Landscape and Urban Planning 167 (2017) 249–256

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Design tool to improve daytime thermal comfort and nighttime cooling of urban canyons

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ARTICLE INFO

Keywords:
Design tool
Urban canyons
Daytime thermal comfort
Nighttime cooling

ABSTRACT

As the urban population increases, the land area occupied by cities has increased at an even higher rate. Given this trend, urban warming has become a global phenomenon that affects outdoor comfort, energy consumption and air quality. Urban climate researchers assess cities' micro-climate behavior in order to be able to propose a suitable urban design. In this sense, urban planners still face a lack of simple tools to evaluate thermal behavior and the comfort conditions of an urban space. This study aims to develop a design tool, which was developed from collected field surveys in a non-forested urban canyon and in 18 representatives of forested ones in Mendoza, Argentina. A linear multivariate thermal comfort model called the COMFA-tool was created and performs well (R^2 = 0.86). The predictive capability of the developed tool was tested. Urban forest variables contribute up to 60% of comfort improvement. The study discusses how confusing it can be to use a solely morphological indicator in forested arid cities (i.e., H/W). Additionally, daytime thermal comfort and nighttime cooling were contrasted. The results presented lead us to think of a compromise solution in terms of designs of urban canyons. We encourage urban planners to use these design tools in order to improve the microclimate behavior of cities.

1. Introduction

In the last several decades, the world has seen an increased gathering of its population in urban areas. This trend is not new, but it is relentless. According to UN-Habitat (2016), in 1990, 43% of the world's population lived in urban areas; by 2015, this had grown to 54%. As the urban population increases, the land area occupied by cities has increased at an even higher rate. It has been projected that by 2030, the urban population of developing countries will double, while the area covered by cites will triple (Angel, Parent, Civco, & Blei, 2011).

One of the best-known urban effects of such development is urban warming, which alters urban climatology, increases the energy consumption of buildings, decreases outdoor thermal comfort in the summer and increases the concentration of air pollutants (Akbari, Davis, Dorsano, Huang, & Winert, 1992; Fujibe, 2009; Grimmond, 2007; Kolokotroni, Ren, Davies, & Mavrogianni, 2012; Wong, Jusuf, & Tan, 2011).

The urban climate is generated from complex phenomena in which many factors are involved. The particular characteristics of each city make it difficult to define effective microclimatic control strategies for all applications. This forces urban planners to confront the problem with a wide margin of uncertainty in the results. For this reason, it is important to understand how cities perform climatically in order to be able to propose an urban design according to the natural resources and the particular features of the cities.

The studies of the microclimatic behavior of cities are based mainly on the following:

(i) Experimental methods associated with the measurement of microclimatic variables. These methods have allowed advances in the knowledge of theoretical models of heat exchange and fluid dynamics between air and urban surfaces (Andrade, Alcoforado, & Oliveira, 2011; Chen et al., 2012; Krüger & Rossi, 2011; Lin, 2009; Mahmoud, 2011; Makaremi, Salleh, Jaafar, & Ghaffarian Hoseini, 2012; Nikolopoulou & Steemers, 2003; Ruiz, Correa Cantaloube, & Cantón, 2015a; Tan, Wong, & Jusuf, 2014; Yahia & Johansson, 2013; Yang, Hou, & Chen, 2011). However, their use and application are limited to the scientific field because they are complex methods that require expensive measurement equipment to acquire the data.
(ii) Computational calculation that models the urban microclimate and thermal comfort. These tools have the advantage of less investment

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http://dx.doi.org/10.1016/j.landurbplan.2017.07.002
Received 7 November 2016; Received in revised form 14 June 2017; Accepted 3 July 2017
0169-2046/

of resources with a good degree of adjustment to the measured data. Additionally, simulations allow for the performance of parametric studies and evaluation of hypothetical urban scenarios (Ali-Toudert & Mayer, 2007; Giridharan, Lau, Ganesan, & Givoni, 2007; Mirzaei & Haghighat, 2010). Among the most well-known tools, we can mention RAYMAN (Matzarakis, Rutz, & Mayer, 2007) and ENVI-met Biomet (Bruse, 2016). The use of these tools presents limitations associated with the demand for a large number of input data and difficulties related to requiring high-performance equipment and system operators with a high level of expertise.

Currently, urban planners still face a lack of simple tools to evaluate the thermal behavior and the comfort conditions of a built environment in the pre-design stage. This is why the development of easy-to-use tools would help urban planners to improve the microclimatic conditions of cities.

Based on this background, the objectives of this work are as follows:

- To develop a design tool that can be used by urban planners to evaluate different design alternatives and select the most efficient from the point of view of increasing habitability in cities.
- To contrast the day and night microclimatic behavior of urban canyons by using easy-to-use design tools.

2. Materials and methods

2.1. Study cases

The Mendoza Metropolitan Area (MMA) is located in central western Argentina (32°53′ S, 68°51′ W, 750 m.750 ma.s.l.). According to the Koppen-Greiger climate classification, it is in an arid continental climate: BWh or BWk depending on the isotherm used (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). It is characterized by cold winters and hot summers, with significant daily and seasonal thermal amplitudes. Winds are moderate and infrequent, the amount and intensity of solar radiation is high, and the average annual rainfall is 198 mm (Gonz & lez Loyarte, Menenti, & Diblasi, 2009). The MMA is considered an oasis city because a major part of the streets are forested.

Nineteen representative urban canyons were selected according to three axes: tree species, street widths and building densities. These characteristics reflect the variety of the prevailing urban features of the MMA. Based on these characteristics, we selected 18 forested urban canyons. The forested canyons had the typical tree species of first and second magnitude. The classification of forest magnitude is based on the end height that a tree reaches 20 years after planting. The first magnitude is for species whose end height exceeds 15 m, such as the London plane tree (*Platanus* × *hispanica* Mill). The second magnitude is from 8 to 15 m, such as for the European ash (*Fraxinus excelsior* L.). In addition, one urban canyon had no trees. Pictures of the forested urban canyons of Mendoza are shown in Fig. 1. We selected three typical street widths: 16, 20 and 30 m; this derives from the MMA urban regulation policies (Regulatory Law N°4341/1978). In relation to building density, we chose low (buildings from 3 to 6 m in height) and high (buildings from 6 to 24 m in height). All selected urban canyons are oriented East-West to show the greatest difference in temperatures in the summer.

Taking into account the features of the selected cases, we decided to explore different types of variables. The variables selected by category are as follows:

- Urban forest structure: solar permeability (SP), number of trees (NT), trees per meter (T/m), mean tree height (MTH), tree cover (TC) and tree view factor (TVF).
- Urban canyon structure: building volume (BV), compactness (C), urban canyon length (UCL), volume/width (V/W), urban canyon width (UCW), volume/length (V/L), mean building height (MBH), height/width (H/W), building view factor (BVF) and sky view factor (SVF).
- Optical properties of materials: vertical surface albedo (VA) and horizontal surface albedo (HA).
- Microclimate: daytime air temperature (DTair), daytime surface temperature of pavement (DTpav), daytime surface temperature of sidewalk (DTsw), daytime surface temperature of walls (DTwall), solar radiation (SR), relative humidity (RH), wind speed (WS), daytime thermal comfort (COMFA) and nighttime air temperature (NTair).

For more information about the selection and description methodology of the urban variables, see Ruiz, Sosa, Correa Cantaloube, & Cantón, 2015b.

2.2. Thermal monitoring

To obtain the values of microclimatic variables, we conducted a measuring campaign from December 17, 2009 to January 26, 2010. The data from this campaign was divided into two periods: daytime (from 9 am to 9 pm) and nighttime (from 9 pm to 9 am). The values of each variable have been averaged for each period. A fixed sensor type H08-003-02 was installed in each urban canyon at 2 m above the ground (Oke, 2004).

In addition, urban canyons were monitored during the daytime between January 8 and January 26, 2010 with a mobile weather station named H21-001. Each urban canyon was divided into four sectors (NE, SE, SO and NO). In each sector, the mobile weather station was moved to a representative point every 15 min. This equipment records air temperature, surface temperature, relative humidity, solar radiation and wind speed data every 15 min. This procedure allowed for the measurement frequency at the same point within the urban canyon to not exceed 1 h.

2.3. SVF Calculation

SVF is one of the most relevant parameters for describing urban structures in complex built environments; i.e., it depends on the morphological and forest urban combinations. There are different methods to obtain the SVF of urban canyons. Digital images acquired from existing urban canyons can be processed with optical software. For hypothetical urban canyon geometries, SVF values can be obtained from simulation software (Bruse, 2009; Chen et al., 2012; Matzarakis et al., 2007; Miguet & Groleau, 2002).

In this study, the SVFs of 19 urban canyons were calculated with “PIXEL DE CIELO”, free software. “PIXEL DE CIELO” obtains accurately

Fig. 1. Forested Urban Canyons of the MMA. (a) Platanus x hispanica and (b) Fraxinus excelsior. Adapted from: Correa, Ruiz, & Cantón, 2010.

the SVF value of a certain urban environment from digital fish-eye images acquired with a digital camera (Correa, Pattini, Córica, Fornés, & Lesino, 2005). For the SVF of hypothetical scenarios, we used ENVI-met® 3.1 (Bruse, 2009) because its algorithm achieves a fine resolution of the results.

2.4. Comfort index

Ruiz & Correa Cantaloube (2015) presented a comparison between six thermal comfort models, contrasted with 667 subjective reports, in order to identify which of the models can be used to most correctly predict the thermal comfort of outdoor spaces of the MMA. They give some recommendations on the use of the indices for arid regions as per the research goals. When the goal is to achieve urban design strategies that maximize habitability, COMFA index (Brown & Gillespie, 1995) is suggested. The values of thermal comfort in summer obtained using the street's SVF and horizontal solar irradiance were the most closely correlated with the subjective reports among the studied models. COMFA is the index with the best predictive ability in summer. This index was the only one that considers the attenuation of solar irradiance from the trees.

For these reasons, the COMFA index was selected in this work. COMFA expresses the energy balance in W/m^2 of an individual in an open environment (Gaitani, Mihalakakou, & Santamouris, 2007). When the balance is near zero, it may be expected that an individual feels thermally comfortable. Fig. 2 describes the sensation of human comfort relative to the values of energy balance. The microclimatic variable "daytime thermal comfort" agrees with the average of the registered values between 5 pm and 6 pm. This time coincides with thermal discomfort peak of the city.

3. Multivariate analysis

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

The PCAs were carried out using the Infostat software (Di Rienzo et al., 2011). The resulting principal components did not achieve a tangible meaning and were not used in the MLR. The original variables defined in the preceding sections were used as independent variables.

The MLR methodology was selected because it establishes 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).

All selected variables are continuous quantitative variables and have a normal distribution and homogeneous variance, as the testing for assumptions shows in the following sections. The explanatory variables for each model were selected based on four criteria: a) high Pearson coefficients with the respective dependent variables; b) absence of multicollinearity; and c) diversity of categories in each model. Table 1 shows the values of the Pearson coefficients for each dependent variable.

Table 1
List of variables with their respective abbreviations grouped into the four categories and the Pearson correlation coefficients of each variable in relation to the comfort indicator (COMFA).

Category	Variable	with COMFA
Urban Forest Structure	Solar permeability (SP)	0.74*
	Number of trees (NT)	−0.49*
	Trees per meter (T/m)	−0.44
	Mean tree height (MTH)	−0.70*
	Tree cover (TC)	−0.76
	Tree view factor (TVF)	−0.67*
Urban Canyon Structure	Building volume (BV)	−0.16
	Compactness (C)	−0.02
	Urban canyon length (UCL)	−0.19
	Volume/Width (V/W)	−0.17
	Urban canyon width (UCW)	0.06
	Volume/Length (V/L)	−0.11
	Mean building height (MBH)	−0.07
	Height/Width (H/W)	−0.10
	Building view factor (BVF)	0.08
	Sky view factor (SVF)	0.56*
Optical Properties of Materials	Vertical surface albedo (VA)	−0.02
	Horizontal surface albedo (HA)	0.04
Microclimate	Daytime air temperature (DTair)	0.39
	Daytime surface temperature of pavement (DTpav)	0.85*
	Daytime surface temperature of sidewalk (DTsw)	0.78*
	Daytime surface temperature of walls (DTwall)	0.62*
	Solar radiation (SR)	0.71*
	Relative humidity (RH)	−0.25
	Wind speed (WS)	−0.09
	Daytime thermal comfort (COMFA)	1*
	Nighttime air temperature (NTair)	0.02

*Significant at the 0.05 probability level.

3.1. Nighttime cooling

In terms of nighttime cooling, we used a previously developed model of nighttime air temperature (Ruiz et al., 2015b). The model is shown in Eq. (1). The goodness of fit is statistically reliable (RMSE = 0.93%).

$$NTair = 23.50 + 1.79 * {}^{H}\!/_{W} - 0.026 * MBH - 0.000000138 * BV + 2.18 * VA \quad (1)$$

where NTair is the nighttime air temperature, H/W is the height/width ratio, MBH is the mean building height, BV is the building volume and VA is the vertical surface albedo.

4. Results

4.1. Thermal comfort model

Regarding the aim of generating a design tool (COMFA-tool), the following variables were selected for a regression model: NT and SP (urban forest structure), SVF (urban canyon structure), and DTwall (microclimatic variable). The model is shown in Eq. (2). The large

COMFA (W/m^2)	Sensation
COMFA < -150	Would prefer to be much warmer
-150 > COMFA < -50	Would prefer to be warmer
-50 > COMFA < 50	Would prefer no change
50 > COMFA < 150	Would prefer to be cooler
COMFA > 150	Would prefer to be much cooler

Fig. 2. Sensation of human comfort relative to the values of the energy balance COMFA.

Table 2
Goodness of fit and testing for assumptions for the developed model. Note that the model meets the assumptions.

Goodness of fit Adjusted R^2	RMSE	Normality Shapiro-Wilks test (W)	Homoscedasticity Studentized Breusch-Pagan test (BP)
0.8606*	13.40%	0.9464	3.3406

*Significant at the 0.05 probability level.

influence of forest variables on thermal comfort is notable.

$$COMFA = -491.59 - 12.90 * SP - 4.86 * NT + 313.23 * SVF + 20.89 * DTwall \quad (2)$$

where COMFA is the daytime thermal comfort, SP is the solar permeability, NT is the number of trees, SVF is the sky view factor and DTwall is the daytime surface temperature of walls.

The goodness of fit and testing for assumptions are shown in Table 2. The adjusted coefficient of determination R^2 is high and expresses a good proportion of explained variability (0.86), and the root-mean-square error (RMSE) is acceptable. The value of the Shapiro-Wilk test (W) is greater than the alpha (0.05); therefore, it is concluded that the data follow a normal distribution. The same occurs with the Breusch–Pagan test (BP): the independent variables are homoscedastic.

The COMFA model was validated with data from a measurement campaign during summer 2015 in seven other forested street canyons of MMA. The p-value > 0.0001 from a T-test for independent samples indicates that the COMFA model has been validated.

The validity ranges of the model were calculated with a confidence level of 95% (Table 3).

4.2. Testing the design tools

The COMFA-tool from Eq. (2) has been elaborated in order for it to be used as a tool for pre-designing urban canyons. This tool involves four variables that are accessible for urban planners. Cantón et al. (1994) and Tak & cs et al. (2016) present values of tree-species solar permeability. The number of trees in each street can be determined according to the planting distance of trees (according to the recommended tree magnitude). The daytime wall surface temperature especially depends on the level of exposure to solar radiation and the optical properties of used materials. Finally, the SVF can be obtained from field data acquired or estimated by using computational calculations from hypothetical situations.

To test the COMFA-tool prediction capabilities, thirty-six urban canyons were assessed. Taking into account the variables involved in the model, the DTwall value was fixed at 31 °C because it is the resulting average, the median and the mode in the monitored cases. The SP and NT vary according to tree species. Typical species that exist in the MMA were used (Cantón, de Rosa, & Kasperidus, 2003), one of first magnitude — *P. hispanica* (SP = 0.098, NT = 18) — and one of second magnitude — *F. excelsior* (SP = 0.162, NT = 25). The NT values were calculated according to the tree planting distance (first magnitude = 11 m and second magnitude = 8 m). The trees were arranged on the two sidewalks in a 100 m length street. The SVF values vary according to building height (3, 6, 12 and 24 m), street width (16, 20 and 30 m) and tree species. These values were calculated by using ENVI-met 3.1 ® (Bruse, 2004) (see Fig. 3a).

Table 3
Ranges of validity for the model.

Variable	Minimum	Maximum
SP	0.1	1
NT	0	30
SVF	0.27	0.88
DTwall	29.16	38.21

Fig. 3a shows that when we compare data acquisition methods for obtaining SVF values, the results are similar. For example:

- As the street width increases and the building height decreases, SVF values are higher. The non-forested cases show higher SVF values at any building height and street width. In particular, for the 16 m street width, the forestation halved the SVF values.
- For the 30 m street width, the impact of the forestation is less obvious. This means that in the cases with an MBH equal to 24 m, the SVF values are similar in the forested and non-forested cases (i.e., maximum ΔSVF = 0.025).
- Forested streets with second magnitude trees have higher SVF values compared to first magnitude trees.

Fig. 3b shows the following results:

- According to sensation ranges of the COMFA index (Fig. 2), no urban canyon presents thermal comfort conditions. This coincides with the empirical results of Correa et al. (2012) and Ruiz (2013).
- As the street width decreases, people feel more comfortable (COMFA values are lower), but larger intervals are observed. In streets 30 m wide, the COMFA varies between 211 and 434 W/m^2, in streets 20 m wide, it varies between 147 and 415 W/m^2, and in streets 16 m wide, the variation is between 92 and 400 W/m^2. The influence of street width on thermal comfort is 1.5–3.8 times higher in forested streets than in non-forested streets.
- As SVF increases, COMFA values increase too, i.e., thermal discomfort increases. A smaller SVF generates an increase of shading on the streets. This highlights the importance of a design that takes into account the relationship between urban morphology and vegetation.
- For the forestation, second magnitude trees achieve the lowest COMFA values (the most comfortable situation). This means that the degree of comfort is between 40 and 70% more acceptable than on the street without trees. While the SP of the second magnitude tree is slightly higher than that of the first magnitude tree, NT is the factor that explains this situation (> NT, < COMFA). It is important to break down the influence of the planting distance according the tree species in order to achieve suitable results.
- In the non-forested streets, the outdoor thermal comfort is dramatically low for any SVF. This observation confirms the marked cooling effect produced by the urban forest.

4.3. Daytime thermal comfort and nighttime cooling

To test the predictive capability of the design tools, the day and night microclimatic behaviors of different urban canyons were contrasted. Figs. 4 and 5 show the thirty-six urban cross-sections with their corresponding thermal comfort and nocturnal thermal behavior.

The values of COMFA were obtained from Eq. (2) by setting the variable values to those of the previous description (see section "Testing the design tools"). The values of nighttime air temperature were obtained from Eq. (1) by setting the variable values as follows. The MBH was set at four heights, two that correspond to the low density (3 and 6 m) and two to the high density (12 and 24 m). The H/W values vary between 0.1 and 1.5, according to the three typical street widths (16, 20 and 30 m) and the four MBH values. The BV values are 4500, 9000, 18000 and 36000 m^3. These results are obtained from the product between the MBH and the buildings' footprints (considering a street length equal to 100 m). The VA was fixed at 0.6. It should be noted that the forest variables do not appear in the nighttime statistical model, unlike in the COMFA-tool.

From analysis of Figs. 4 and 5, in terms of daytime thermal comfort, we see that all the scenarios have thermal discomfort due to heat. The

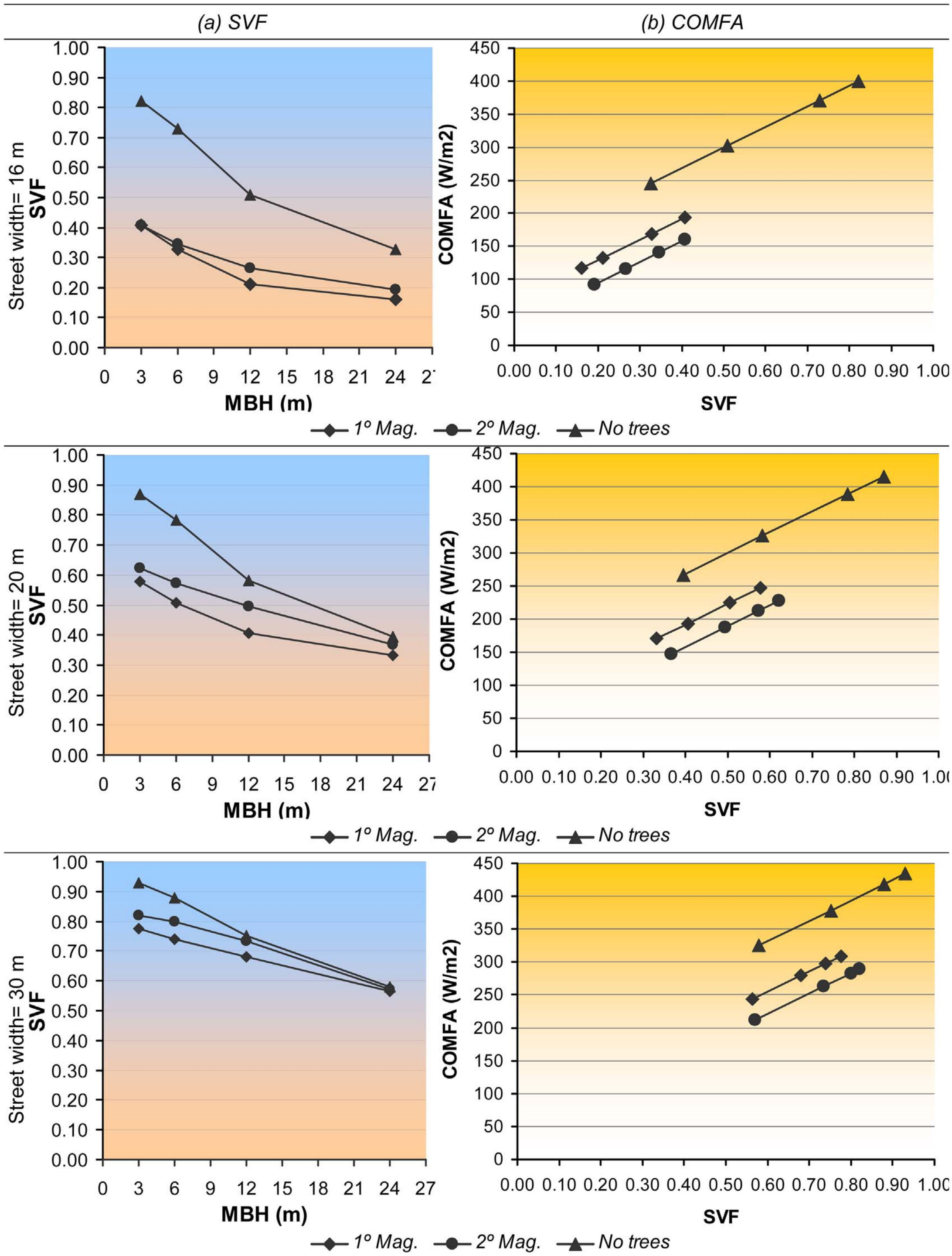

Fig. 3. (a) SVF values according to building heights, street widths and tree species. (b) COMFA responses according to the COMFA-tool.

best scenario is the second magnitude forested canyon with the highest H/W ratio (1.5). On the other hand, the worst scenario is the non-forested canyon with the lowest H/W ratio (0.1). The habitability improves by creating shadows in the canyon through the combination of morphology and forestation. When forested and non-forested configurations are compared, there is a difference of up to 240 W/m2 using equal urban morphology (UCW = 16 m, MBH = 3 m, H/W = 0.2). This demonstrates the important contribution of the urban forest in cooling outdoor spaces (up to 60%).

In terms of nighttime cooling, there is not a marked difference among the assessed scenarios (ΔNTair = 1.9 °C). However, when the worst and the best scenarios are compared, opposite responses occur for both periods. Therefore, we can deduce that nocturnal cooling is greater in lower and wider urban canyons compared with higher and narrower ones (the best scenario is the non-forested canyon with the lowest H/W ratio). Irradiative cooling strategies are possible thanks to the broad sky view.

5. Discussion

The H/W ratio has been widely used as an indicator of the irradiative and convective conditions of a street (Offerle, Grimmond,

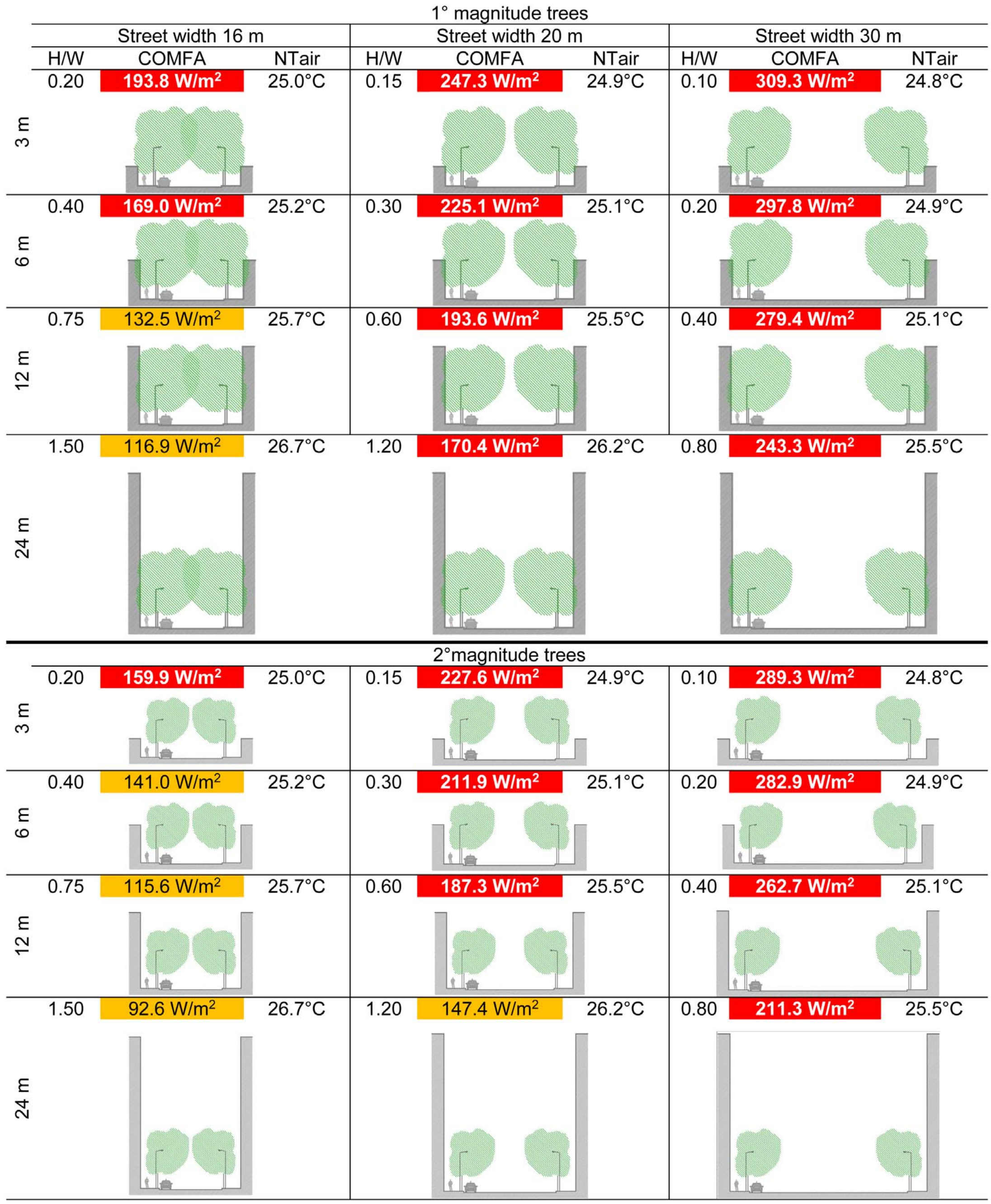

Fig. 4. Comfort and NTair values for each of the twenty four forested urban cross-sections tested.

Fortuniak, & Pawlak, 2006; Oke, 1988; Ratti, Di Sabatino, & Britter, 2006). In particular, Ali-Toudert & Mayer, (2007) and Shashua-Bar & Hoffman (2004) have discussed urban geometry in arid cities. According to Mohammed & Chang (2015), in extreme hot-arid climatic zones, mitigating the UHI intensity and enhancing the microclimate depend on two main descriptors of the urban canyon's geometry, namely, H/W and orientation. Shishegar (2013) found that the availability of solar energy on the street's facades decreases rapidly with the increase of the aspect ratio of the canyon.

However, the results of this study warn us about how confusing it can be to use the H/W as the only morphological indicator in forested arid cities, where vegetation plays a preponderant role. Regarding the results, it can be noted that the urban scenarios with the same H/W ratio have different COMFA responses (e.g., forested scenarios with an H/W = 0.40 have ΔCOMFA = 46%, with non-forested equal to 2%).

Another result that is important to note is that the scenarios with better conditions of outdoor thermal comfort during the day have the highest nighttime air temperatures. These high night temperatures generate an increase in the energy consumption. For instance, Papanastasiou et al. (2013) studied the impact of UHI on energy consumption in Volos, Greece. They found that UHI intensity reaches 3.1 °C during summer nights, with almost twice the cooling load in the city with respect to the suburbs. For this, it is important to arrive at a compromise solution in terms of urban planning. While giving proper zoning to the city, the urban warming can be reduced, improving the thermal habitability and avoiding overheating.

In terms of zoning, the residential areas (low density) must have better nighttime air temperature (lower energy consumption). Outdoor thermal comfort can be improved with more green spaces near these areas (e.g., forested squares and parks for recreational activities). In the study city, low density areas are defined as those buildings with no more than 2 floors (6 m height), inserted at any street width (16, 20 or

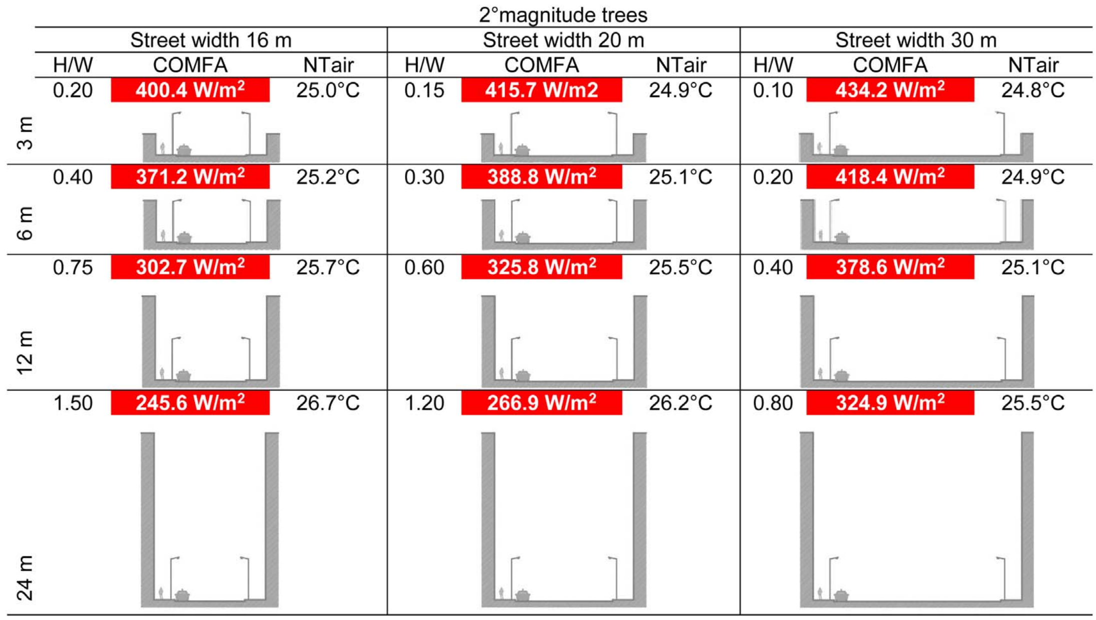

Fig. 5. Comfort and NTair values for each of the twelve non-forested urban cross-sections tested.

30 m) and forested with any tree species.

The mixed-use areas (high density) should have better outdoor comfort. This criterion is because the activities in these areas mostly occur during the daytime. To achieve this, the developed design tools can predict that narrow streets (16 or 20 m width) with buildings of 12–24 m height and forested with a second magnitude tree will have the best thermal comfort. For 30 m width forested streets, only 24 m height buildings achieve acceptable comfort conditions. However, it is important to remember that high concentrations of buildings and impervious surfaces increase the irradiative heating, intensifying the urban warming at night.

On the other hand, it is interesting to note that the results obtained and the urban recommendations coincide with those reported for the study city and other regions (Alchapar, Cotrim Pezzuto, Correa, & Chebel Labaki, 2016; Correa, Ruiz, Cantón, & Lesino, 2012; Krüger, Pearlmutter, & Rasia, 2010; Shashua-Bar, Tsiros, & Hoffman, 2012), both in microclimatic monitoring and simulations. This point demonstrates the good performance of the design tool developed.

6. Conclusions

The study presents a design tool carried out by developing a statistical model that performs well ($R^2 = 0.86$). The aim of this tool is to help urban planners know the outdoor thermal comfort conditions of an urban canyon according to the COMFA index. The urban variables involved in the model can be set up in the planning stage of the built environments. Additionally, a nighttime air temperature model that was previous developed was used to complement the results. These two models are considered very reliable design tools for urban planners. The results of testing of the COMFA-tool, in line with previous research, showed that forested urban canyons are the best option to provide the greatest urban warming reduction and increased habitability. Urban forest variables contribute up to 60% in comfort improvement. The study discusses how confusing it can be to use an only morphological indicator in forested arid cities (i.e., H/W). Therefore, it is important to analyze all the characteristics involved in the urban canyons' energy balance. The results presented lead us to think of a compromise solution in terms of designs of urban canyons. Planning strategies can improve microclimatic performance by generating proper urban zoning. We strongly encourage urban planners to use these design tools that help to predict the urban canyons' behaviors in design decisions.

Acknowledgments

This work was supported by the Agencia Nacional de Promoción Científica y Tecnológica (ANPCYT) [grant numbers PICT 2011-0611]; and the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) [grant number PIP 2011-00640].

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