329	10.8949
NTair	0.6396*	0.93	0.9517	3.7689

Table 5
Morphological characteristics and its relationships used for daytime nomograms.

BV (m^3)	9000	9000	230000	230000
MBH (m)	3	6	15	30
UCW (m)	16/20/30	16/20/30	16/20/30	16/20/30
T/m (trees/m)	0/0.13/0.20/0.23	0/0.13/0.20/0.23	0/0.13/0.20/0.23	0/0.13/0.20/0.23
Halb	0.22/0.32/0.54	0.22/0.32/0.54	0.22/0.32/0.54	0.22/0.32/0.54
DTwall (°C)	31	31	31	31

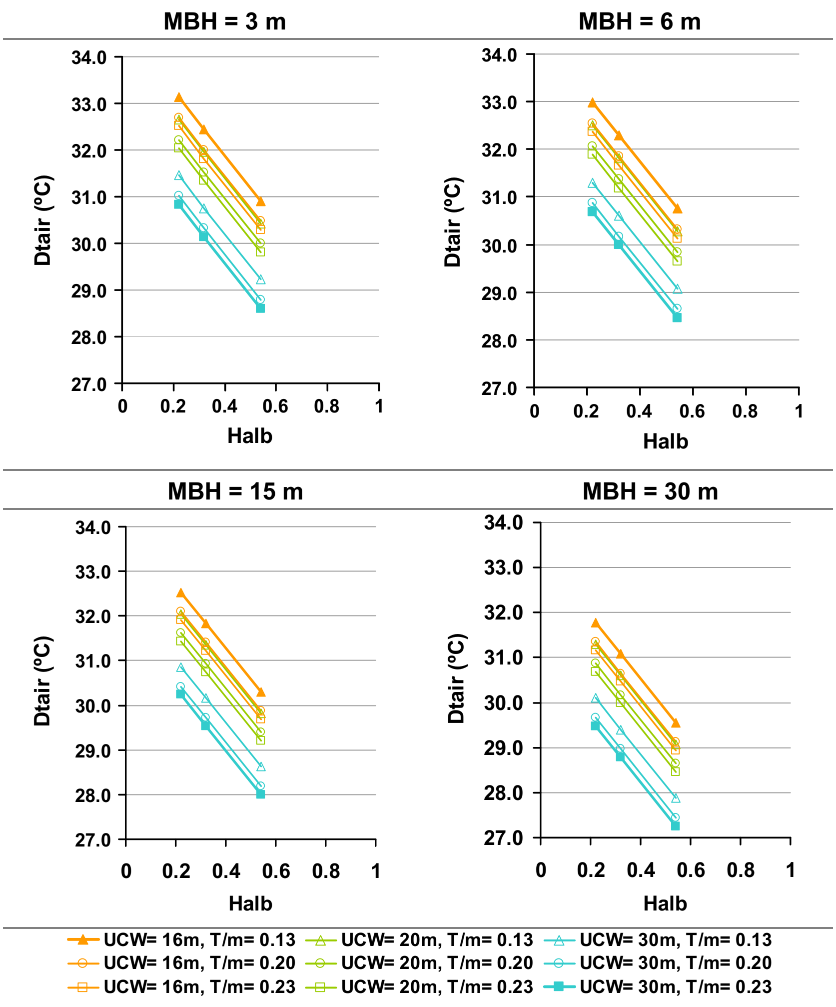


Fig. 6. Nomograms of daytime air temperature in accord on developed models.

horizontal albedos the three typical values in the MMA were used (Alchapar et al., 2014). And the DTwall is set at 31 °C because it is the resulting average, the median and the mode in the monitored cases.

Figs. 6 and 7 shows the five nomograms of the daytime air temperature. The results suggest that:

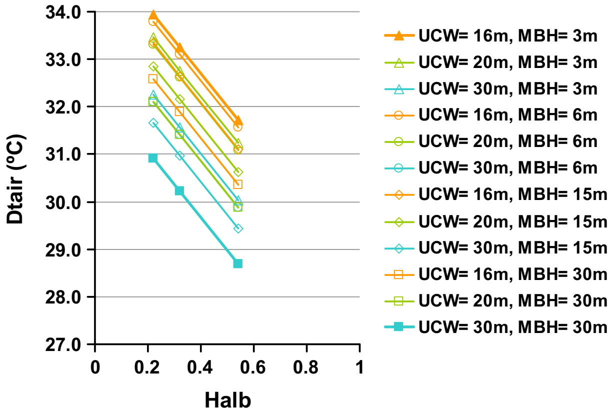


Fig. 7. Nomogram of daytime air temperature in non forested urban canyons.

- Among the graphed cases, the best response is composed of a large density of trees (0.23 trees/m = 8.5 m of tree spacing), a high horizontal albedo (equal to 0.54), and high and wide urban canyons (30 m wide by 30 m high). This configuration offers cooling of 6.8 °C less than the worst proved configuration.
- On the other hand, the worst thermal response is given by using fewer trees (0.13 trees/m = 15 m of tree spacing), a low horizontal albedo equal to 0.22, and low and narrow urban canyons (16 m wide by 3 m high).
- When mean building height, horizontal albedo, and the number of trees are constant, a greater urban canyon width determines a lower air temperature (1.3 °C for every 10 m wide). This highlights the influence of increasing the convective exchange of the urban canyon surfaces during the heating period.
- As the urban canyon height increases, and all other variables are fixed, daytime air temperature decreases 0.8 °C for every 15 m (5 stories).
- With a greater density of trees and the other variables constant, the air temperature is lower. If the trees are planted every 6.5 m apart (0.23 T/m), there is a decrease of 0.6 °C in the daytime temperature when compared to 15 m of distance between the trees (0.13 T/m). This condition is a result of the shading and cooling by evapotranspiration.
- An increase of 0.10 in the horizontal albedo produces an air temperature decrease of 0.7 °C in fixed canyon width and height and number of trees. This indicates that the higher reflective capacity of horizontal surfaces lowers temperature and cools the surrounding environment.
- Urban canyons without trees are the warmest. Except with a mean building height equal to 30 m, which is 0.5 °C cooler than the forested low density configurations (MBH = 3 m) and 0.4 °C cooler when compared to MBH = 6 m. Both of these exceptions should have a fixed ratio of tree spacing equal to 0.13 (15 m between trees). This means that forested low density configurations are warmer than the 30 m high building density scheme without trees. Buildings produce shadows which cool the air.

3.1.2. Nighttime temperature

For the regression model of nighttime air temperature we selected four variables: BV, MBH, H/W, and VA. The NTair model is shown in Eq. (2). Unlike DTair model, only morphological and optical variables are present in this model. The most important variables are MBH and VA. This last variable has little range of variability (between 0 and 1), unlike MBH, which varies in the order of meters. In addition, BV has a low coefficient but takes values in the order of thousands of cubic meters. The UCW is defined from the values of MBH and the height–width ratio, which have relatively low values in the city of Mendoza.

$$\mathrm{NTair} = 23.50 + 1.79 * H/W - 0.026 * \mathrm{MBH} - 0.000000138 * \mathrm{BV} + 2.18 * \mathrm{VA} \quad (2)$$

In Table 6 the values of each variable used in the regression model are presented to graph the two nomograms of the nighttime period. Two constructive densities are used (low = 9000 and high = 23,000 m^3). For each density there are two respective mean building heights: 3 and 6 m for low density, and 15 and 30 m for high density. The H/W ratio varies between 0.10 and 1.88 because the typical widths of urban canyons are 16, 20 and 30 m. Also, the vertical albedos are represented in five possibilities that represent the common values in the study cases.

Fig. 8 shows two nomograms of nighttime air temperature in the two building volumes used.

This analysis shows that:

- There is a relationship between building density and the range of thermal response. For example, for low density, there is a difference of 1.9 °C between the best and the worst alternatives studied. However, for high density, the difference is 3.5 °C.
- Low BV (9000 m^3), low MBH (3 m), low H/W (0.10), and low vertical albedo (0.30) is the best configuration in terms of thermal response, among the cases considered (nighttime air temperature = 24.3 °C).
- The worst UC configuration has the highest values of morphological variables and material optical properties (BV = 230,000 m^3, MBH = 30 m, H/W = 1.88 and VA = 0.96). Its air temperature can rise up to 28.1 °C.
- The temperature decreases up to 2.7 °C for configurations where building height is equal and the width of the canyon is greater. This may be due to the convective and the radiative exchange rates that facilitate cooling the air.

Table 6
Morphological characteristics and its relationships used for nighttime nomograms.

BV (m^3)	9000	9000	230000	230000
MBH (m)	3	6	15	30
UCW (m)	16/20/30	16/20/30	16/20/30	16/20/30
H/W	0.10/0.15/0.19	0.20/0.30/0.38	0.50/0.75/0.94	1.00/1.50/1.88
Valb	0.30/0.45/0.63/0.80/0.96	0.30/0.45/0.63/0.80/0.96	0.30/0.45/0.63/0.80/0.96	0.30/0.45/0.63/0.80/0.96

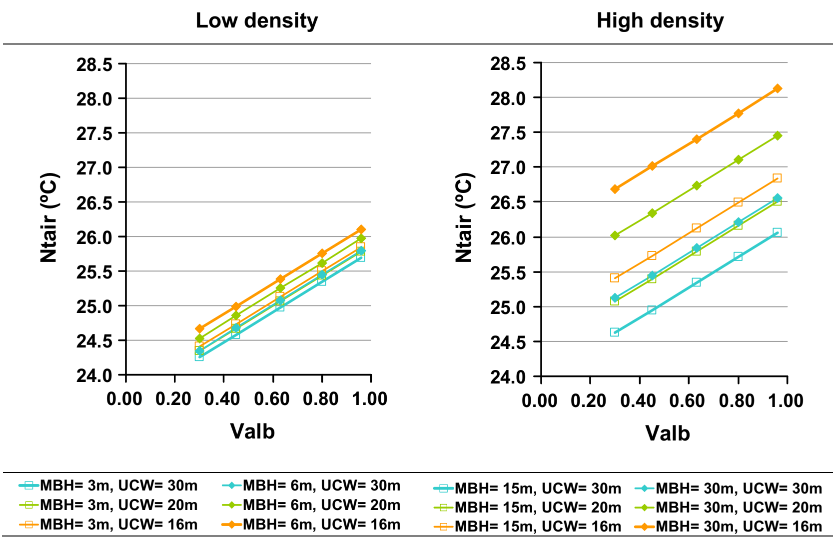


Fig. 8. Nomograms of nighttime air temperature in accord on developed models.

- When H/W ratio decreases—either because MBH is lower or higher UCW, to equal BV and VA, cooler configurations are obtained. Lower values of MBH and constant UCW in high density schemes, the air temperature decrease by 2.7 °C compared with 1.7 °C in low density. If the UCW increases and MBH remains constant, the difference is 5 times more pronounced for high density configurations when compared with the low density. This might be due to the high H/W ratio configurations, which do not allow a proper convective and radiative cooling exchange.
- With a decrease in the vertical albedo, the air temperature also decreases considerably for the low and the high building densities. An increase of 0.2 °C in nighttime air temperatures is found for equal values of the morphological variables (H/W ratio, BV, and MBH) and an increase of 0.1 in the vertical albedo. The albedo is a property of materiality involved in the absorption of solar radiation and therefore occurs only during the day. However, it is noteworthy that the building mass can accumulate a lot of energy due to multiple reflections between the walls of the urban canyon. This energy is then stored, so the air temperature is higher when the ratio of reflected solar radiation is high.

3.2. Morphological expressions

A series of possible urban configurations were developed from results of multivariate regression models. This research does not want to cover the entirety of the urban morphologies, but seeks to analyze the typical configurations of the urban canyons in Mendoza.

Urban canyons configurations in both geometrical dimensions—UCW (horizontal dimension) and MBH (vertical dimension)—were generated for day and night. Figs. 9 and 10 show the best (left column) and the worst (right column) thermal behavior for low and high building density. In addition, the value of main involved variables is presented.

During the day, thermal behavior of the high density forested urban canyons remains 1.3 °C cooler compared with the respective cases of low density. The increase of the building height helps to keep the canyons cooler through the shadow effect. Besides, the cooler configurations for both densities are those with a canyon width equal to 30 m. This is produced through the convection in the canyon. When forested and non-forested configurations are compared, there is a difference of 1.4 °C using equal urban morphology. This demonstrates the important contribution of the urban forest in terms of cooling the outdoor spaces through shading and evapotranspiration.

For nighttime, the low building density presents the best combinations. Radiative cooling strategies are possible thanks to the broad sky view. For high-density configurations, in canyons 16 m wide, the sky vision is largely blocked by buildings and trees. For this width, the thermal differences reach 2.3 °C between 3 and 30 m in building height. Therefore, we can deduce that cooling possibilities will be greater at lower and wider urban canyons when compared with higher and narrower ones.

4. Discussion

The recommendations for growth and urban renewal are presented. Broadly these recommendations seek to mitigate the effect of the UHI. The features of the MMA include high heliophany, low relative humidity, low frequency and intensity of winds and high thermal inertia. Therefore, convective exchanges are practically discarded and radiative exchanges generate the only possibilities of cooling. In this regard, strategies that contribute to the reduction of direct solar gain during the day, generate the heat trapping effect during the night. From these considerations, it is important zoning the city to avoid overheating and mitigate the effect of the UHI.

4.1. City growth

In this context, these results aim to identify the best urban configurations in terms of thermal behavior. From the point of view of urban growth planning, the study recommends forested urban canyons that are 6 m buildings high (2 stories) for residential areas—low density.

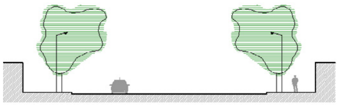
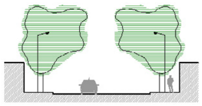
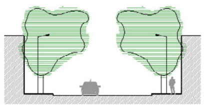
Configuration	The best		The worst
BV (m^3)		9000 (low density)	
Morphological expression			
MBH (m)		3	
UCW (m)	30		16
H/W	0.10		0.19
Valb	0.30		0.96
T/m (trees/m)	0.23		0.13
Halb	0.54		0.22
DTwall (°C)		31	
DTair (°C)	**28.6**		**33.1**
∆DTair (°C)		**4.5**	
NTair (°C)	**24.3**		**25.8**
∆NTair (°C)		**1.5**	
Morphological expression			
MBH (m)		6	
UCW (m)	30		16
H/W	0.20		0.38
Valb	0.30		0.96
T/m (trees/m)	0.23		0.13
Halb	0.54		0.22
DTwall (°C)		31	
DTair (°C)	**28.5**		**33.0**
∆DTair (°C)		**4.5**	
NTair (°C)	**24.4**		**26.1**
∆NTair (°C)		**1.7**	

Fig. 9. The best and the worst cross-section's configuration in low building density according to thermal behavior for day and nighttime.

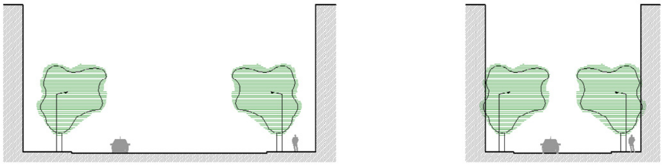
For forested and high-density cases, morphologies that are 30 m high (10 stories) have a better performance during the day because of the significant role that tall buildings play for shading, which helps reduce urban heat (Middel et al., 2014). However, it is important to remember that high concentrations of buildings and impervious surfaces increase the radiative heating intensifying the UHI effects at night. The other case analyzed (15 m high – 5 stories) shows a better nocturnal behavior but reaches higher temperatures during the day. Therefore, we recommend using morphologies that are 30 m high (tall buildings) for areas concentrated for daytime activities. However, if the goal is to generate a mixed use (residential and commercial), no more than 15 m is recommended to achieve a greater night cooling.

4.2. Urban renewal

If global sustainability requires the maintenance of urban areas, the development of cities necessarily involves the rehabilitation of urban land consolidated (Higueras, 2009).

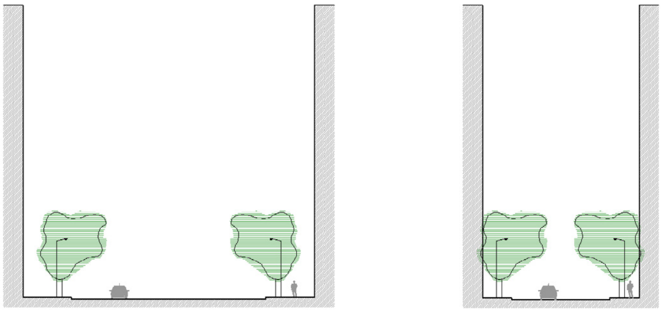
Configuration	The best	The worst
BV (m^3)	230000 (high density)	

Morphological expression



MBH (m)	15	
UCW (m)	30	16
H/W	0.50	0.94
Valb	0.30	0.96
T/m (trees/m)	0.23	0.13
Halb	0.54	0.22
DTwall (ºC)	31	
DTair (ºC)	**28.0**	**32.5**
ΔDTair (ºC)	**4.5**	
NTair (ºC)	**24.6**	**26.8**
ΔNTair (ºC)	**2.2**	

Morphological expression



MBH (m)	30	
UCW (m)	30	16
H/W	1.00	1.88
Valb	0.30	0.96
T/m (trees/m)	0.23	0.13
Halb	0.54	0.22
DTwall (ºC)	31	
DTair (ºC)	**27.3**	**31.8**
ΔDTair (ºC)	**4.5**	
NTair (ºC)	**25.1**	**28.1**
ΔNTair (ºC)	**3.0**	

Fig. 10. The best and the worst cross-section's configuration in high building density according to thermal behavior for day and nighttime.

From the results of the nomograms, the optical property of materials (albedo) is the variable that generates the most impact on thermal conditions. This modification is an appropriate strategy for the UHI mitigation because rebuilding the city is not usually a feasible alternative. According to Luxán et al. (2009), building rehabilitation saves 60% of energy when compared with tearing it down and rebuilding it as well as avoiding the numerous environmental impacts.

During the day, horizontal albedo becomes relevant (sidewalk and driveway). The air temperature decreases 2.2 °C when the albedo value varies from 0.22 to 0.54 and the MBH, the UCW and NT remain constant. To obtain this change in the value of albedo, it is necessary to replace the asphalt and dark pavements with concrete and light pavements.

On the other hand, at night, the most meaningful improvement would be achieved by modifying the building facades with low albedo materials. For example, when the vertical albedo is modified from 0.96 to 0.30, the air temperature decreases 1.4 °C for low density and 1 °C for high density. This can be achieved by substituting white glossy paints for dark thick facades.

These results highlight the importance of the urban planner decisions on the city rehabilitation and the improvement of energy consumption. In order to anticipate future modifications or renovations, these determinations need to be useful and unchanged by the end of the century (Masson et al., 2014).

5. Conclusions

For the aim of this study, day and nighttime air temperature models were developed. The RMSE were 2.51% and 0.93%, respectively.

From the initial set of 18 variables grouped into four categories—urban forest, morphological, material and microclimatic, only six of them explain, throughout PCA, the daytime air temperature. Then, the regression model involves five variables: BV, MBH, UCW, HA and DTwall. For air temperature at night, six variables are significant in the PCA and four of them integrate the model: BV, MBH, H/W, and VA. The equations reveal that during the day all the variables of the four groups interact, but at night only the morphological and material variables have weight.

The nomograms representing both models show that an adequate combination of variables could decrease the air temperature up to 6.8 °C in the daytime, and up to 3.5 °C at night. The handling of the four sets of variables has a higher impact during daytime when compared to nighttime air temperatures.

Furthermore, approximately 30–40% of the effect corresponds to the modification of the albedo of the horizontal and vertical envelops, for daytime and nighttime respectively. This result spotlights the importance of the appropriate selection of materials for pavements and facades.

On the other hand, during the day, the urban canyons without trees are the warmest. Even though some cases of forested low density schemes are warmer than those of high building density without trees. This highlights that buildings create a shadow, which cools the air.

The best and the worst morphological expressions were elaborated in terms of thermal behavior as recommendations to be included for building code decisions. Forested canyons that are 30 m wide and buildings that are 6 m high give the best performance in both periods for residential areas. However, for forested high density cases, there is no single configuration that offers the best thermal performance for both periods. For this reason, the best zoning (business or mixed uses) for these areas will be a challenge for urban planners. Otherwise, for renewal, the focus should be in the modification of the albedo of urban surfaces.

Finally, it is important that urban planners take into account better urban policies to be more effective, create appropriate design, and make informed planning decisions. These include all aspects of planning, not only from thermal standpoint.

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